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# A FURTHER STUDY OF THE AIR VORTEX METHOD OF SPINNING YARNS

Presented

by

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TO MY DEAR SISTER SOBHANA

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## ABSTRACT

The present study is a continuation of Hirway's work on the air vortex method of spinning yarns. A critical study of the working of Hirway's apparatus led to some modifications to the apparatus including the spinning tube design. These modifications resulted in a substantial improvement in the spinning performance of the spinner. A control exercised on the static charge level in the spinning tube was found to be beneficial to spinning.

Experiments were conducted to optimise the spinning tube design. The shape and size of the tangential inlets and also those of the yarn exit hole were altered. The effect of the tube material and the bore size on the spinning performance was found. The effect of tube transition was considered in some detail.

The theories of air and fibre flows were analysed and the theory of yarn movement was discussed. The process of fibre assembly leading to the yarn formation was also dealt with.

Torque tests were conducted with different yarn lengths, air pressure differences, yarn materials and spinning tube designs. The factors which control the nature and amount of torque were found. From this, it was possible to obtain the conditions favourable to the maximum torque insertion rate in the yarn.

Yarn tension was also measured under identical conditions to those which existed during the torque tests. The air flow rate in the various spinning tube designs was measured. The power consumed by the spinner was calculated for the different set-ups when working with different air pressures.

Photographs showing the different aspects of vortex spinning, viz., fibre flow path, yarn shape etc., were obtained.

Finally, the structure and properties of the vortex yarns was studied from the photographs of the fibre arrangement in the yarns.

# CONTENTS

Page

Page

Page

Page

## SECTION III

## ADVANCED THEORY OF VORTEX SPINNING

Page

Page

Page

# SECTION I

# I N T R O D U C T I O N

## CHAPTER 1

## INTRODUCTION

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# INTRODUCTION

## 1.1. A BRIEF HISTORY OF SPINNING

### 1.1.1. Early spinning

The art of spinning dates back beyond historical records and it is reasonably supposed that the simple process of hand spinning was known and practised about 6000 years ago.

In hand spinning a well opened and cleaned mass of cotton is held in one hand and the projecting fibres are slowly pulled off and simultaneously twisted between the thumb and the forefinger of the other hand. The cohesion between the fibres enables short lengths of yarn to be spun.

Possibly the first known mechanical means employed to spin staple yarns from the sliver consisted of the distaff and the spindle. The downwards pull of the rotating spindle produced a reasonably good yarn from the sliver on the distaff and this yarn was wound on to the spindle. This method of spinning was in common use until about two centuries ago.

The next development was the Spinning Wheel in which a rotating wheel replaced the movement of the operator's arm for imparting the rotary movement to the spindle. This spinning wheel was used in India from very early times although it was introduced into Europe in the fourteenth century only. In a further improvement known as the Saxony Wheel a foot treadle was used to change the reciprocating motion into a circular motion.

The various developments which have led to the modern mechanised spinning had their beginning during the era of the Industrial Revolution in England. This Industrial Revolution brought in its wake stupendous changes in the economic world by the invention and large scale use of cotton spinning machinery. Sherer[1] wrote that Watt's steam engine, Hargreave's spinning jenny, Arkwright's mule, Cartwright's loom and Kay's fly shuttle seized the entangling threads of cotton and out of them wove a new destiny.

1.1.2. Roller drafting

There appears to be a controversy as to whether John Wyatt or Lewis Paul invented the idea of roller drafting although in 1738 Lewis Paul was granted a patent for his roller drafting spinning machinery. Now for the first time mechanical means were employed to attenuate the fibres. In 1770 James Hargreaves took out a patent for the Spinning Jenny which consisted of a wooden framework carrying a movable carriage and a number of spindles driven by bands from a cylinder rotated by a handwheel. During its operation predetermined lengths of rovings held between the spindles and the carriage were drafted by the movement of the latter away from the former and twist was inserted by the rotation of the spindles. Thus in the Spinning Jenny the process of twisting while stretching was mechanised.

The adaptation of roller drafting was perfected by Arkwright in 1769 in his patented Spinning Frame which is generally acclaimed as the fore-runner of the roller drafting spinning frame of the present day. A multi-spindle machine. The Arkwright's "water-frame" drafted the roving by means of three pairs of rollers dead weighted by a lever system and imparted twist by flyers which also wound the spun yarn on to the bobbin with the help of a series of hooks. Water power was first used to drive Arkwright's spinning machine, hence the name "water-frame".

1.1.3. Mule spinning

The drawing rollers of Arkwright's frame and the stretch and twisting arrangement of Hargreave's jenny were combined together in the invention of Crompton's mule in 1779. Crompton's mule, because of its crude construction, required considerable manual labour with skill. Richard Roberts improved it and produced the self-acting mule.

The mule spun yarn was not subjected to a winding-on tension during the twisting process and, therefore, the tension upon it was not necessarily greater than that imposed by its own weight. On this account the mule was capable of spinning a weaker yarn than any other type of spinning machine and it was, therefore, pre-eminent in the production of the finest yarns. Moreover the low spinning tension enabled the spinning of a higher count of yarn from a given quality of material than any other machine. The mule spun yarn because of the peculiar nature of the spinning process, possessed certain characteristics which were not so easily obtained in other later methods of spinning. The yarn produced was fuller, softer to handle, more level and more hairy than yarn spun on the ring frame which succeeded the mule.

However, mule spinning was a discontinuous process as it involved the stoppage of the drafting mechanism during the time that the spun yarn was wound on to the body of the spindle. The intermittent nature of mule spinning accounted for its low production rate per spindle. The floor space requirements for the machine was large. The mule was a complicated machine and it needed highly skilled labour. The combination of all these disadvantages far outweighed the advantage gained in yarn quality.

1.1.4. Ring spinning

In 1828 John Thorpe patented a ring concentric with the spindle but the credit for the invention of the ring traveller is attributed to Addison and Stephens (1829) of New York and Jenks (1830) of Pawtucket, Rhode Island. However, Thorpe was granted a patent in 1844 for a ring traveller of the present form. From then onwards, the ring frame system made headway in the domain of cotton yarn manufacture and this process became fairly well established by the end of the last century. Owing to its comparatively simple and inexpensive operation together with its high productivity, the ring frame gradually replaced the mule which is no longer generally used for cotton spinning although in certain countries it is still used for certain special classes of work.

The advancements made in textile technology have created many changes in processing technique. During the last 50 years, ring spinning has attained a high degree of perfection although the basic spinning principles remain still the same. High draft systems have been developed. These are essentially efficient drafting mediums with improved mechanical design and so it has been made possible to attain given standards of yarn regularity at very much high levels of draft. The yarn package size has been increased and also high spindle speeds have been achieved by the use of improved bearings designed to withstand heavy unbalanced loads. The improvements made in rings and travellers and the use of balloon control rings are also important factors in attaining high spindle speeds. New and better materials and methods of construction together with improved lubrication techniques have enhanced the standards of quality of the ring frame. All these developments have contributed much towards the economy of performance of the ring frame of today. Economies have also been achieved by increasing the size of the creel package and the introduction of pneumatic underclearers and travelling cleaners. However, over the last two decades, labour costs have greatly increased and in spite of the several advancements made spinning still remains one of the most expensive single processes in yarn manufacture.

## 1.2. LIMITATIONS OF THE RING SPINNING SYSTEM

### 1.2.1. Introduction

When ring frames were first introduced, relatively short lift, low speed machines were employed. These were more productive than the mules and proved sufficiently adequate under the conditions existing at that time. Since then, the economics of spinning, particularly of coarse count yarns, has increasingly demanded large packages and high yarn delivery speeds. The modern ring frame is a highly developed spinning system and possibly because of this, the various factors controlling its production rates have been fully investigated. The Limitations to further improvements in ring spindle productivity arise due to the economic and technological considerations of the system. These two factors have to be taken into account together to give a better understanding of the limitations imposed on the system as a whole.

### 1.2.2. Technical limitations

There are some basic technical limitations in the ring frame which impose a restriction on attaining further increases in package size and production rates than has hitherto been achieved. An increase in package size substantially reduces the cost of doffing and subsequent handling costs of yarn. The production rate may be increased by raising the spindle speed and this is done with a view to reduce the capital cost per unit of production.

#### 1.2.2.1. Limit of package size

The package size may be increased by increasing either the ring diameter or the spindle lift or both of them together.

##### 1.2.2.1.1. Ring diameter

A large ring diameter allows the building of a yarn package of a correspondingly large diameter. For a constant yarn speed and spindle speed, the linear velocity of the traveller increases with ring diameter. Again, for a given ring and traveller, there is a limiting traveller speed above which (a) the friction between ring and traveller causes excessive wear and burning and (b) the centripetal forces act on the yarn to produce undesirably high tensions which will tend to result in a high end-breakage rate. Thus this limiting traveller speed seems to impose a restriction on the maximum ring diameter that can be used for a particular range of counts.

1.2.2.1.2. Spindle lift

An increase in spindle lift permits the building of long packages. For a particular yarn count at a given spindle lift and speed, there is a minimum yarn spinning tension below which it is difficult to spin because of balloon collapse. When the balloon height increases, the balloon radius also increases until it reaches a maximum value after which the balloon collapses and spinning becomes quite impracticable. Thus it seems that the dynamics of the yarn balloon enforce certain limitations on high spindle lifts. The use of control rings or the more recent invention of "collapsed balloon" spindles solve, to a great extent, the problems related to balloon collapse.

1.2.2.2. Limit of spindle speed

The use of very high spindle speeds may be limited by the following factors:-

(a) yarn delivery rate,
(b) yarn balloon,
(c) end-breakage rate,
(d) yarn strength and
(e) traveller velocity.

1.2.2.2.1. Yarn delivery rate

The yarn delivery rate is limited by the ability of the operator to make a satisfactory piecing when a yarn breakage occurs. The limiting speed for manual piecing is around 750 inches per minute when spinning coarse counts. Since it is more difficult to piece up fine yarns than coarse yarns, it is the general practice to keep the delivery rates lower for fine counts. Nevertheless, this limit may be raised by the use of automatic piecing mechanisms at the expense of increased capital charges.

1.2.2.2.2. Yarn balloon

For a given count, spindle lift and spindle speed, there is a minimum yarn tension below which the balloon collapses. For an average quality, medium twist cotton yarn of 40 tex spun on a 2 in. diameter ring[2], the maximum balloon tension that can be used without successive end-breaks occurring is about 40 gf (equivalent to about 1 gf per tex). For a spindle speed of 10,000 r.p.m., the balloon height should not greatly exceed 9 inches. Thus it appears that for any spindle speed, there is a balloon height above which the end-breakage rate becomes excessive. Even innovations such as balloon control rings provide only a limited increase in spindle speed.

1.2.2.2.3. End-breakage rate

With a given traveller, the yarn tension varies approximately as the square of the spindle speed. At high speeds, the greatly increased spinning tension causes the number of end-breakages per spindle hour to increase rapidly and above a certain speed, it becomes excessive. The spindle speed at which this occurs depends to a large extent on the yarn strength.

1.2.2.2.4. Yarn strength

Owing to the reduced yarn twist in the region between the lappet and the front roller nip, there is a resultant reduction in yarn strength in this region. This imposes a limit on the spindle speed. A technological limit to high speed production is also set by the fibre itself. Fibre and yarn stresses become excessively large at high production rates so that even small variations in them result in yarn breakage.

1.2.2.2.5. Traveller velocity

Traveller speed is also one of the major limiting factors in high speed spinning. Until few years ago, a maximum speed of about 70 feet per second was widely accepted. High traveller speeds produce frictional heating of the ring and traveller surfaces. This causes traveller burns and eventually results in traveller breakages. Ring damage may also occur which gives rise to peaks in yarn tension which leads to an increased number of end-breakages. Unlubricated travellers cannot be run very fast because of the excessive heat generated in them while lubricated travellers running at very high speeds cause rapid wear of the traveller and the ring. The practical limit of the traveller speed depends particularly on the weight and shape of the traveller, the ring diameter and the contour of the ring flange. The commonly used C-section traveller makes only partial contact with the ring. It has a high centre of gravity and it tends to cant over during running. The recently developed elliptical traveller has a low centre of gravity and presents a large bearing surface to the ring. Hence this traveller can be run at higher speeds than the C-section traveller. Traveller speeds have been further increased by the use of anti-wedge rings (introduced in 1953) when they are used in conjunction with elliptical travellers. In these rings, the bearing surface between the ring and the traveller has been extended to reduce the wedging of the traveller by matching the ring profile to the traveller section. It is claimed that this combination will permit traveller speeds of over 100 feet per second. The maximum permissible traveller speed has been still further raised by recent developments in ring and traveller manufacture, such as the use of micro-etched ring surfaces and molybdenised travellers. It is claimed that the traveller speed with these improved conditions can reach up to 125 feet per second on a 2 in. diameter ring. Traveller speeds have greatly increased during this decade. It is rather difficult to foresee wherefrom any further improvements can emerge to further increase the maximum traveller speeds of today. At least for the present moment, it appears that a limit in this direction has been reached.

1.2.3. Economic limitations

The three important factors that decide the economics of spinning are the labour cost, capital cost and power cost. In view of the rising cost of labour it seems quite reasonable to reduce the labour cost at the expense of capital and power. A study of the economic factors has led to two major developments in the modern ring frame design. Firstly, the yarn package size has been increased by increasing both the ring diameter and the spindle lift. Secondly, high spindle speeds have been used.

The package sizes were increased because the cost of power to drive larger packages had decreased in relation to the cost of labour to doff and rewind them. Similarly, the spindle speeds were increased because the cost of power had decreased in relation to the capital cost of the ring frame.

Large packages are used essentially to reduce labour requirements but often a substantial increase in machine utilisation is also effected. In addition, there may be an improvement in yarn quality because of the reduction in piecings after spinning. The optimum package size may be evaluated by counterbalancing these advantages gained against higher capital costs for machines, extra floor space, increased end-breakage rate and increased power consumption. Also, there is a general tendency to lower the spindle speeds as package sizes are increased thereby reducing the production rate. Furthermore, large packages necessitate the use of balloon control rings which tend to make the operations of piecing and doffing slightly more difficult. The latter increases the cost of doffing though only to a small extent. Balloon control rings also tend to increase the hairiness of yarns.

In order to reduce the capital cost per unit of production, the production per spindle hour has been increased by raising the spindle speeds. Apart from the technological limitations mentioned in 1.2.2.2., the use of very high spindle speeds is also limited by economic considerations. Higher spindle speeds lead to higher power costs.

It may be noted that package power (power required to rotate the package against the resistance offered by the air drag on the surface of the package) and spinning power (power required to overcome ring-traveller and yarn-traveller friction, to rotate the yarn between package and thread guide against the air resistance) together with the secondary spindle power (power required to drive spindles, tapes and tin rollers) constitute the major components of the total power required on the ring frame. According to DeBarr and Catling[(2)], the package power required per unit of production is approximately proportional to $(\text{ring diameter})^{2.75}$ and also to (spindle speed)$^{1.5}$. Since there is no direct increase in production rate due to an increase in ring size, the spinning power per unit of production increases rather more rapidly than the ring diameter. However, the spinning power per unit of production is proportional to (spindle speed)$^{2}$. When the combined costs of capital and power are taken into account, it is doubtful if the use of very high spindle speeds and very large packages will, in any way, reduce the spinning cost per unit of production.

Considering the economic factors, it will be found that the three primary costs of spinning (labour cost, capital cost and power cost) are closely inter-related and form an eternal triangle of ring spinning economics. Basically, the problem is that some costs increase whilst others decrease. Capital costs per unit production may be reduced by increasing the power costs. Doffing and rewinding costs may be reduced by increasing the package size but, for the same spinning speed, the power costs and the capital costs are increased. The power cost can be reduced by running the spindles at low speed but this leads to a low production, thereby increasing the capital costs. Small package sizes will permit comparatively high spindle speeds but the doffing and the winding costs will increase and the machine utilisation will be low. Catling(3) showed that in ring frames the combined doffing and winding costs are about the same as the power costs. So it appears that it may not be possible to reduce any single cost component without effecting an increase in other cost components. A compromise to this complex solution can only be arrived at by determining the optimum package size and spindle speed for a particular range of counts by taking into consideration both the technological and economic factors.

### 1.2.4. Conclusions

The modern ring frame has reached a high degree of mechanical and technical perfection. Its limitations on spindle speeds and package sizes have been fully examined. In actual practice, an optimum package size for a particular range of counts is initially determined when ordering new frames. Optimum spindle speeds are arrived at later for each yarn count. Any further increases over the optima may only prove uneconomical.

All the limitations of the ring spinning system discussed earlier point to the fact that the problem of further increasing the productivity of the ring frame is unlikely to be resolved except by a system which dispenses with the ring and traveller and also with the dead weight of the package on the rotating spindle.

## 1.3. SPINNING DEVICES WITHOUT THE USE OF RING AND TRAVELLER

There are various methods of spinning without the aid of a ring and traveller and only the important ones are discussed below.

### 1.3.1. Flyer spinning

Flyer spinning introduced at the beginning of the sixteenth century is a fairly old method. Although this method is still used for the spinning of worsted and bast fibres, it is no longer used for the final spinning in cotton yarns because of its limitations in speed. It is quite unlikely that speeds in excess of about 4,000 revolutions per minute can be used owing to the deformation of the flyer arms.

1.3.2. Cap spinning

In an attempt to dispense with the flyer, Danforth, in 1828, invented a cap spinning spindle capable of running at speeds up to 7,000 r.p.m. In cap spinning, the lower edge of a stationary cap serves as a thread guide and exerts the necessary tension on the yarn which is wound on a rotating bobbin inside the cap. Thus the cap replaced the ring with its traveller. The advantage of this system is the possibility of spinning very fine worsted yarns but here too the maximum speed is limited to about 10,000 turns per minute.

1.3.3. Pot spinning

Cylindrical pots can be operated at speeds of 20,000 to 25,000 revolutions per minute without imposing any great tension on the yarn. The yarn is laid in layers on the inner wall of the pot and held in position by centrifugal forces. Twist is inserted by the rotation of the pot. After the spinning is completed, it is necessary to rewind the yarn from the pot to a bobbin. Any break occurring during rewinding interrupts the operation. However, a feeler inserted through the top of the pot picks up an end almost instantaneously and rewinding then continues. To start spinning, it is necessary to insert a seed yarn. This system which originated in England has been recently further developed in Japan by the use of a pneumatic guide for the yarn. Even though high rates of production have been obtained by this method, it is not entirely satisfactory mainly because of yarn wastage in rewinding. The wastage is usually much higher than with the conventional ring frame system. Moreover, in the event of any accidental stoppage of the frame the yarn remaining in the pots constitutes a wastage of material. The power consumption and the floor area required per spindle are high. The warming up of the pot during spinning causes drying of the yarn resulting in hairiness which tends to create yarn entanglements in later clearing operations.

1.3.4. Can spinning

Can spinning is the reverse of pot spinning. The roving is placed inside a can and it is withdrawn from the centre. Rotation of the can imparts the necessary twist. Owing to the absence of any drafting mechanism, this machine is limited to the spinning of coarse and low twist yarns only. The rotational speed of the can is also limited because of its large dimensions.

1.3.5. Spinning with floating rings

In a system of spinning with floating rings, the traveller is replaced by a light weight floating ring placed concentrically inside a fixed ring. The outer diameter of the floating ring is slightly smaller than the inner diameter of the fixed ring. The yarn moves in the gap between the two rings and its tension lifts the ring bodily upwards. This inner ring is, therefore, kept floating during spinning. The disadvantages in this system are (a) the difficulty experienced during starting of the machine and (b) the difficulty in piecing up because the yarn is wedged tight between the two rings until the inner ring is brought into floating position.

Attempts have been made to keep the inner ring floating by means of magnetic induction. One other important point is that the weight of the floating inner ring must be exactly matched to the yarn tension during spinning. Taking into consideration all these drawbacks, it appears that this method is not capable of improving on the productivity of the conventional ring frame.

### 1.3.6. Two-for-one twisters

Spinning with "two-for-one" twisters allows the production rate to be doubled by imparting two turns of twist to the yarn for each turn of the spindle. In this case, the drafting unit or the package building unit is necessarily confined within the envelope of the yarn balloon. A limitation on high operating speeds is imposed by the mechanics of the yarn balloon. It is also difficult to piece up an end when it breaks because of the large size of the balloon. Although it is possible to spin a yarn by this method with the resultant advantages of double twisting, this mechanism has been found to be expensive and complicated for normal operation. Hence it is doubtful if this system would provide any substantial improvement over the conventional methods of spinning.

### 1.3.7. General conclusions about spinning methods working without ring and traveller

All the above systems of spinning suffer mainly from two disadvantages. In all but one case, the method of twist insertion has been achieved by relative rotation of the yarn package and the creel package. Therefore the need to turn the spindle with the dead weight of the package on it leads to an excessive increase in power consumption, particularly when the size of the yarn package builds up. Secondly, there is the frequent necessity to stop these spindles for doffing purposes.

It, therefore appears that the successful spinning machine of the future will be a machine which is capable of high productivity with low power consumption and which dispenses with the relative rotation between the supply and yarn take-off. It must also be capable of running continuously (or nearly so) which means that the frequent doffing must be eliminated and that large yarn packages in cone or cheese form will be produced. Not the least important, however, is that the machine must be as simple as possible in its construction and in operation. This difficult specification could not be met by any of the spinning systems mentioned earlier in this chapter. Hence it is necessary to consider systems of spinning which are basically of a completely different nature from the conventional methods.

## 1.4. BREAK SPINNING

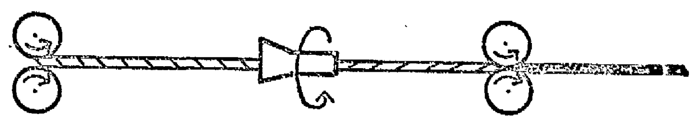
Various new concepts of spinning have been suggested from time to time during the last few decades and some of them have been experimented upon. These unconventional methods of spinning are generally based on an entirely different principle of spinning. One is known as "break spinning" in England and "open-end spinning" on the Continent. It is appropriate to point here that the idea of break spinning had been in the minds of inventors for more than a century and early patents date back as far as the early 1800s. The term "break spinning", however, is of recent origin. The potentialities of break spinning have been appreciated for the last few years only because there has recently been a reappraisal of the economic design possibilities of the ring spinning system which showed it to have reached its limit as far as productivity is concerned.

Break spinning is so called because breaks are introduced in the flow of fibres between the creel and the yarn package. A break is essential in order to avoid the need for relative rotation of the supply and final package and at the same time insert true rather than false twist. Twist is introduced by merely rotating the yarn end at the break. The alternative name open end spinning has been given because the forming yarn to which the fibres attach themselves is free and unrestrained. It is only by imparting a rotation to this open end that spinning of yarn is achieved.

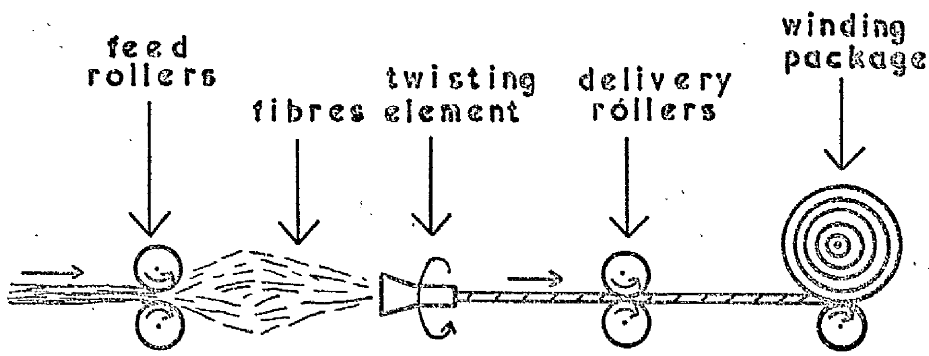
The indispensable nature of the break can easily be understood from a study of Fig. 1.1. If a yarn gripped between two pairs of rollers is twisted by the rotation of a twisting element placed about midway between the rollers, then false twist will be the result. On the other hand, a break in the flow of fibres between the supply roller and the twisting element will enable a true twist to be imparted to the yarn.

1.4.1. Advantages of break spinning

This particular aspect of the break offers additional advantages. Yarn packages can be built as large as may be desired without incurring high power costs. Doffing can be virtually eliminated. Rewinding can also be eliminated if quality and cleanliness of the yarn produced are sufficiently satisfactory to produce a quality fabric. Also, high twisting rates are possible and this, in turn, is likely to yield increased production rates per spindle hour. Consequently, the capital costs may be reduced without an undue increase in power costs. All these points are in favour of the break spinning system which is still in its early years of develop-



a) False Twisting




b) Break Spinning

Fig. 1.1

DIAGRAM SHOWING THE PRINCIPLE OF BREAK SPINNING ment. It seems to be almost certain that the advent of break spinning will be much earlier than it was hitherto anticipated. There was a time when break spinning was thought to be a highly speculative proposition but today it has reached a stage when, in the not-too-distant future, it may possibly offer a practical system of spinning. Research studies in several of the break spinning techniques are being conducted at the present moment in many laboratories of the world. Useful yarns have been spun from different fibres on the various systems. The twist insertion rate has been, in certain cases, up to 30,000 turns per minute and it is reported that yarns up to 80s cotton counts have been spun.

### 1.4.2. Limitations of break spinning

In general, the break spun yarn has a different yarn structure as compared to that of a ring spun yarn. Hence the appearance and character of the break spun yarn differs quite considerably from that of a conventional yarn. This factor might give rise not only to further processing difficulties but also to considerable marketing problems. A lack of flexibility in obtaining yarns of desired characters might be another disadvantage. In some cases, the twist per inch might not be precisely controlled in the wide range that is normally possible in the ring spinning system.

The breaking tenacity of open end yarn is lower than that of a ring spun yarn of equivalent count. This reduction in tenacity varies from 10% to 40%. Even though the yarn tenacity is low, this yarn can be subsequently processed to produce fabrics for certain end uses because of the extremely good evenness and, therefore, good strength regularity of the yarn. In the break spinning process, the yarn spinning tension is quite low. The break spun yarn is generally softer and more extensible than a ring spun yarn. The yarns are usually 'full' and because of this property, the fabrics produced from them possess good cover.

1.4.3. Methods of break spinning

The various break spinning methods may be broadly classified into three categories. They are as follows:-

(a) mechanical methods,

(b) electro-static methods and

(c) fluid methods.

These methods are briefly discussed here since they are dealt with in detail in the next chapter.

1.4.3.1. Mechanical methods

With the mechanical methods, the twisting element is rotated by mechanical means. An example of the mechanical method of break spinning is the Czechoslovakian[(4)] drum spinning machine-BD 200- which produces a good yarn for weaving and knitting purposes. Nevertheless this machine has its problems too. It was said to consume about 80 watts per spindle as against an equivalent figure in terms of a ring spindle of about 30 watts per spindle when spinning[(2)] 16 c.c. at 10,000 r.p.m. on a 2 in. ring. Even taking into consideration the increased production rate per spindle and also the elimination of doffing and winding costs, it appears that the increased power consumption will nullify, to a certain extent, the advantages gained by this system. Moreover, it is quite possible that such a high speed precision built machinery will increase the maintenance costs. It is likely that continuous running of the machine will cause a coating of wax, dirt etc., to be deposited in the interior of the spinning drum, especially when spinning cotton fibres and it is not yet known if this coating will have any detrimental effect on the spinning performance.

1.4.3.2. Electro-static methods

It has been found possible to exercise control even on individual fibres by the use of electro-static charges. This principle has been made use of in these methods. However, the presence of high voltage gradients associated with the constant danger of di-electric breakdown (which may cause large sparks) can prove to be a source of great trouble. The forces exerted on the fibres are so small that they are likely to be of limited use for practical purposes.

1.4.3.3. Fluid methods

In most of the fluid methods, a vortex in the fluid is generally utilised for imparting twist to fibre assembly to form a yarn. The fluid method may be subdivided into two groups based on the nature of the medium used for transportation of the fibres. They are (a) hydraulic methods and (b) air vortex methods.

1.4.3.4. Hydraulic methods

In the hydraulic methods, fibres suspended in a liquid stream (usually water) are made to flow through small tubes, either stationary or rotating, and emerge from a narrow orifice. Rotation of the liquid causes the fibres to assemble on the tube wall and it also provides the twist that is so necessary to bind fibres together to form a yarn. However, in certain cases, the twisting elements are mechanical contrivances and this limits the rate of twist insertion in the yarn.

The hydraulic methods seem to have many disadvantages. The use of relatively large quantities of liquids is quite likely to present handling difficulties. Surface tension effects may have an adverse effect on the uniform dispersion of fibres in the medium. Furthermore, the need for drying the wet fibres in the resulatant yarn would necessarily involve the use of expensive drying equipment.

1.4.3.5. Air vortex methods

Of the various unconventional methods of spinning yarn, the one employing the technique of air vortex has interesting potentialities. Vortex spinning is, of course, only one of many forms of break spinning which are currently being investigated. Much work still remains to be done on this system before it can be pronounced a complete success.

It is interesting to note that even as early as 1928, Balls[5] wrote in his book "..... I must confess to an uneasy suspicion that some non-mechanical method is lying in wait for some inventor who is not so familiar with the existing methods as to be prevented from seeing something otherwise obvious". Balls's prediction seemed to have come true with Gotzfried's[6] invention of the air vortex method. This method is simple as it has no mechanically moving parts. The process of spinning is done by pneumatic means only.

In Gotzfried's[6] method of air vortex spinning, fibres moved along a stream of air into a vortex generated in a tube. One end of the tube was exhausted by a suction pump and the other was closed by a nozzle with tangentially placed air inlet holes. Fibres were fed into the tube at a position which was midway along the tube length. Yarn was formed by the attachment of a portion of these fibres flowing in the vortex to the forming yarn. The vortex introduced twist into the forming yarn. Yarn was withdrawn from an axial hole in the nozzle end of the tube and it was wound directly on to a winding package.

In this method, after their release from the supply rollers, the fibres were free to travel along with the air currents. This caused a break to be introduced in fibre flow. The free end of forming yarn was rotated by the vortex. Thus the basic requirements for break spinning are fulfilled and hence the air vortex spinning may be rightly considered as a form of break spinning.

Catling[7], while commenting on Gotzfried's method, states

> "The vortex really exists although it cannot be seen. It is completely reliable and it introduces twist into yarn with a quite remarkable absence of fuss and bother. Even a very simple mock-up permits one to spin yarns of a quality which is very encouraging. Unfortunately, the sophistication of design which is needed to produce yarn of a commercially acceptable quality has proved somewhat elusive, but the long term prospects for this system are good".

While discussing the various unconventional methods of spinning yarns, Lord[8], with special reference to the air vortex method, states

> "It is possible to create vortices rotating at phenomenal speeds without the use of any mechanically moving parts. In theory at least, using air it would seem possible to attain fantastic rates of twist insertion without the disadvantages suffered

by all mechanical devices but in practice these twist insertion rates have not yet been achieved".

Several different methods of feeding fibres into the vortex tube have been tried. Gotzfried[6] used a plucking device to open out the fibres from a sliver. In Hirway's[9] device, a drawn sliver was attenuated in a drafting mechanism and the drafted fibres were fed into the vortex tube. Chandarana[10] succeeded in presenting fibres directly from a card cylinder of a conventional revolving flat type card. It may also be possible to supply the fibres from a modern high speed card. Whatever the nature of the fibre feed, the success of these methods will depend, to a great extent, on the performance of the vortex spinning technique itself.

Work done by Hirway[9], based on Gotzfried's method, was quite encouraging even though the quality of yarns produced by him was far from satisfactory when compared with the commercial standard yarns. According to him, the capital and power costs of air vortex spinning machinery were likely to be less than in the case of the conventional machinery. He further added that if a reasonable quality of yarn could be produced, then the air vortex method stood a good chance of competing with orthodox methods.

The air vortex system, as used by Hirway, had certain drawbacks. The yarn produced was less even and much weaker than conventionally spun yarns. The production rates were not high as might be suggested by the high vortex speeds used. It was not possible to obtain continuous lengths of yarn because of frequent breakages during the spinning process. In addition to the fibres going to waste during yarn breakages, a great amount of fibres was collected as waste in the suction pump because only a small portion of the fibres supplied was attached to the forming yarn.

It was felt that the disadvantages mentioned above may be greatly reduced in their magnitude and some of them may even be completely eliminated. Attempts made towards this aim would indeed prove to be a stimulating challenge in view of the fact that the air vortex method possesses certain inherent advantages. The main advantage of the air vortex spinner, when compared to other forms of break spinners, lies in its extreme simplicity of design and the complete absence of mechanically moving parts. This is precisely where this spinner stands a good chance of scoring over the precision built, high cost drum type break spinner. The capital cost of the air vortex spinner is likely to be low because of its simple design. Air which is the medium used for fibre assembly and twist insertion is available free and in abundance. Furthermore, shortening of the spinning process by linking the vortex spinner to the early stages in yarn manufacture (as on cards or draw frames) may bring about radical changes in the economics of spinning. In view of these favourable features, it was thought that efforts made to minimise the drawbacks of this system but, at the same time, retaining in full measure its attractive qualities would prove to be a worthwhile and rewarding project for research. A detailed study of this method may also throw light on its various limitations.

Taking into account all the foregoing considerations, it seemed that a development of Hirway's work offered scope for substantial advances in the subject. It was, therefore, decided to conduct a further study on Hirway's method of air vortex spinning of yarns.

# CHAPTER 2

# SURVEY OF LITERATURE

# CHAPTER 2

# SURVEY OF LITERATURE

## 2.1. INTRODUCTION

A survey of literature in the field of unconventional methods of spinning yarn showed that though the term "break spinning" or "open-end spinning" was of recent origin, the idea of this principle was in the minds of at least a few inventors even as early as the beginning of the last century. It is not known if any of these ideas took a practical shape then. In fact, it seemed that no serious thought was ever given to these proposed techniques at that time. It might be presumed that these novel ideas were too much ahead of their times.

The great potentialities of unconventional methods were appreciated only about a decade ago when it was realised that conventional spinning had almost reached the limitations in production and productivity. Slater[11] observed that even though there were sharp increases in machine productivity of preparatory spinning machines(cards, draw frames and speed frames) during the last two decades, the productivity of the ring frame had shown only a little improvement. This is illustrated in Fig. 2.1. The very slow rate of increase in ring frame productivity seemed to suggest that the maximum limit in this direction was almost achieved. The attention of the textile research organisations and the machinery makers was, therefore, focussed on alternative methods of spinning staple yarns. A preliminary investigation into this subject was made from the Patent Specifications and this brought to light many relatively unknown but quite ingenious methods of spinning yarns. Some of the more promising systems from among

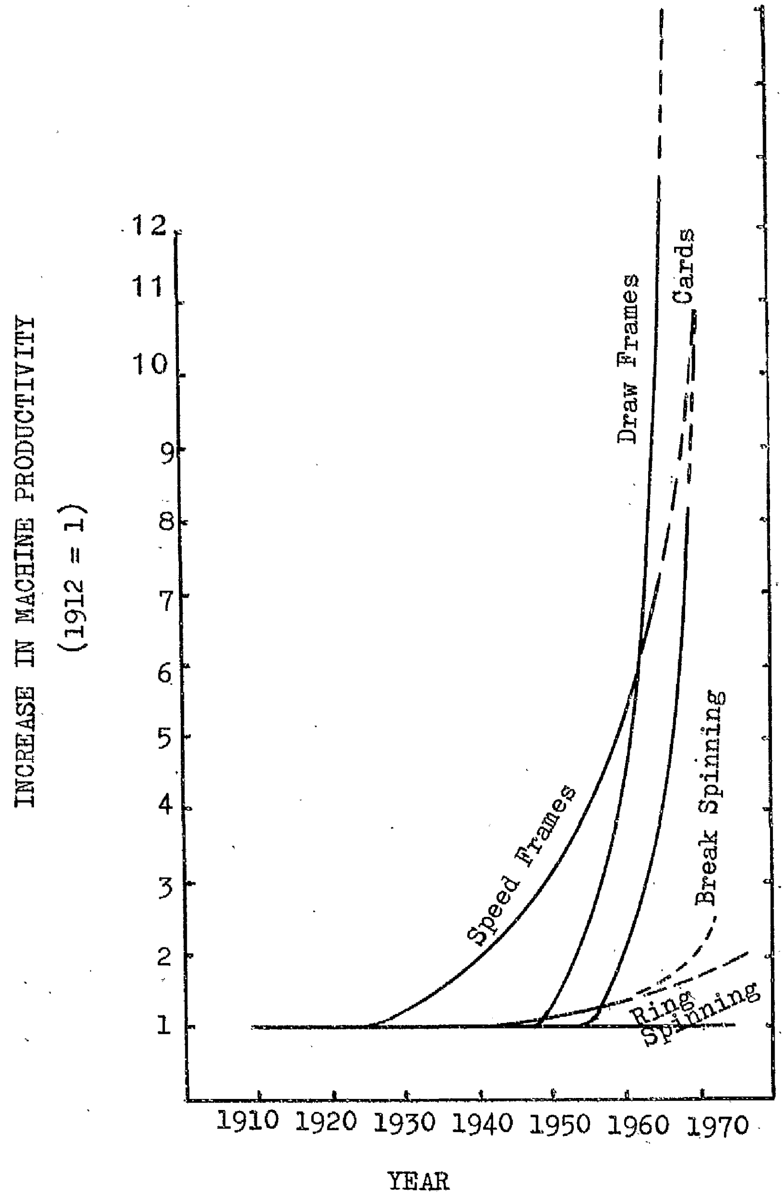



Fig. 2.1

RISE IN PRODUCTIVITY OF SPINNING MACHINERY these patents have been taken up for further study and research in various countries. These ideas have been transformed into practical working models and a thorough investigation of the various problems of their working performance is being currently conducted in many research institutions.

During the last five years, great interest has been evinced in break spinning. Although work in this field is proceeding in many countries, very little has been published so far in scientific journals. It is only in recent years that some interesting papers have started appearing in technical magazines. Most of these papers dealt with a documentary study in this subject while only a few of them relate their experimental findings. Much of the information contained in this chapter was obtained from the British and United States Patent Specifications. These patents described the mechanical parts of the inventions in great detail but it was regrettable that many of them scarcely mentioned their working performance. Some of the patents which were published towards the end of this research were not, however, included in this review.

The unconventional spinning methods have few things in common with the conventional spinning system. Sometimes, it may be that certain conventional machines, such as, cards, may be modified to feed fibres into the unconventional spinners and on occasion a conventional drafting system is used. Beyond these points, there seems to be nothing in common. The use of drafting devices for attenuating the rovings or slivers fed is often quite different from the conventional roller/apron drafting system. Some of these opening devices are in fact miniature taker-in type cylinders.

Those unconventional spinning systems now universally known as break spinning or open-end spinning, differ completely fromthe traditional methods in their principle of yarn formation. The fibrous material, whether it be in the form of bale,lap, sliver or roying should be fully opened into individual fibres and these fibres are then presented to the spinning elements where they are reassembled and a yarn is formed. The various fibre separating-cum-feeding devices are taken up in detail in Chapter 3.

## 2.2. A SHORT HISTORY OF BREAK SPINNING

The history of break spinning may be broadly divided into two parts. The first part consists of a survey of literature that appeared more than fifty years ago. The second part deals with literature reviewed during the period from 1915 to recent times.

It is not possible to review in this chapter all the material published so far on this subject. Quite a largenumber of the devices, especially in the early years, seemed to be almost similar in their design. Therefore a selection was made to present only those devices which seemed to possess some originality.

### (a) Survey of literature covering the early years

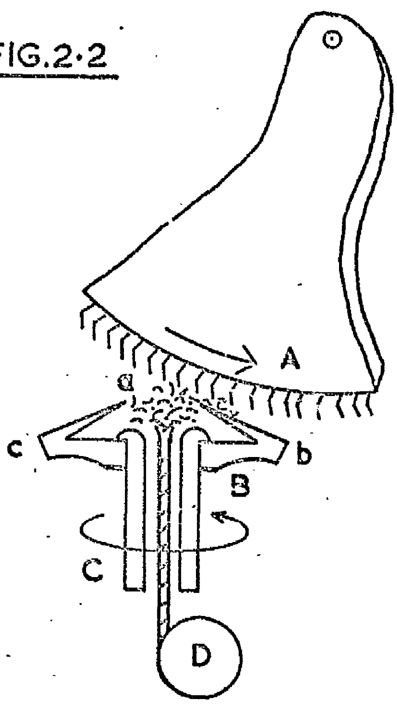
It is generally believed that Professor Barker in the early 1930s was the first to conceive the idea of the break spinning. This belief is belied by the fact that during the last quarter of the nineteenth century many patents were granted for devices based on the principle of break spinning. Even during the first half of the same century a few patents were issued which were relevant to mechanisms based on this principle. A patient search by the author through the brittle pages of the early British Patents revealed that in 1807 an Englishman, Samuel Williams[12], obtained a patent relating to a method of spinning yarn based on what was then thought to be an entirely novel principle and which is known today as break spinning. Therefore it appeared that Samuel Williams was perhaps the pioneer in the concept of break spinning.

Samuel William's method was concerned with spinning yarns directly from the card cylinder. A conical comb B with its teeth converging towards the apex rotated on a hollow axis BC(please see Fig. 2.2.). This comb was placed closely to a card cylinder A. Rotation of the comb transferred the fibres from the cylinder to the comb. A seed yarn introduced into the hollow axis BC was laid on the comb surface and the fibres from the comb attached themselves to the seed yarn. Twist was imparted to the forming yarn by the rotation of the comb. The spun yarn was withdrawn by a pair of rollers and then wound on directly to any desired package.

It is quite likely that this method might produce a fairly satisfactory yarn at low rates of yarn withdrawal. High speeds of comb rotation needed for high rates of production may throw out the embedded fibres into the atmosphere. This may cause not only atmospheric pollution and fibre wastage leading to high yarn irregularity but it may also result in frequent yarn breakages. All these factors may give rise to large irregularities in the final yarn. Threading of a seed yarn seems likely to be difficult.

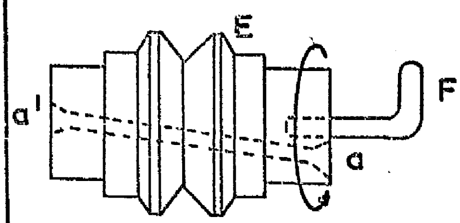
Paul Robin[13] (1839) suggested the use of spinning tubes mounted near ring doffers of a roller and clearer card. The ribbon of sliver from the doffer was passed round a hook F and then through an inclined hollow portion aa' of a spinning tube (Fig. 2.3.). Rotation of the tube caused yarn formation.

FIG. 2·2



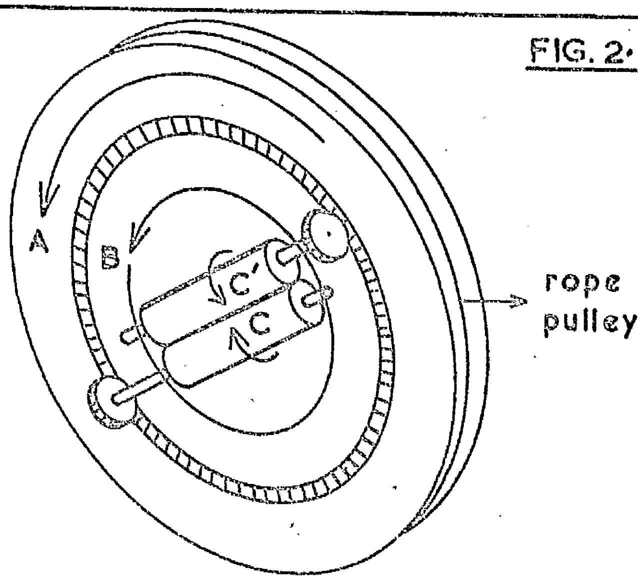

1807 WILLIAMS' SPINNER

FIG. 2·3




1839 ROBIN'S SPINNING TUBE

FIG. 2·4




1900 SPEAK & SEDGWICK'S SPINNING DEVICE.

A simple device patented in 1864 by Suckow[14] was more or less an inverted Barker's spinner. It consisted of a rapidly revolving tube having a small hole at right angles to the bore. Fibres from drawing rollers entered the tube and then assembled on to a seed yarn already introduced into the tube hole. Withdrawal of the seed yarn through the hole produced a yarn.

It is interesting to note that most of the patents taken out later in the last century employed ring doffers of cards to feed fibres into spinning and twisting tubes. Changes among these patents were noticed only in the design of these tubes which were claimed to spin yarns directly from cards. Count George De Vanssay[15] (1864) proposed that the web from the doffer was to be compressed in a rotary or a rubbing apparatus but he did not mention any details of these mechanisms. Condenser spinning with rubbing belts seemed to have been first suggested by Mackie[16] in 1865. It may be mentioned in this context that condenser cards used widely in the woollen industry and, to a somewhat lesser extent, in the cotton waste spinning for spinning yarns directly from cards almost work on the break spinning concept. The use of travelling bands for rubbing the web and thereby forming a yarn was also put forward by Johnson[17] in his earlier patents in 1897 and in 1898. However in his later mechanisms the rubbing apparatus was replaced by twisting tubes.

Holden[18] (1865), Lake[19] (1869), Woodhouse and Chaffer[20] (1871) and Brandon[21] (1884) referred to twisting tubes but gave very little or no details of these devices. The first complete details of a spinning tube was furnished by Speak and Sedgwick[22] in their patents in 1900. In short, this tube was a mechanism containing a pair of drawing rollers cc' capable of being rotated on their own axes as well as bodily together with the tube A (Fig. 2.4.). The rotary movement of the rollers cc' on their axes pulled the fibre web from the doffer while the bodily rotation of the two rollers together with the tube A formed a yarn, provided that a break was maintained in the fibre supply. The movement of the former controlled the yarn withdrawal rate and that of the latter determined the twist in the yarn. Instead of a twisting tube, it was suggested that the sliver web could be acted upon by three rollers all revolving in the same direction.

Phillips[23] (1900) described a spinning machine which was similar to the Barker's apparatus described later in section 2.3.1.1. Metcalf[24] (1901) suggested the use of a spinning tube. The fibres supplied by a drafting mechanism were subjected to the action of a comber type roller. These fibres were then transferred and collected on the surface of the twisting tube. Yarn was supposed to be formed at the point of the rotating twist tube. It is highly doubtful if the fibre cohesion would be sufficient to produce a reasonably good yarn.

In an application to bast fibres, the use of revolving trumpets for twisting the loose fibres issuing from the doffer and forming them into a strand was proposed by Archibald[25] (1869) and Hawley and Palmer[26] (1911). Archibald's description of the apparatus is neither clear nor complete. In Hawley and Palmer's method, a suitably constructed collar constituted a bearing for a revolving condensing trumpet. The bell-shaped trumpet was formed with a band pulley on the outside and in the mouth of the trumpet were fixed a number of flat blades. These blades were tapered from the mouth to the throat of the trumpet and they were placed longitudinally at equidistant spaces. Fibres presented to the trumpet from a moving conveyor belt were collected and simultaneously twisted together by the rotation of the trumpet. The resultant yarn was wound in a suitable package. How far this method would work out in practice is highly speculative. It seems to be certain that the exercise of precise control over fibres during the presentation might pose problems.

Many of the devices mentioned above were unique in spinning concept and some of them seemed to employ simple mechanisms only. In spite of the many patents issued in this field, it is not really known to what extent, if any, these devices were made and tried out in practice during those years. It must be emphasized that the above mentioned devices could be considered as break spinners only if a break occurred in fibre flow and a true twist was inserted in yarn.

<u>(b) Survey of recent literature</u>

Even a cursory glance at the patents issued during the last two decades and, in particular, those granted in the last five years will indicate that there has been a great upsurge in research activities in this field. This dramatic increase in the number of break spinning units is evident from Fig. 2.5. The methods are numerous and, therefore, it seems absolutely essential to classify them into groups in order to have a clear understanding. These may be broadly classified on the basis of the principal types of force employed for both fibre assembly and twist insertion. Strictly speaking, in most of the systems it is rather difficult to attribute a certain type of force as being solely responsible for yarn formation since it is known that a combination of various types of force

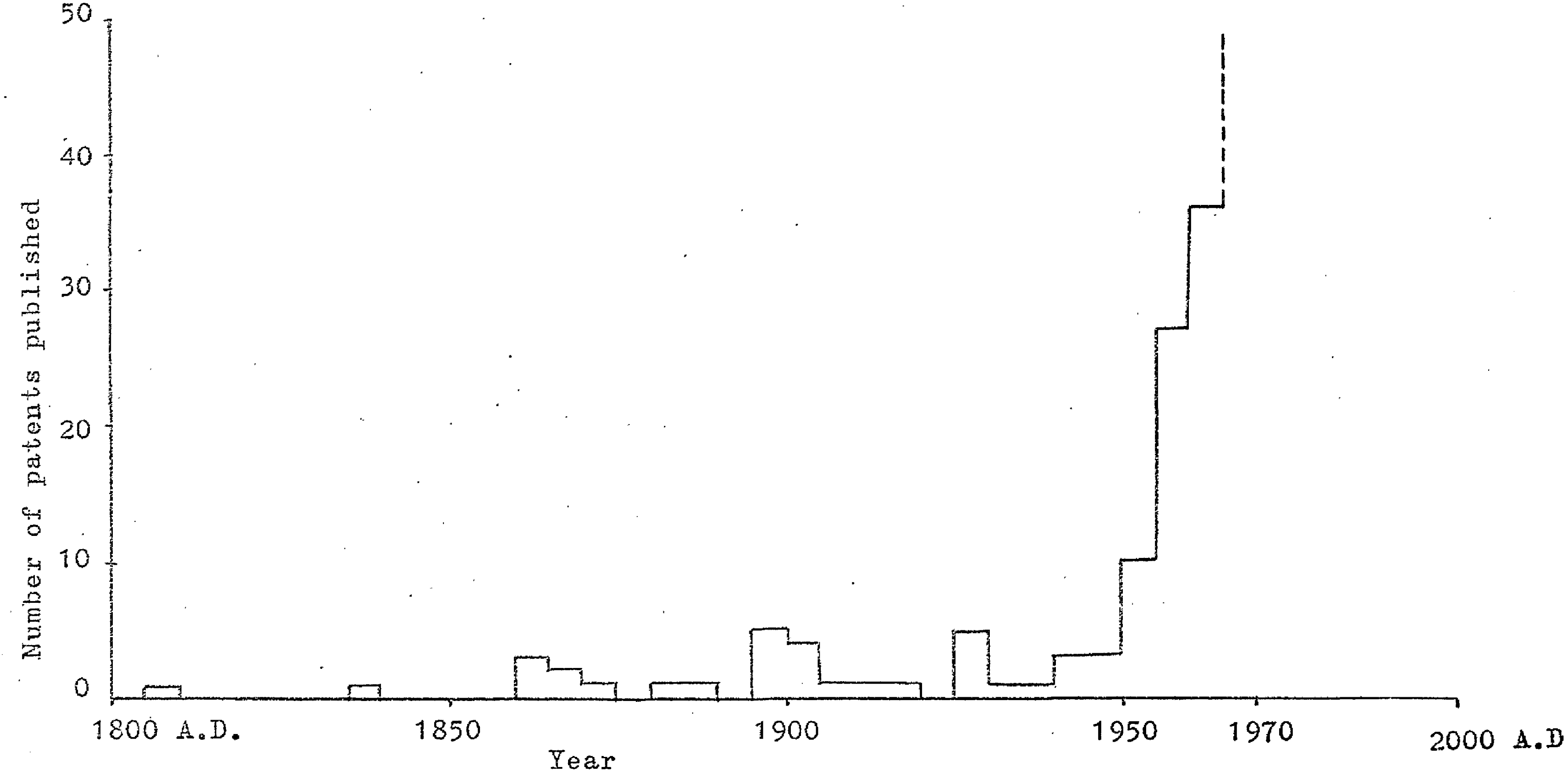



Fig. 2.5.

HISTOGRAM SHOWING THE GROWTH OF BREAK SPINNING PATENTS FOR EVERY FIVE YEAR PERIOD usually produces the yarn. In certain cases, as in fluid systems, either hydraulic or pneumatic forces are employed for fibre assembly and mechanical means are used thereafter for twist insertion. Thus, even if all the forces forming a yarn are known, it becomes sometimes quite difficult to know exactly the predominating force involved in any apparatus. Hence, it can only be emphasized that the various methods have been very broadly classified into four groups without any rigid demarcation line between them. The classification as outlined by Hirway has been adopted here. The four principal groups are as follows:-

(1) Mechanical methods,

(2) Electro-static methods,

(3) Hydraulic methods

and (4) Pneumatic methods.

Each apparatus is described under the inventor's name and the descriptions are, in most cases, accompanied with schematic diagrams to illustrate clearly the main principles underlying these methods. The various methods are presented as far as possible chronologically according to their date of publication. The description of the apparatus is usually followed by comments. Hirway's review of literature is included almost in its entirety to make the survey as complete as possible. Most of the recent methods are briefly reviewed in order to bring the present survey up to date.

## 2.3. MECHANICAL METHODS

The mechanical methods are subdivided into two parts. They are (a) methods other than drum spinning and

(b) drum spinning methods.

## 2.3.1. Methods other than drum spinning

### 2.3.1.1. Barker[27] (1934)

One of the earliest attempts in the development of a break spinner was carried out by Professor Barker and Binks in the early 1930s. In Barker's method, a yarn was formed by overlapping successive tufts of fibres and inserting one turn of twist as each tuft was added. The essential parts of this system are shown in Fig. 2.6.

During each cycle of operation, the tuft of roving presented by the supply rollers A was detached intermittently by the contact of a nip formed by the top roller B and a raised portion C on the periphery of the spinner roller D. The detached tuft was attached to the yarn formed in the previous cycle. Adjacent to the raised portion C was a radial entry for the detached tuft which was delivered through an axial exit in the spinner D. The insertion of one twist for each revolution of the individually driven spinner was made possible due to one end of the tuft remaining free. The spun thread was wound directly onto a winding package.

A fundamental limitation imposed by this method is that the intermittent break introduced must be repaired at such regular intervals that true twist rather than false twist is introduced into the yarn. As the resultant yarn is essentially a series of twisted tufts, it may tend to give rise to short term variations in yarn thickness. Work at Shirley Institute[28] showed that the original Barker machine would spin at a maximum speed of about 4,000 revolutions per minute. The fibre loss was about 50%. At high speeds of roller rotation, air currents were generated at the periphery of the rollers. The pneumatic force combined with the centrifugal action probably caused the fibres to leave the collecting surface. With a shroud

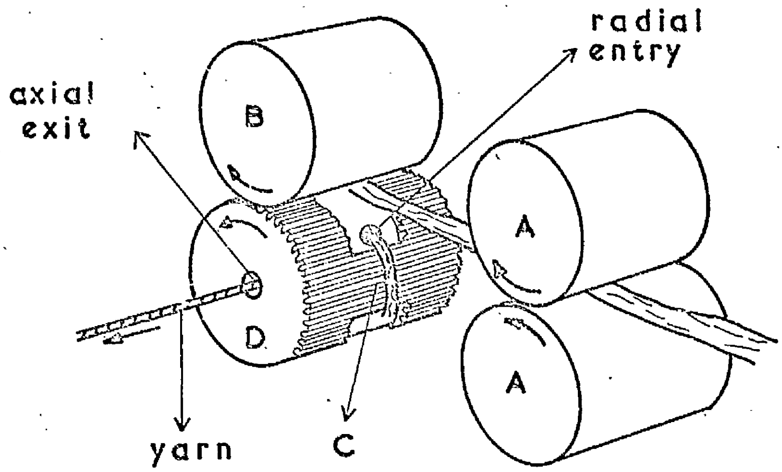



FIG. 2·6 BARKER'S SPINNER

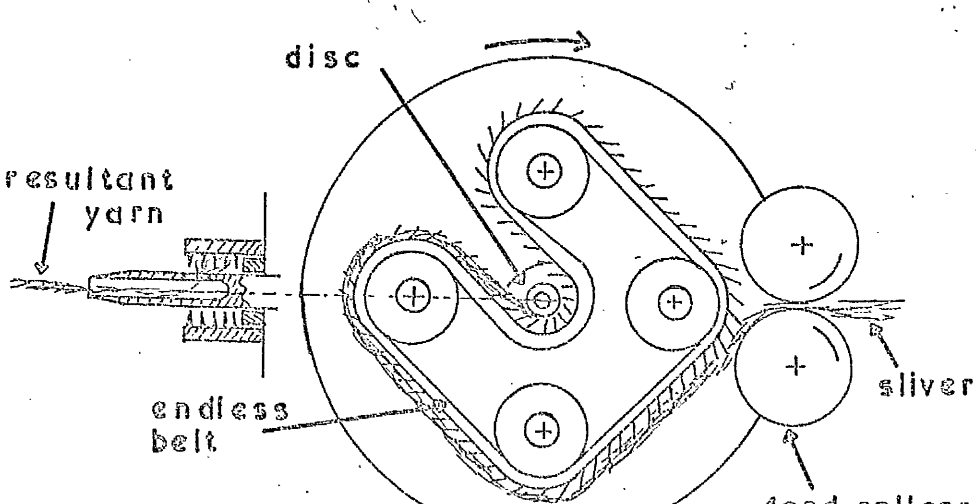



Fig. 2·7
MEIMBERG'S DEVICE

enclosing the spinner roller, the fibres thrown off the surface were deflected back and, therefore, the chances of fibre capture by the forming yarn were increased. In fact, it was claimed that the use of shroud reduced the fibre loss to about 10% and improved the spinning performance generally. Cotton yarns from 10s to 40s c.c. were claimed to have been spun from $\frac{7}{8}$ in. and $1\frac{3}{8}$ in. staple respectively at speeds up to 15,000 r.p.m. Thus the maximum spinning speeds were nearly of the same order as that obtained with the modern ring frame. However, reasonably good yarns were obtained with almost 8,000 r.p.m. Even the best yarns produced by the system were much inferior in both strength and evenness when compared to ring spun yarns. Thus with the existing design of the apparatus, it appears that it may be quite difficult to spin good yarns at production rates demanded today. Moreover the piecing up of a broken thread may not be really easy.

2.3.1.2. Meimberg[29] (1953)

In Meimberg's method, a rotating endless belt covered with wire teeth similar to card fillet combed the fibres fed by a pair of feed rollers. This belt was mounted on a disc which rotated about its own axis at a considerably faster rate than that of the belt. In its path, the belt at one point passed close to the axis of the disc. The combed fibres on the surface of the wires were removed towards the side in a direction along the axis of the rotating disc which twisted the fibres into a yarn. This device is shown in Fig. 2.7.

In most spinning systems described here, the individual fibres float freely inside the spinners and are assembled afterwards into a yarn. However, unlike these methods, Meimberg's device has the advantage that the individual fibres are held securely by mechanical means throughout the spinning operation. This ensures a uniform distribution of fibres. It may be that this condition may not hold good at high speeds. The needles might bend easily and the guiding means for the needle belt are liable to collect dirt, lint, dust etc. The unit might be expensive to make. It is also doubtful if the fibre removal from the wires will be fully efficient. This device might be useful for spinning long staples. It was reported[30] that this device produced only indifferent yarns and could not be operated at speeds anywhere near the speeds normally run by drum type break spinner.

2.3.1.3. Meimberg[31] (1960)

Fibres presented by the drafting rollers were laid continuously in thin, uniform layers on the surface of a rapidly rotating cylinder covered with combing needles. In this method, the twisting element was a flyer placed loosely on the cylinder shaft, as shown in Fig. 2.8. The flyer was arranged in such a way as to peel off the fibre layers from the cylinder. This was achieved by rotating the flyer at a speed a little greater than that of the cylinder. The rotation of the flyer also introduced twist into the fibre assembly at the point it left the cylinder surface. The spun yarn was withdrawn through a guide eye at a rate depending on the count and twist requirements of the yarn.

Since the yarn is formed by peeling off a number of layers superimposed upon each other, it may be reasonably expected that this yarn will be uniform in thickness. This system seems to be attractive indeed in view of its simplicity but its operating speed is limited by the difficulty of retaining the fibres on the cylinder surface at high speeds. Furthermore difficulties may arise in presenting fibres to the cylinder due to the air currents generated at the periphery of cylinder.

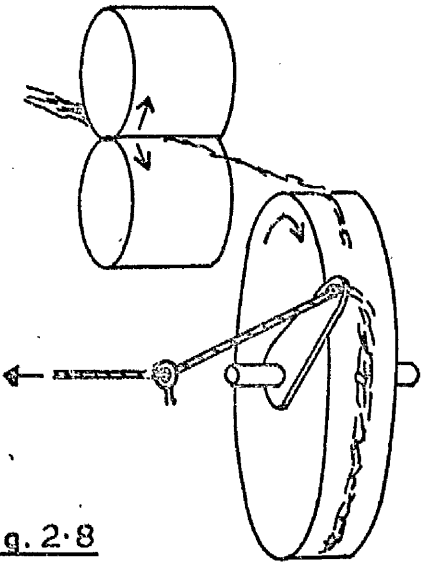


Fig. 2·8

MEIMBERG'S SPINNER

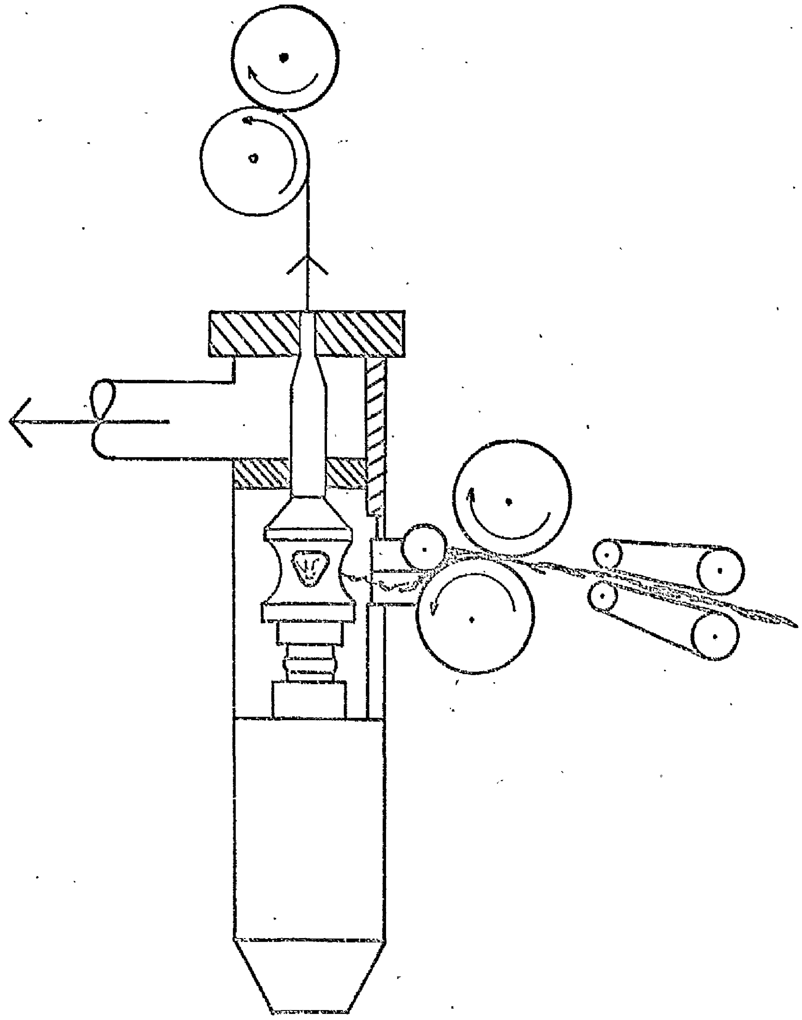


Fig. 2·9

KEELER et al SPINNER

2.3.1.4. Keeler et al[32] (1960)

The principle of this method was a development of Barker's spinner. Conventionally drafted fibres fed into a current of air were carried along a path perpendicular to the axis of rotation of a twisting element which was a hollow rotor with a number of radial holes. This is shown in Fig. 2.9. The rotation of the twisting element changed the course of the air current and caused fibres to twist together into a yarn as the air current passed through the hollow rotor.

It would seem that this method may not produce a reasonably good yarn because the centrifugal action of the twisting element is likely to throw out the fibres impinging on its surface.

2.3.1.5. Pavek[33] (1961)

Disorderly arranged fibres conveyed by an air stream struck against the top edge of an orienting tube and were bent over, either inwards or outwards, as shown in Fig. 2.10. They were, therefore, oriented parallel to the axis of the tube. These fibres were then brought into contact with the needles of a rotating funnel-shaped spinning basket where they condensed onto the inner surface and were finally withdrawn continuously as a yarn through its bottom opening. Pavek[34] in 1963 suggested the employment of the spinning baskets at the cards. A number of them could be arranged side by side across the width of a card. As a further improvement in shortening the spinning process, he[35] proposed in 1964 that the fibres were to be opened up by the action of a rotary fan provided with teeth or needles on its vanes. The air stream produced by the fan conveyed the individual fibres into the spinning basket.

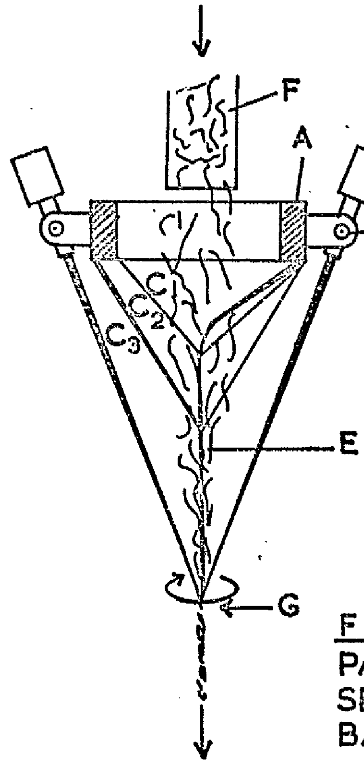
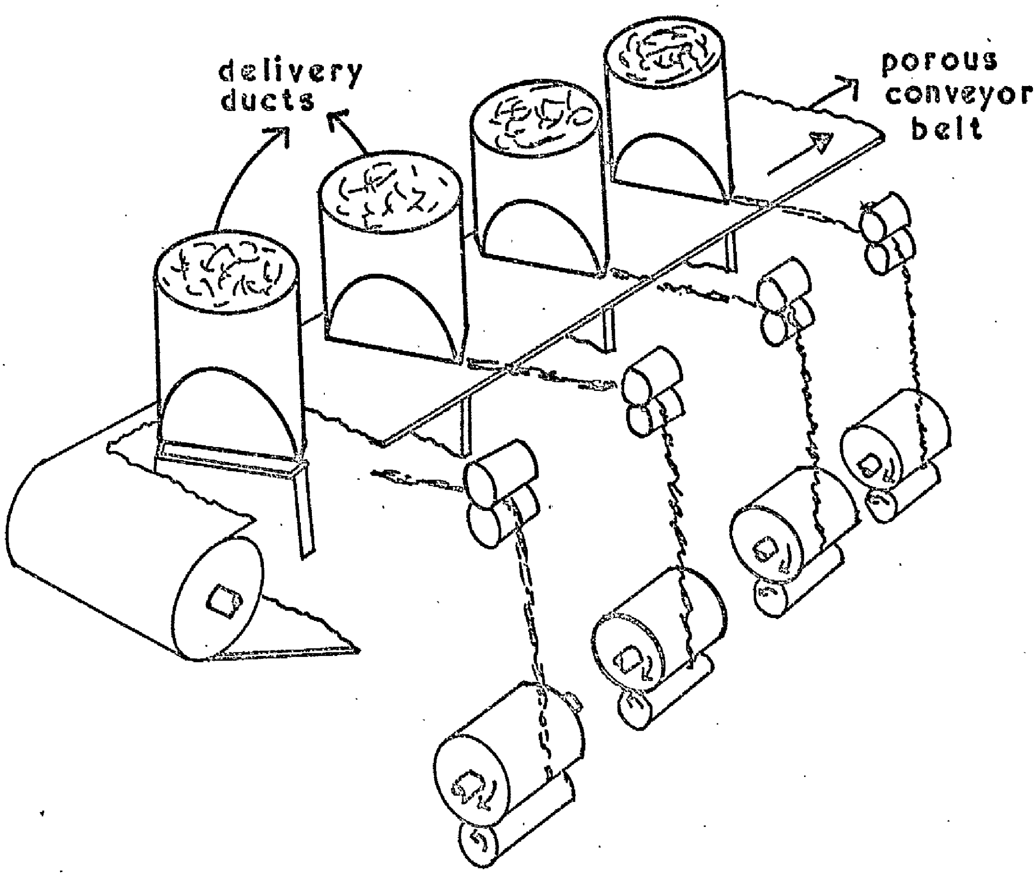



Fig. 2·10
PAVEK'S
SPINNING
BASKET




GREENWOOD'S METHOD

Fig. 2·11

Svaty and Hula's[75] device adopted Pavek's concept of axial fibre assembly. It differed from Pavek's spinner in respect of (a) the spinning element and (b) the means employed for fibre transportation. Instead of the needles used in the Pavek spinner, the spinning element consisted of a conical shaped chamber. The rotation of the conical chamber with radially placed holes near its top created sufficient suction necessary to transport the fibres from an opening device to the inner surface of this spinning chamber.

Hula's[76] and Isomura's[77] devices also employed conical spinning chambers for fibre assembly and twist insertion. All the above mentioned devices may be grouped under the axial assembly type of break spinners.

The advantages and disadvantages of Pavek's spinner are given below. However these are applicable, in a general manner, to the break spinners of the axial assembly type.

The spinning basket consisted essentially of a number of steel needles whose points pressed lighly onto a central 'leader' needle. Due to the action of these needles, the fibres are likely to be made parallel to each other. Perhaps this may be the reason for the production of lean yarns in this system. The radius of the twisting element need only to be small because

(a) the fibre flow is almost axial and

(b) there does not seem to be any definite relationship between this radius and the staple length of the fibre used.

This spinning system is quite attractive indeed as regards its simplicity of its working and the scope it offers for running at potentially high speeds because of the smallness of the spinning element. Again the small size of the spinner may also lead to a relatively low power consumption although the necessity to use an air stream to carry the fibres will tend to increase the power required to some extent. Withdrawal speeds of up to about 1100 in./min and twisting speeds of up to 20,000 r.p.m. have been achieved.

Even though this system seems to have the advantages mentioned above, it is felt that it may be difficult to obtain high rates of production because of the possible difficulties in handling air borne fibres and also because of possible limitations imposed by the needles. The complex design of the spinning basket and the cost of pumping air is unlikely to make this system economically attractive. There is also a possibilty that the fibres may gather together in lumps if the air flow becomes turbulent. Since the fibres will tend to loop around the needles as they proceed to the assembly point, there may be some loopiness in the final yarn. The loopiness will tend to reduce the effective staple length of the fibres and this, in turn, will tend to make the yarn weak. It was reported[28] that the yarn strength was usually weaker than ring spun yarn by about 25% to 40%.

In summing up, it may be said that further improvement in spinning performance of this type of spinner is necessary in order to make it reach the stage of commercial development.

2.3.1.6. Greenwood et al[36] (1963)

The deliver duct for a fibre carrying a fluid stream and the suction duct were arranged in close proximity to the upper and lower surfaces respectively of an endless porous conveyor belt and arranged at an angle to the direction of travel of the belt, as shown in Fig. 2.11. The fibres were continuously deposited on the conveyor at positions in alignment with the delivery ducts. The relative angular movement of the conveyor imparted a rolling action to the fibre array which was withdrawn from the moving conveyor surface by a pair of rollers. Twist was inserted due to the rolling action of fibres by the moving conveyor surface. Conventional yarn winding employed.

It is doubtful if the rolling action alone will provide the necessary twist to form a reasonable yarn. It might be difficult to achieve high rates of production because when the conveyor is worked at high periphereal speeds, the air currents produced would have an adverse effect on the alignment of fibres.

2.3.1.7. Kyame and Copeland[37] (1963)

This method is based on the principle of the Barker spinner and it was developed at the Southern Regional Research Laboratory, U.S.A. The mechanical embodiment of this method consisted of a partly hollow cylindrical metal spindle with a small hole running diagonally in its solid forward end, as shown in Fig. 2.12. At the surface terminus of the rear hole end was a circumferential slot which was connected to the hollow interior of the spindle and was fitted with a stack of thin metal plates spaced close to each other. The plates extended radially inwardly across the hollow part of the spindle. When air was exhausted out of the spindle, the conventionally drafted

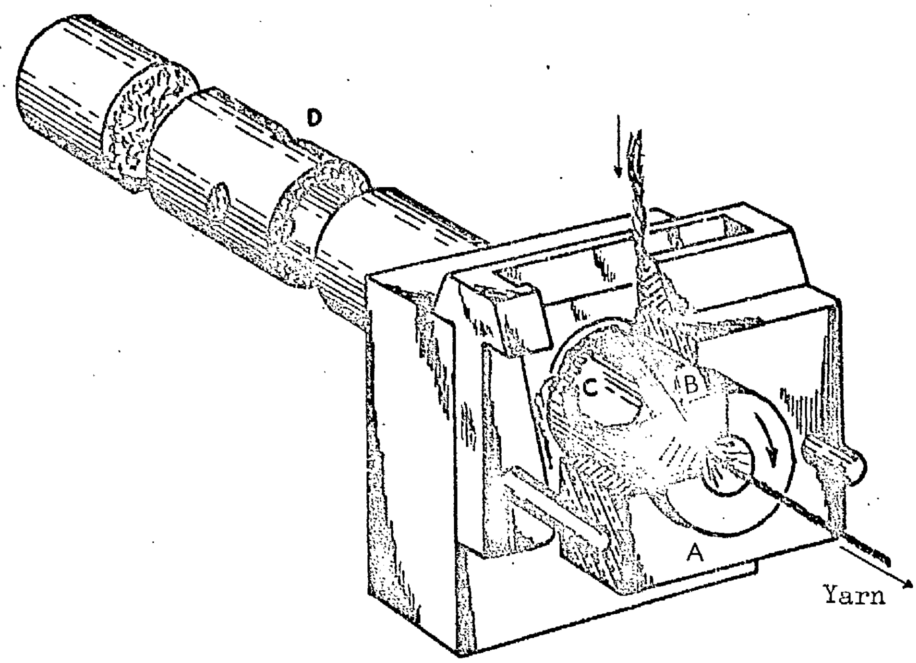



Fig. 2.12.

KYAME AND COPELAND'S SPINNER

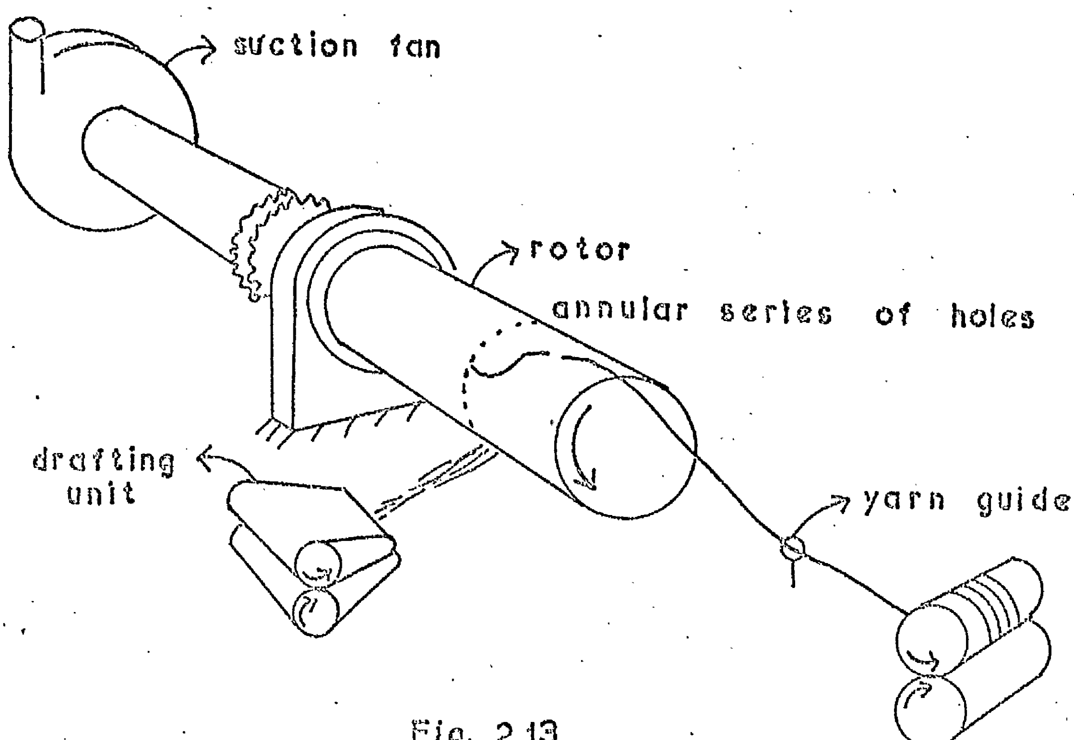



Fig. 2.13

PUTNAM'S METHOD

fibres were drawn through the slits to be intimately intermingled. An orderly transfer of fibres from roving to spindle was accomplished by a spring loaded rubber-rimmed idler roller which pressed against the spindle body. A seed yarn was used to start the machine. The spindle, the drafting unit, the yarn delivery rollers and the winding unit were all started simultaneously. Fibres drawn through the spindle were brought into intimate contact with the rotating free end of a twisting yarn and the twist was transferred from the yarn strand to the fibres. The rotation of the spindle inserted twist in the yarn.

Initially this apparatus produced yarns at speeds of up to 400 in./min. Guides and suction grids necessary to prevent the tendency of the fibres to leave the surface proved helpful in increasing further the speeds of production. It was claimed that by careful shrouding of the rollers, better yarns were produced and speeds up to about 1200 in./min were achieved. However, at very high speeds, the fibre loss may be excessive and this will lead to deterioration in yarn quality. The radial forces acting on the fibres are proportional to the square of the speed and directly to the roller radius. Thus it appears that a limit on the rotational speed of the roller is imposed by these radial forces tending to throw the fibres away from the roller surface. The minimum size of the roller is governed by the fibre length so that the fibre should not fully wrap itself around the roller. Moreover when working with a large number of spindles it would be difficult to prevent blockage occurring in the yarn chamber and in the plates. Furthermore this complex device would be expensive to make because of the high precision required in the manufacture of fine air suction grids, shrouds covering the rollers etc.

2.3.1.8. Putnam[38] (1964)

The apparatus consisted of a rotor closed at one end and with an internal vacuum chamber, as shown in Fig. 2.13. The rotor had an annular series of holes connecting the periphery and the inner vacuum cavity. Fibres are attached to these holes and a ring of circumferentially aligned fibres are built up along a narrow zone on the outside of the rotor. The fibre zone continuously changed its fibre content due to the removal of fibres in the form of a yarn. The yarn passed over the free end of the rotor in an orbiting balloon path, through a yarn guide co-axial with the rotor and was finally taken up on the winding device. A motor was used to drive the rotor, feed roller and the winding device in synchronous relation with each other.

The angular velocity of the rotor is substantially limited due to the action of centrifugal force on yarn tending to break it at the point of formation.

2.3.1.9. Meimberg[39] (1964)

The fibres passed in a steady flow over an opening unit which consisted of an input wheel and a faster delay wheel both with sharp needles embedded in them, as shown in Fig. 2.14. The fibres then passed onto the inner surface of a rapidly rotating thin-walled spinning drum having an inwardly directed annular groove fitted with needles (or tooth vanes) radially angled against the direction of rotation of the drum and provided with ports. Open fibres were drawn into the rotating drum by the suction created through the ports in the wall and were then deposited among the needles. At a removal point, the fibres were drawn off through a twister unit placed outside the drum. The spun yarn was delivered by a pair of rollers and wound on a package by a winder.

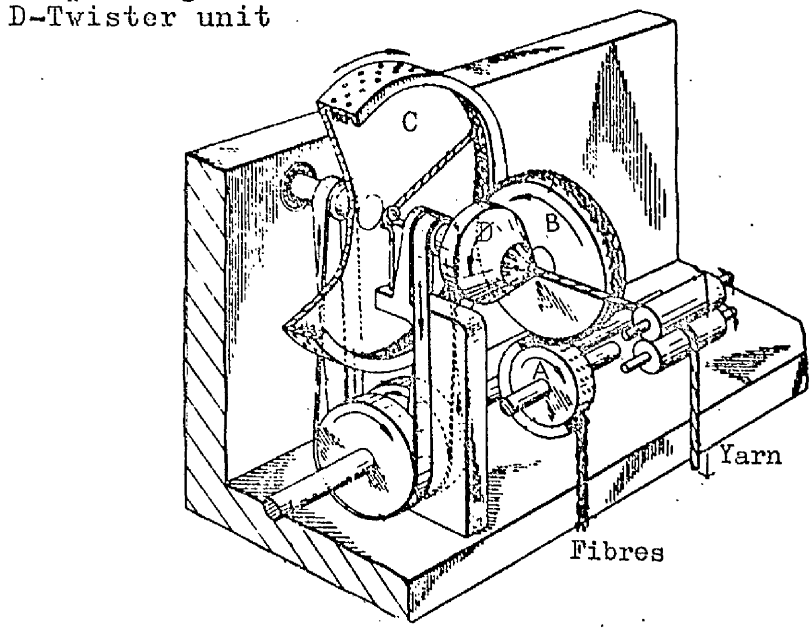



Fig. 2.14.

MEIMBERG'S SPINNER

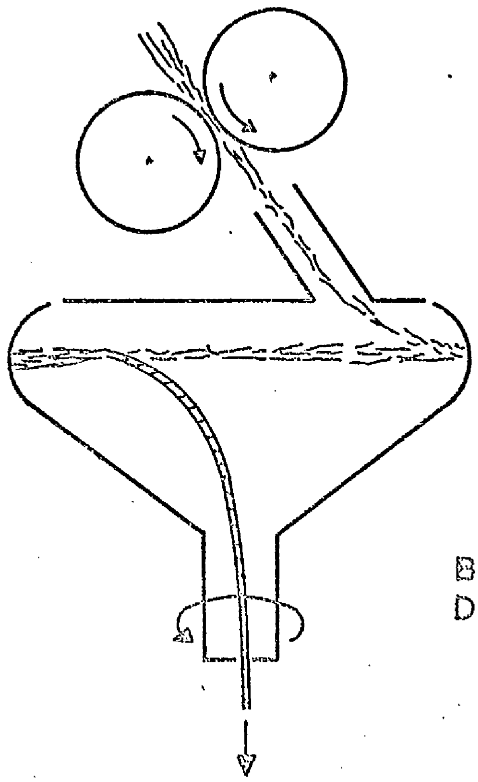


FIG. 2·15 (a)

BERTHELSEN'S DRUM SPINNER

The deposition of fibres on the inner wall of drum was left to chance and also fibres drawn off were gripped purely by chance. As the yarn end progressed around the needle rim, it intercepted periodically the fibre feed. Due to this, looped and unstraightened fibres were likely to be bound into the forming yarn. All these lead to an irregularity in the yarn. The flow of false twist into that part of the yarn which was still in the spinning drum( where it was most needed in order to reduce the influence of the centrifugal force and to prevent the breaking of yarn) was restricted by the narrow take-off guide. A further drawback was that in the case of a break in the yarn, a seed yarn had to be introduced into the rotating spinning drum and this would be rather difficult.

2.3.2. Drum spinning methods

2.3.2.1. Berthelsen[40](1937)

Berthelsen of Denmark was perhaps the inventor of centrifugal spinning, now known as drum spinning. In this method, the fibres from the drafting rollers were passed through an inclined tube of a rapidly rotating drum. Due to the centrifugal and pneumatic forces acting on these fibres, they were laid on the inner surface of the drum. A seed yarn introduced into the drum collected the fibres. Twist was imparted by the drum. Yarn was withdrawn and wound on a suitable package. Fig. 2.15.(a) shows Berthelsen's spinner.

2.3.2.2. Williams[41](1957)

This method consisted of a drum rotating within a housing B. Air was evacuated out of the housing through the opening O. Fibres entered the drum through the inlet $D_1$ which was made larger than the outlet $D_2$. The circular wall of the drum had numerous holes. Centrifugal and pneumatic forces placed the fibres on the inner surface of the drum. A seed yarn

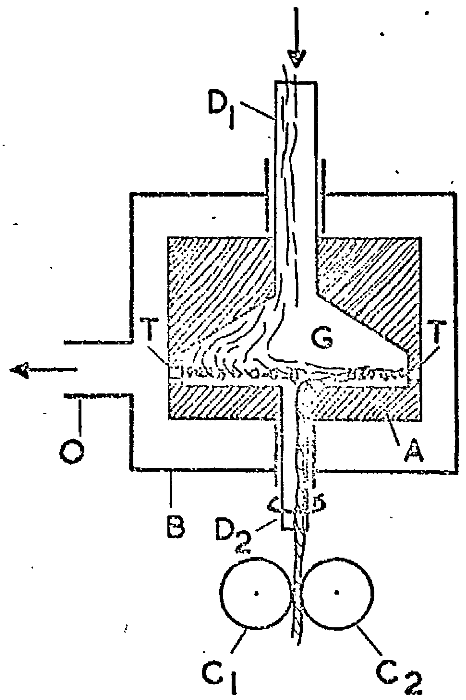



FIG. 2·15
WILLIAMS'
DRUM SPINNER

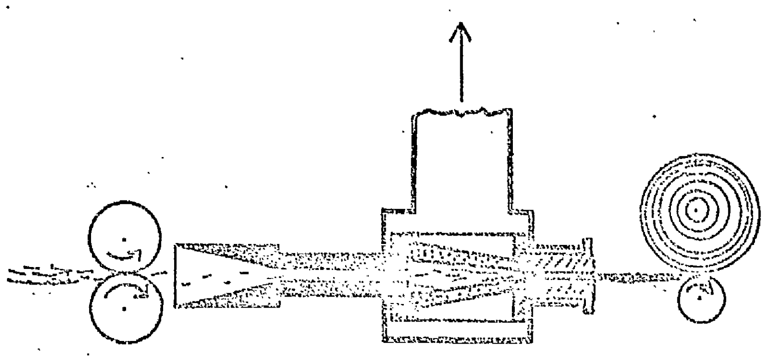


FIG.2·16 STRAITR'S SPINNER

introduced through $D_2$ picked up these fibres. The rotation of the drum twisted them and formed a yarn. The resultant yarn was withdrawn by a pair of rollers $C_1$ and $C_2$. It was then wound on a package. Williams' device is shown in Fig. 2.15.

2.3.2.3. Straitr[42] (1961)

The spinning chamber was formed by a cone of porous material. Rotation of this chamber within a housing expelled the air through the porous wall and caused an intake of air through the inlet nozzle. This helped in bringing in the feed fibres. Fibres on the inner surface of the conical spinner were attached to a seed yarn inserted through the exit nozzle. Yarn formed was withdrawn and wound on a package. Stratr's spinner is shown in Fig. 2.16.

It would appear that the porous material used for the spinner would be subjected to frequent choking up by the fibres. To obtain high production, it is necessary to rotate this drum at high speed and the porous material may not be sufficiently strong for such a use and even if reinforcements were used, the speeds will be restricted.

2.3.2.4. Cizek et al[43] (1963)

A pair of feed rollers supplied the roving into the tapered end of a stationary tube whose other end was secured to a sleeve. Fixed to the bottom of the sleeve was a tubular part whose other end had two radially projecting arms with outlet passages extending in opposite direction and transverse to the axis of rotation of the twisting element, as shown in Fig. 2.17. The Rotation of the tubular part forced air out of the outlet passages and sucked fibres into the stationary tube, carried them downwards through the outlets and deposited them on the surrounding circular bowl-shaped collecting surface that also formed the twisting element. The rotary action of the drum

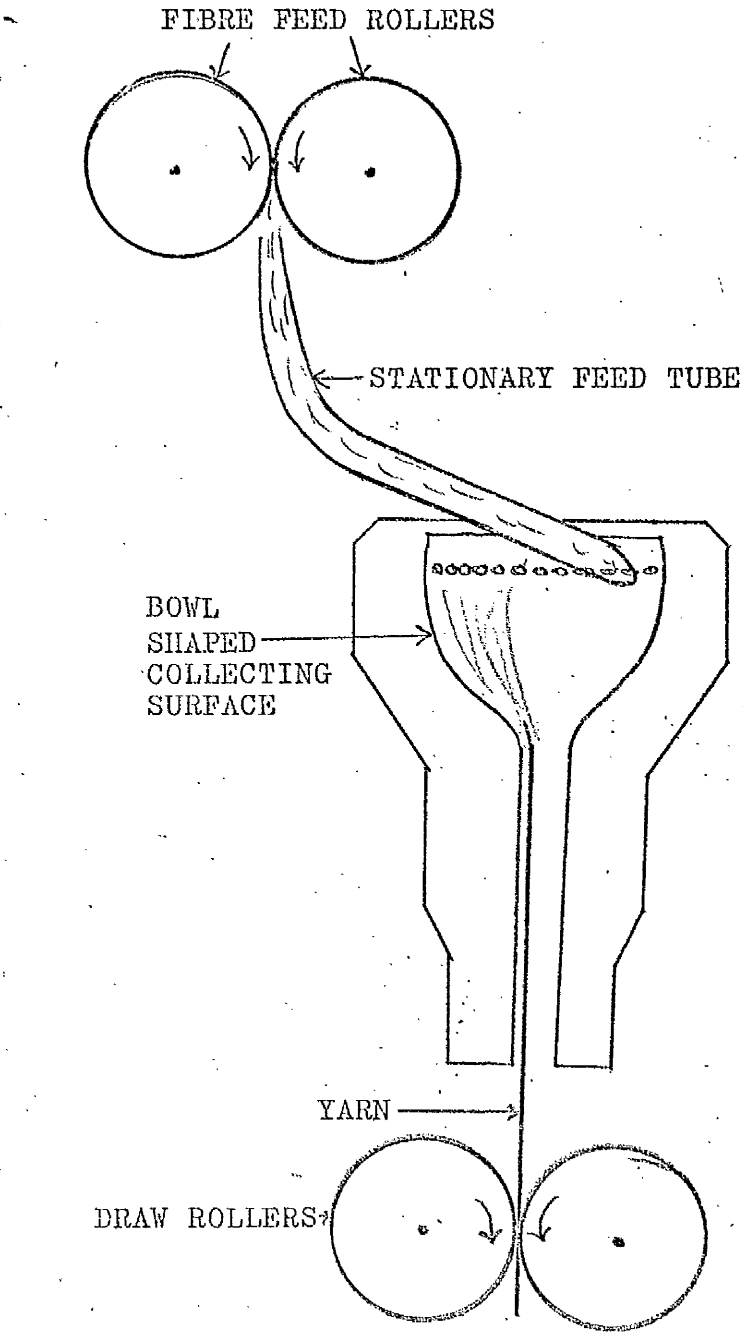



Fig. 2.17.

CIZEK ET AL SPINNER

twisted the fibres into a yarn which moved along through the tubular guide by the action of drawing rollers.

2.3.2.5. Cizek et al[44] (1964)

This method was an improved version of the previous one. The fibrous material supplied by feed rollers were drawn through a flattened part of a feed tube onto the collecting surface of a spinning drum. This spinner is shown in Fig. 2.18. The spinning drum was attached co-axially to the hollow rotor of an electric motor whose rotation generated an air current inside the drum due to the reduced pressure. The spinning drum was formed by two cones with a common base and had, at the place of largest inner diameter, its collecting surface with a number of suction holes communicating with channels onto a spiral casing. Fibres were drawn off from the collecting surface in the form of a yarn through an outlet opening and finally wound on a package. Drum speeds of about 30,000 r.p.m. were stated to be practicable with this apparatus.

With the exception of the electric drive, these are believed to be the basis on which the V.U.B. machines KS 200 and the new BD 200(described in section 2.3.2.8.) were designed. Quite good yarns have been spun using this system as described by Lord[45].

2.3.2.6. S.A.C.M. method[46] (1965)

In the method developed by the Societe' Alsacienne de Constructions Mecaniques of France, the spinning drum used is a rather flat pot-type. Small holes were drilled near the fibre collecting surface. The rotating drum then acted as a centrifugal fan, the air stream entering into the drum from both the inlet and outlet openings and escaping out through the holes in the periphery of the drum. An imaginary neutral zone was claimed to be formed inside the drum by the action

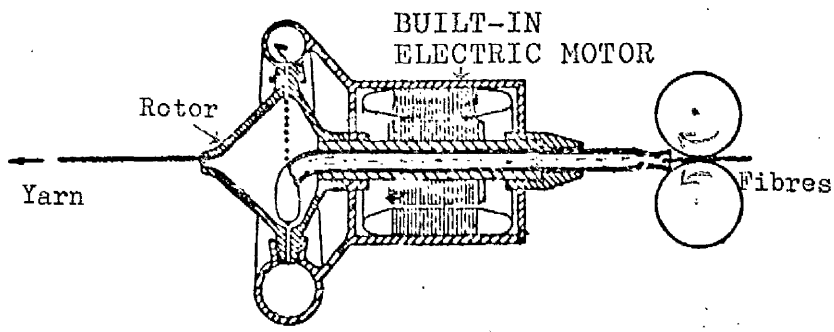



Fig. 2.18.

CIZEK'S SPINNER

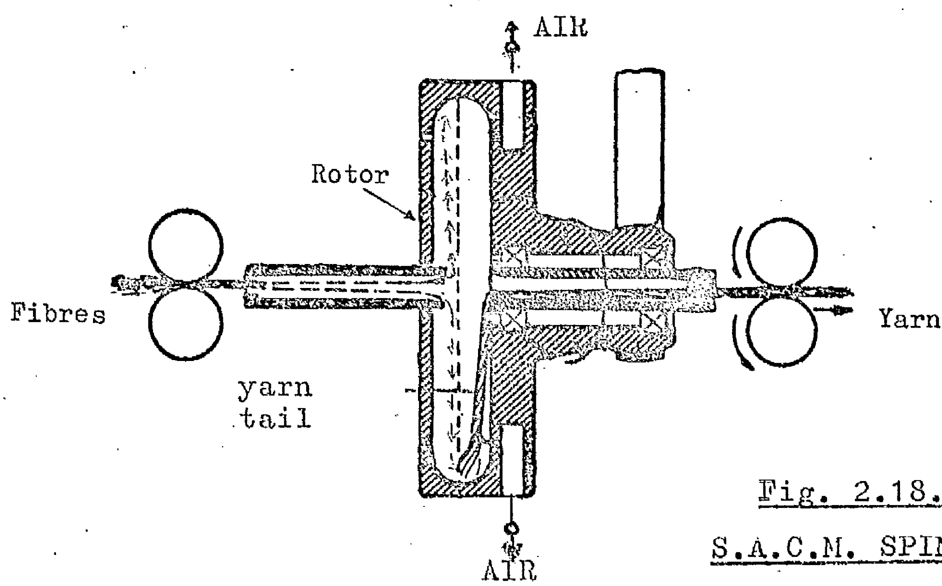



Fig. 2.18.(a)

S.A.C.M. SPINNER

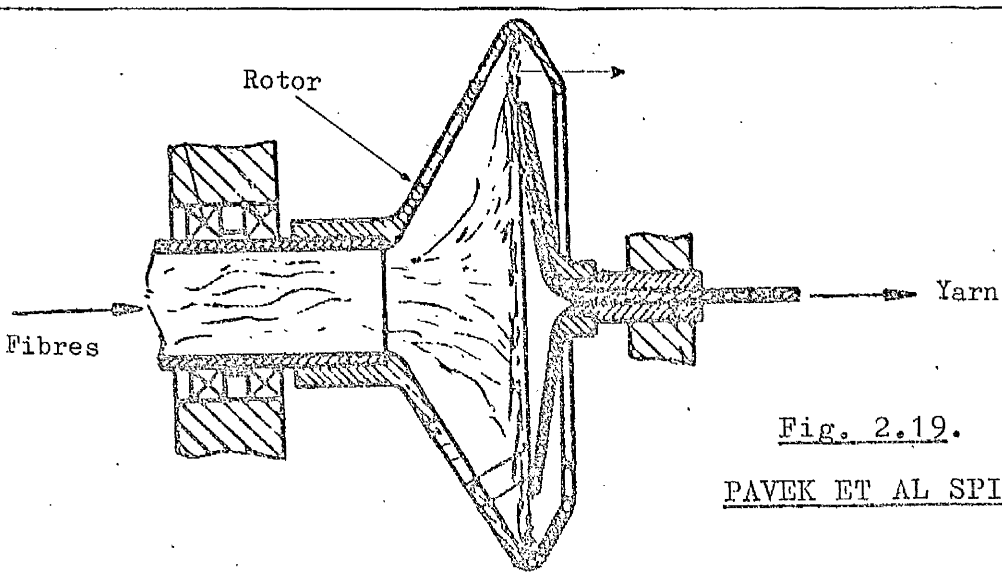



Fig. 2.19.

PAVEK ET AL SPINNER

of both the incoming streams of air meeting each other. This zone was supposed to prevent the incoming fibres coming into direct contact with the yarn produced inside the drum. Fibres introduced through the inlet opening were carried along with the air stream and placed along the circular wall and they arranged themselves well stretched out and parallel to each other. The end of a seed yarn inserted through the outlet opening picked up these fibres. The drum rotation imparted twist and formed them into a yarn which was wound directly on a package in the usual way. Please see Fig. 2.18.(a).

Tests on such a device has been made by Khatua[47] who found that fairly good yarns could be made. However the configuration leads to a large diameter which means that the safe speed of the drum is limited as compared to some of the other types.

2.3.2.7. Pavek et al[48] (1966)

This method employed a drum similar to the one described by Cizek et al and mentioned in section 2.3.2.5. Instead of an electric motor directly coupled to the drum as in Cizek's method, a pulley on the drum was driven by an external means. Another difference was in the design of the yarn delivery tube which, in this case, terminated at its inner end in a funnel-like part, as shown in Fig. 2.19. This was so arranged that the plane of the funnel mouth was substantially co-planar with the plane passing through the drum at its position of maximum diameter. This funnel was claimed to considerably reduce the yarn tension thereby offering a possibility of increasing the yarn delivery speeds.

2.3.2.8. V.U.B. BD 200 machine[49] (1967)

This machine developed by Vyzkumny Ustav Bavlnarsky of Czechoslovakia is a successor to KS 200 machine which was exhibited at the International Textile Fair at Brno in 1965. The KS 200 used a four roller two apron drafting system but this was replaced by a single zone combing draft device in the BD 200 machine. The BD 200 machine was first publicly shown in the St. Louis Exhibition held in France in September, 1967, and it may be said that this machine is the first commercial break spinning machine of the drum type.

The working of a spinning unit in the BD 200 machine (which, as the name implies, consists of 200 spinning units) was described by Rohlena[50] and it is given below with reference to Fig. 2.20:-

The creel package consists of a cross wound narrow cheese sliver bobbin and it is placed at the lower portion of the machine. The sliver passes through a fibre separation-cum-feed device which consists of a trumpet condenser A, a feed roller B with a presser C, a combing roller D covered with fine wire points and a channel E for the transport of fibres into the spinning drum F. The sliver should be broken down into fibres by the action of the fast moving wire points of the roller D. The centrifugal forces of the fibres combined with the high velocity air stream(created by the suction of the spinning drum F) flowing into the channel E assist in the removal of the fibres from the roller surface. Fibres carried through one end of the drum are deposited as layers on the inner surface of the drum which is vee shaped. A seed yarn introduced from the other end of the drum presses on the ribbon of fibre layers. This ribbon attaches itself to the seed yarn. The rotation of drum imparts the necessary twist to the fibre assembly to form a yarn. When fibres are fed continuously and the forming yarn withdrawn, it is possible to obtain continuous lengths of yarn which is then finally wound onto a cheese package.

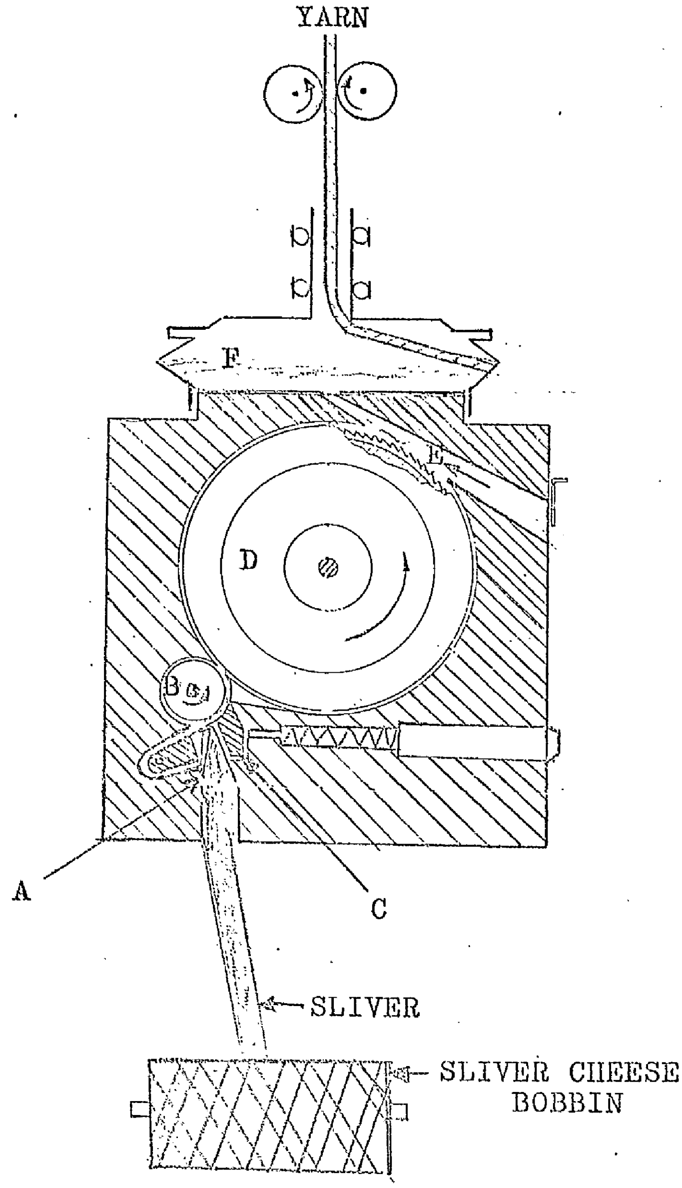



Fig. 2.20.

V.U.B. BD 200 SPINNER

Yarns of good quality were claimed to have been successfully spun from the following fibres :-

(a) cotton,

(b) ~~wool~~

and (b) fibre mixtures consisting of

(i) cotton and viscose

and (ii) polyester and viscose.

The yarn produced is very regular and superior to the ring frame yarns but the yarn strength is less than that of an equivalent count of yarn spun by the ring frame. However the strength regularity is better than that of the conventional yarns and it is claimed that the strengths of the weakest portions of the respective yarns are about the same.

In view of the tremendous interest created in the textile research and industry by the introduction of this machine, it was thought relevant to include the working particulars of BD 200 machine. They are as follows:-

(a) Speed of drum - 30,000 r.p.m.; diameter of drum - 3 in. approx.

(b) Speed of comber roller - 8,000 r.pm.; diameter of roller - $2\frac{1}{4}$ in. approx.

(c) Staple length range - 1 in. to $1\frac{9}{16}$ in.

(d) Yarn counts can be spun in the range of 12s to 40s c.c. (50 to 15 tex) with a creel sliver of 0.148 to 0.267 hank (4 to 2.2 ktex).

(e) Twist range at 30,000 r.p.m. - 14.1 to 38.6 t.p.i.

(f) Total draft in the spinning unit(including the draft in fibre separation device and 'condensation' in the drum)- 25 to 440.

(g) Yarn production rate - 22 to 59 yards per minute. This is about 2 to 3 times that of the ring frame.

(h) Weight of yarn package - $2\frac{1}{2}$ lbs. approx.

(i) Size of yarn package - 9 in. diameter X $3\frac{1}{2}$ in. width.

(j) Total power consumption - about 16 kW for 200 spinning units.

2.3.3. General comment on drum spinning methods

In view of the recent developments in this form of break spinner, it is considered relevant to give the general conclusions arrived at so far with regard to this spinning method and the yarn quality obtained from it.

(a) A wide range of counts can be spun and these yarns are generally superior to the ring spun yarns with regard to evenness. The yarns are also relatively free from neps.

(b) The mean strength of these yarns is lower (about 10% to 20%) than that of an equivalent ring spun yarn but the strength regularity is better and, therefore, there is little difference in strength at the weakest points of the two yarns.

(c) The drum spun yarns have increased elongation at break.

(d) These yarns are more bulky than ring spun yarns.

(e) They possess increased abrasion resistance.

(f) Drum speeds of about 30,000 r.p.m. have been achieved and yarn production rates of 2 to 3 times that of the conventional methods are possible.

In short, the drum spinning method has already entered into the initial stages of commercial application.

However this system, as it stands at present, has its problems too. High drum speeds impose high hoop(or bursting) stresses in the material of the drum which may burst if the safe limit is exceeded. Thus, according to Lord[51], the safe speed for aluminium drum would be around 80,000 r.p.m. for a diameter of about $1\frac{1}{2}$ inches. High-tensile light alloys with a capacity to withstand high hoop stresses developed during running may further increase the drum speed but such materials may be too expensive. Alternatively, fibre reinforced plastics may be a good and inexpensive substitute. It is believed that the modern technology could certainly produce material for the drum to withstand very high speeds. So the drum material does not seem to be a limiting factor in attaining high speeds. At very high speeds, the bearings would present problems too. The ball bearings would require extremely small tolerances in their fitting. It appears that ball bearings mounted within close tolerances are readily available. It is desirable to sleeve them into the housing on the rubber mounts of the bearings. Lubrication too would create problems because the life of the ball bearings would be generally short. Air bearings might offset the disadvantages associated with ball bearings and they might, in addition, reduce noise level and power consumption. However not much work seems to have been carried in the realm of very high speeds with air bearings and there may be some unforeseen technical problems. Air bearings might need very close tolerances in manufacture and it is important that there should not be any appreciable imbalance on the loads of moving parts at such high speeds, as any slight imbalance might result in the unit being thrown away from its bearings.

The most important single factor against high drum speeds is the economics involved with the power cost. The power consumption of the present size drum when operated at high speeds with conventional bearings is very much higher than that consumed by a conventional spindle. According to Lord[51], the power consumption is directly proportional to $(\text{drum diameter})^4$ and $(\text{drum r.p.m.})^{2.6}$. From this, it would appear that the power consumption (and hence power costs) would seem to impose a limitation on the economics of this spinning system, especially when very high drum speeds of the order of 100,000 r.p.m. are envisaged.

## 2.4. ELECTRO-STATIC METHODS

### 2.4.1. Oglesby et al[52] (1955)

The principle employed by Oglesby was based on the utilisation of electro-static forces for fibre alignment. Loose cotton was fed by a pair of rollers onto a roller similar to the taker-in of the card, as shown in Fig. 2.21. Fibres were removed by a doffing brush and blown off through an opening of the doffer housing into the space between a pair of electrodes carrying a static p.d. of about 20 kilo Volts. Fibres were parallelised axially between the electrodes and they were withdrawn from the field in timed relation to their collection. Finally they were twisted mechanically to form a yarn.

### 2.4.2. Lord[53] and Jejurikar[54] (1962)

An apparatus for generating a rotating electro-static field was developed. A high voltage 6 phase system was used with each phase connected to a 6 electrode system. A rotating electro-static field was produced. It was found that a fibre could be rotated when under the influence of this field.

### 2.4.3. Arschinov et al[55] (1965)

A schematic diagram of this device is shown in Fig. 2.22. A sliver was fed to a rotating drum covered with fine needle points. The sliver was supposed to be separated into fibres which were thrown upwards by centrifugal force and carried away by air currents through an outlet duct. Fibres then passed into an electro-static field maintained between two conical electrodes, the apices of the electrodes being located at either end of the axis of the field. The apex of one electrode was formed by a twist tube fitted with a spring-loaded ball which acted as a clamp on the yarn being spun. The fibres aligned themselves along their length between the electrodes and were gripped by the ball and drawn onto the twist tube by a set of

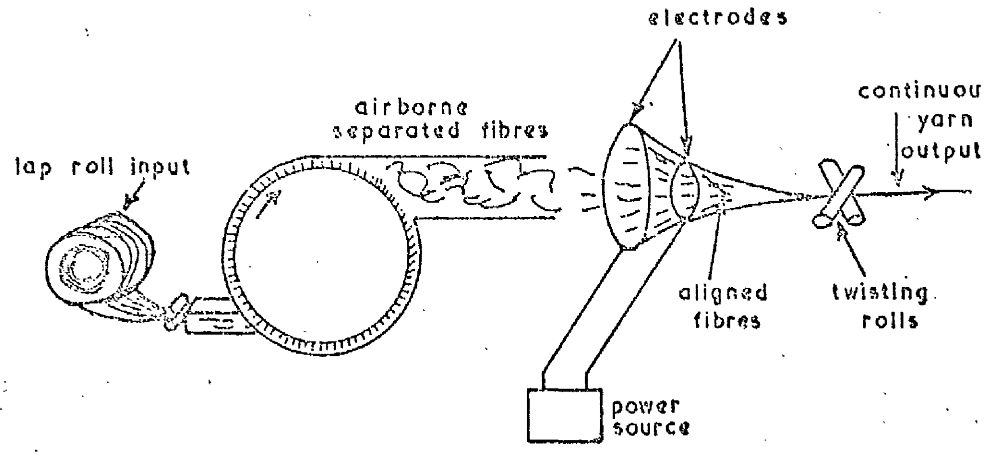



Fig. 2.21

OGLESBY'S SYSTEM

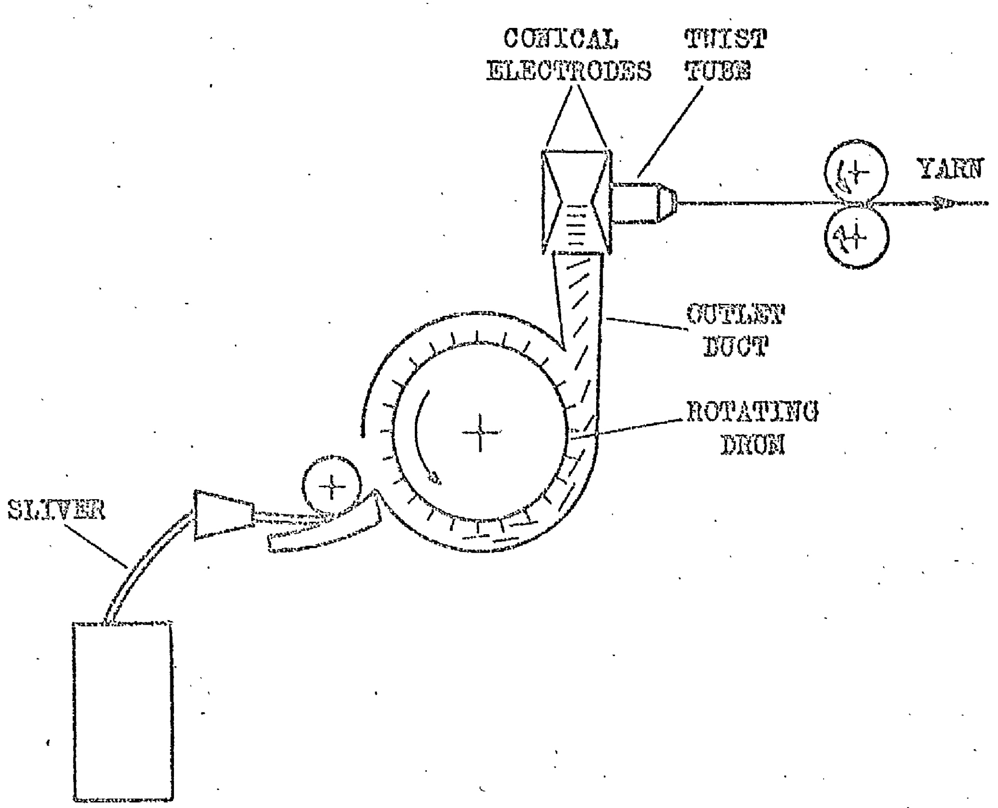



Fig. 2.22.

ARSCHINOV'S SYSTEM

rollers mounted on the other side of the electrode. Yarn was spun by the insertion of twist on the fibre assembly by the rotation of the twist tube. The spun yarn was wound directly onto a package.

It is really doubtful if the fibres will be presented to the electrodes in an individual state.

2.4.4. Battelle [56] method (1967)

Roving from a bobbin was passed through a conventional drafting system. Drafted fibres were drawn by an electro-static field into an electro-static spinning head. The drafting unit and spinning head were connected to oppositely charged poles. The fibres under the influence of these charges acted as dipoles and, therefore, tended to align themselves. The electro-static field thus served to orient the fibres during their transportation into the spinning head where they were reassembled and twisted to form a yarn. Finally the yarn was taken up on a winding package.

It is claimed that good quality yarns can be produced at higher production rates than the ring frame and that labour, power and capital costs can be considerably reduced. However this method is still in its early stages of research and it is yet to be seen if this method can fulfill all its claims and become a really successful commercial application.

2.4.5. General comments on electro-static methods.

Reports by Lord and Jejurikar showed that the results obtained with the electro-static devices were extremely dis-appointing. The alignment of fibres was reasonably good at very low speeds but as the speed was increased it became increasingly difficult to control the fibres with field strengths that could be maintained in air. Potentials of up to 7 kV/cm were tried but the yarn produced was very poor even at low uneconomic speeds. High voltage gradients were needed to produce quite modest forces. There is always an inherent danger of charging up neighbouring bodies. It is also likely that there may be dielectric breakdowns causing sparks which are to be especially avoided when handling fibres that are inflammable.

It is doubtful if the fibres will be presented in an individual state to the electrodes, especially when the fibres are in tuft form because the electro-static forces may not be sufficient to disentangle and align these fibres. It was found that the electro-static forces by themselves were insufficient to introduce any useful twist into a fibre assembly. All these considerations suggest that the opening of fibre masses into individual fibres and later twisting the fibre assembly should be accomplished by means other than electro-static. Most of the methods described above used mechanical means for this purpose. The function of electro-static field, therefore, seems to be merely the alignment of fibres. As pointed out earlier, it is highly uncertain if the fibres can be properly aligned at production speeds which would be economical in the present day.

Therefore it seems very unlikely that the electro-static break spinner, in its present state of development, is of any commercial importance and its future prospects appear to be bleak, when compared with that of the other forms of break spinning.

## 2.5. HYDRAULIC METHODS

### 2.5.1. Strang[57] (1955)

A stream of liquid having fibres suspended in it was caused to flow through a smooth walled tube, a portion of which was rotated about its own axis, as shown in Fig. 2.23.

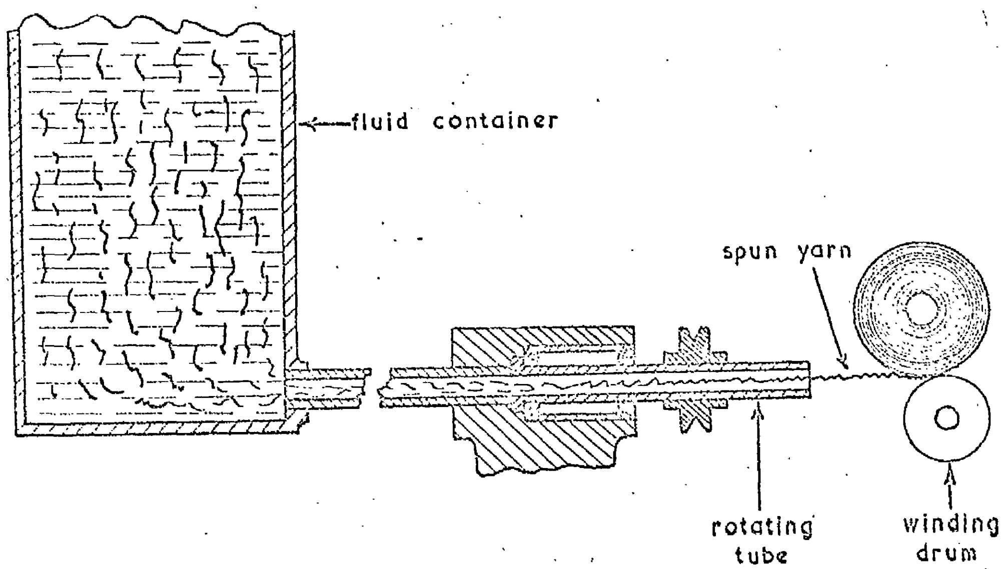



Fig. 2.23.

STRANG'S METHOD

Rotation of the tube frictionally entrained the flowing liquid so that the latter rotated about the tube axis. This imparted twist to the fibres suspended in the stream. The twisted fibres were drawn off as a continuous strand and finally separated from the liquid.

2.5.2. Strang[58] (1957)

An improved method over the previous one, the apparatus was specially meant for the preparation of cored strands comprising of fibres having different characteristics for the core and on the surface of the yarn.

2.5.3. Keeler et al[59] (1958)

False twist was imparted to drafted fibres to form a strand as the fibres entered a vortex at the upper end of a downwardly flowing liquid in the chamber A, as shown in Fig. 2.24. The strand was then delivered into the field of action of a rapidly rotating body of liquid in chamber B whereby true twist was added to fibres of the strand.

2.5.4. Strang et al[60] (1960)

Fibres suspended in a stream of liquid flowed through a stationary conduit. A portion of the stream was rotated by the action of a tangential jet of high pressure liquid. The high angular velocity provided twist to the fibrous material. Yarn was wound in any suitable manner.

2.5.5. General comment on hydraulic methods

Although a liquid was used to convey fibres into the twisting element, the actual twisting, in most of the cases, was performed by mechanical means only. Hence an upper mechanical limit on the operating speeds would be imposed. In this system, the fibres are randomly distributed in the fluid. The fibres are not sufficiently straightened during

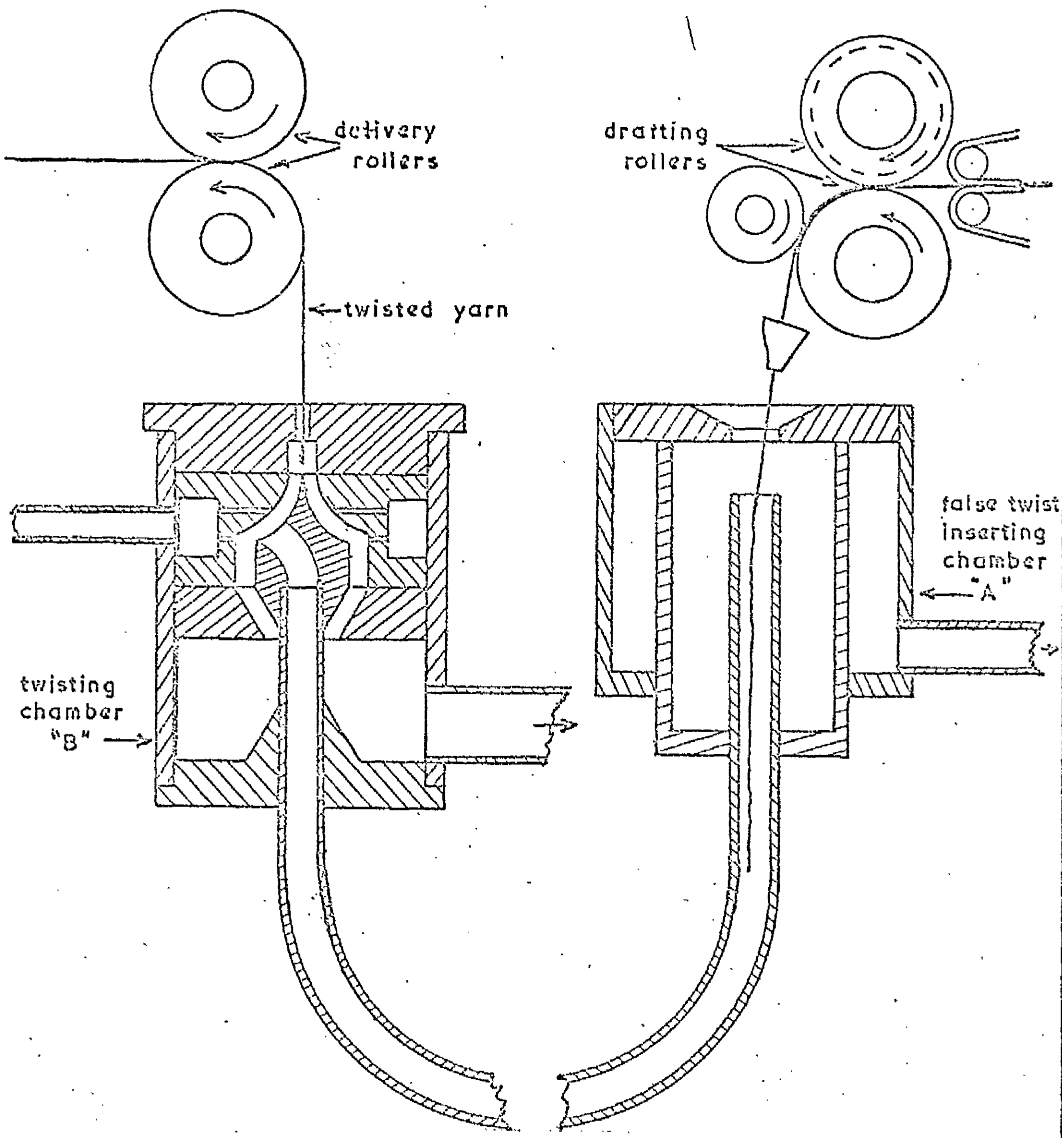



Fig. 2.24.

KEELER ET AL SPINNER

the process. No means are provided whereby precise control over fibre assembly could be exercised. Hence it may become difficult to produce fairly regular yarns. Surface tension effects would play an important part and, therefore, uniform dispersion of fibres in the liquid medium might be rather difficult. However chemical treatments of the medium may modify the surface tension effects. The coagulation of wet fibres as well as the deposition of fibres on the walls of the container and the tube would affect the regularity of yarn produced. Furthermore the prevention of liquid leakages and the control of humidity in the manufacturing place might prove to be a constant source of problems. Drying of the wet yarn need the use of expensive drying equipments.

## 2.6. PNEUMATIC METHODS

### 2.6.1. Gross[61] (1930)

In this method, fibres were sucked directly from a card web and blown into a pear-shaped centrifuge by means of a fan. The wall of the centrifuge had small perforations. Rotation of the centrifuge spread out the fibres along the inner wall. A small ball placed freely inside the centrifuge was supposed to keep the fibres pressed against the wall. Fibres were collected by a starting yarn. Twist was inserted by the rotating centrifuge and a yarn was formed. This yarn was then taken through a false twister provided with leaf springs. The yarn was finally withdrawn by a pair of rollers and wound on a suitable package. A thread-break detector operated electrically was also included.

Blowing fibres into the centrifuge may lead to the formation of tufts with randomly oriented fibres. This may be detrimental to spinning. Morover the starting of the system as well as piecing up a broken thread do not seem to be practical.

2.6.2. Mayo[62] (1948)

Mayo proposed a method of pneumatically separating, parallelising and spinning fibres into a twisted yarn. Fibres from a bale were blown by an air nozzle into a series of chambers which ultimately led to a cyclone separator where the individual fibres were subjected to the action of air jets, as shown in Fig. 2.25. The aligned fibres were withdrawn from the bottom part of the cyclone separator, passed through a mechanical twister and finally wound on a bobbin.

This method appeared to be not a feasible practical proposition because separation of fibres by pneumatic means alone is very difficult.

2.6.3. Gotzfried[6] (1959)

In this method, an air vortex was used to twist fibres into a yarn. Card sliver was fed through a plucking device. The fibres were carried by an air stream into a tube at about its mid-point. The tube was surrounded by a casing. This is shown in Fig. 2.26. One end of the tube was fitted with a nozzle having two tangential holes on its side for air entry and an axial hole for the yarn exit. The other end of the tube was connected to a suction device with a vacuum range equivalent to 600 mm. (24 in.) of water. The vortex created inside the tube rotated the fibres and inserted twist to form a yarn. The apparatus was started by feeding a seed thread into the nozzle (with the suction on) whereupon the fibres attached themselves to the seed yarn. Yarn was drawn off against the air current by a pair of rollers and it was then wound on a package.

2.6.4. Gotzfried[63] (1961)

A device based on almost the same principle as the

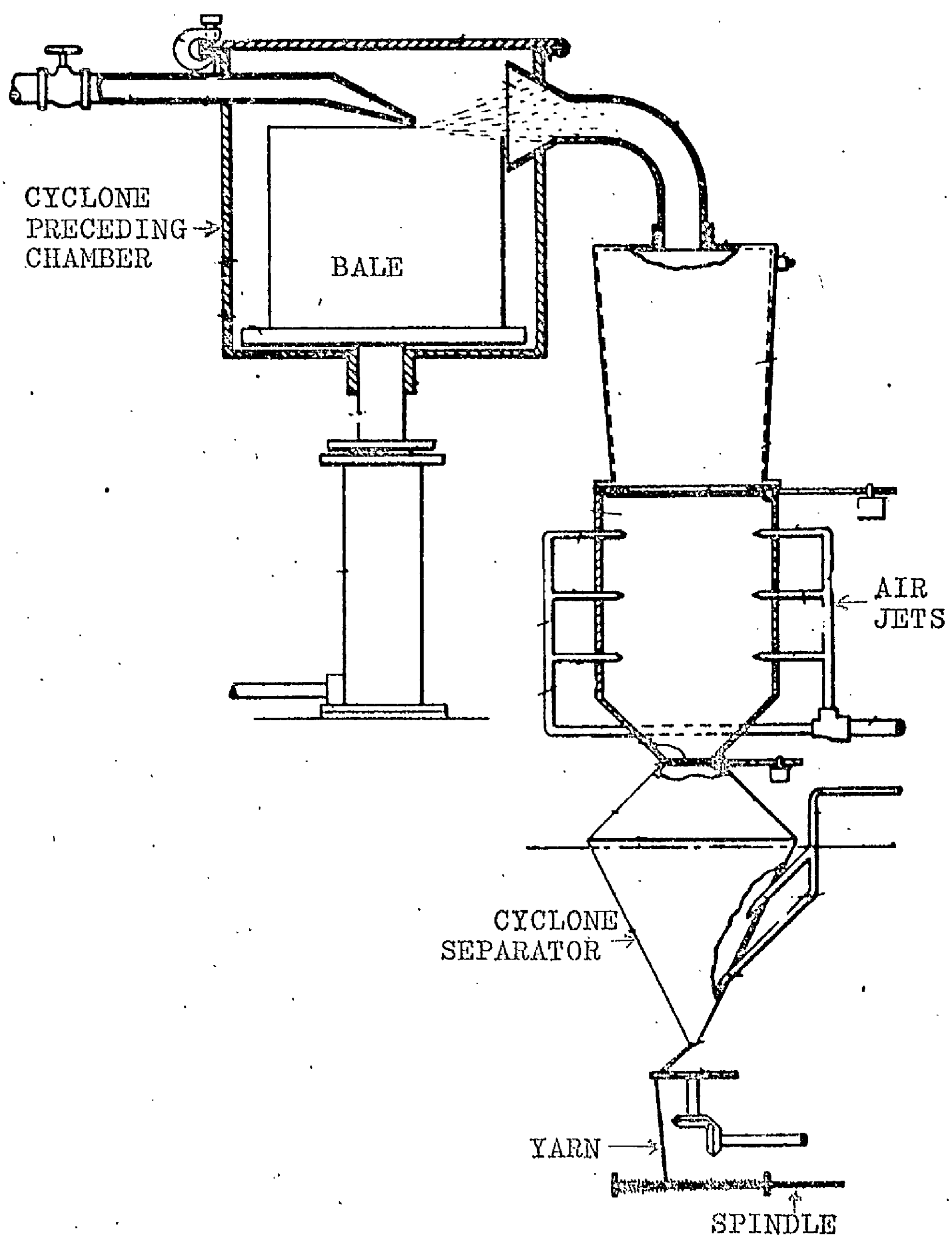



Fig. 2.25.

MAYO'S SYSTEM

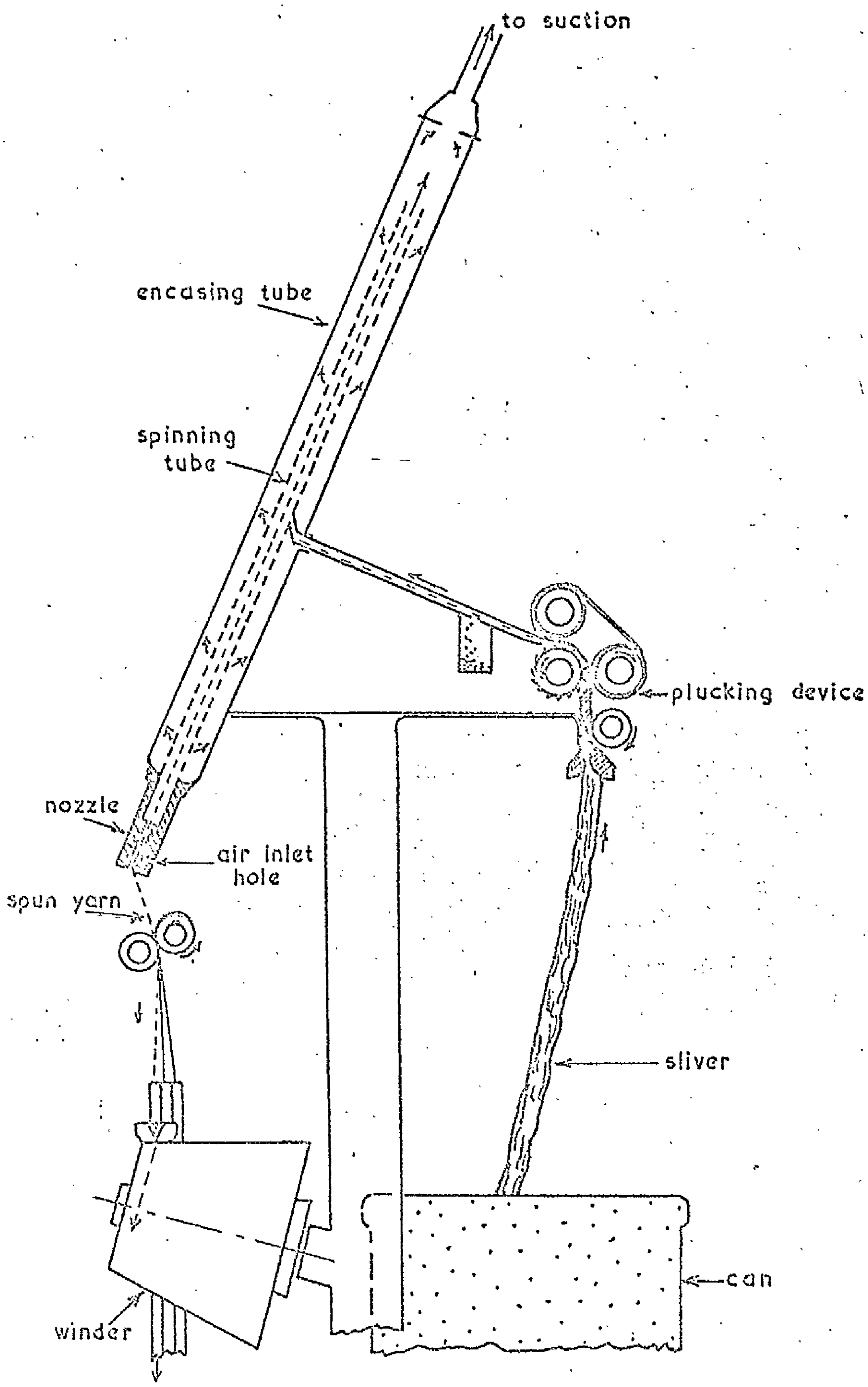



Fig. 2.26.

GOTZFRIED'S METHOD

previous one but using compressed air instead of suction was the subject of a later patent granted to Gotzfried. Here the top of the tube C is placed in a circular chamber B into which compressed air was sent by the tube 1, as shown in Fig. 2.27. This air passing through the tangential holes created a vortex. Yarn was formed as in the device using suction.

2.6.5. Urano et al[64] (1963)

Roving was fed into a fan chamber. The fast revolving blades of the fan rotating at about 16,000 r.p.m. opened out the fibres which were then carried away by air currents generated by the fan into a twister unit. The twister unit consisted of a spindle and a cap, as shown in Fig. 2.28. The fibres assembled themselves into tufts in the twister unit and the tufts were twisted together to form a yarn. The air current escaped to the outside through a small hole in the cap. The spun yarn was withdrawn from the twister unit by a pair of rollers. A spindle speed of about 20,000 r.p.m. was claimed to be possible by this method.

It appeared that this method was later on abandoned owing to the poor quality of yarn produced.

2.6.6. Hirway[9] (1964)

The principle of Hirway's method was based on Gotzfried's air vortex method of spinning yarns. The apparatus consisted of a vortex tube with a nozzle having two tangentially placed air inlet holes and an axial hole for the yarn withdrawal. This is shown in Fig. 2.29. The vortex tube was encased in a larger tube which was connected by means of a long flexible pipe to a suction pump. A drafting unit with two pairs of rollers supplied the attenuated fibres into one of the inlet

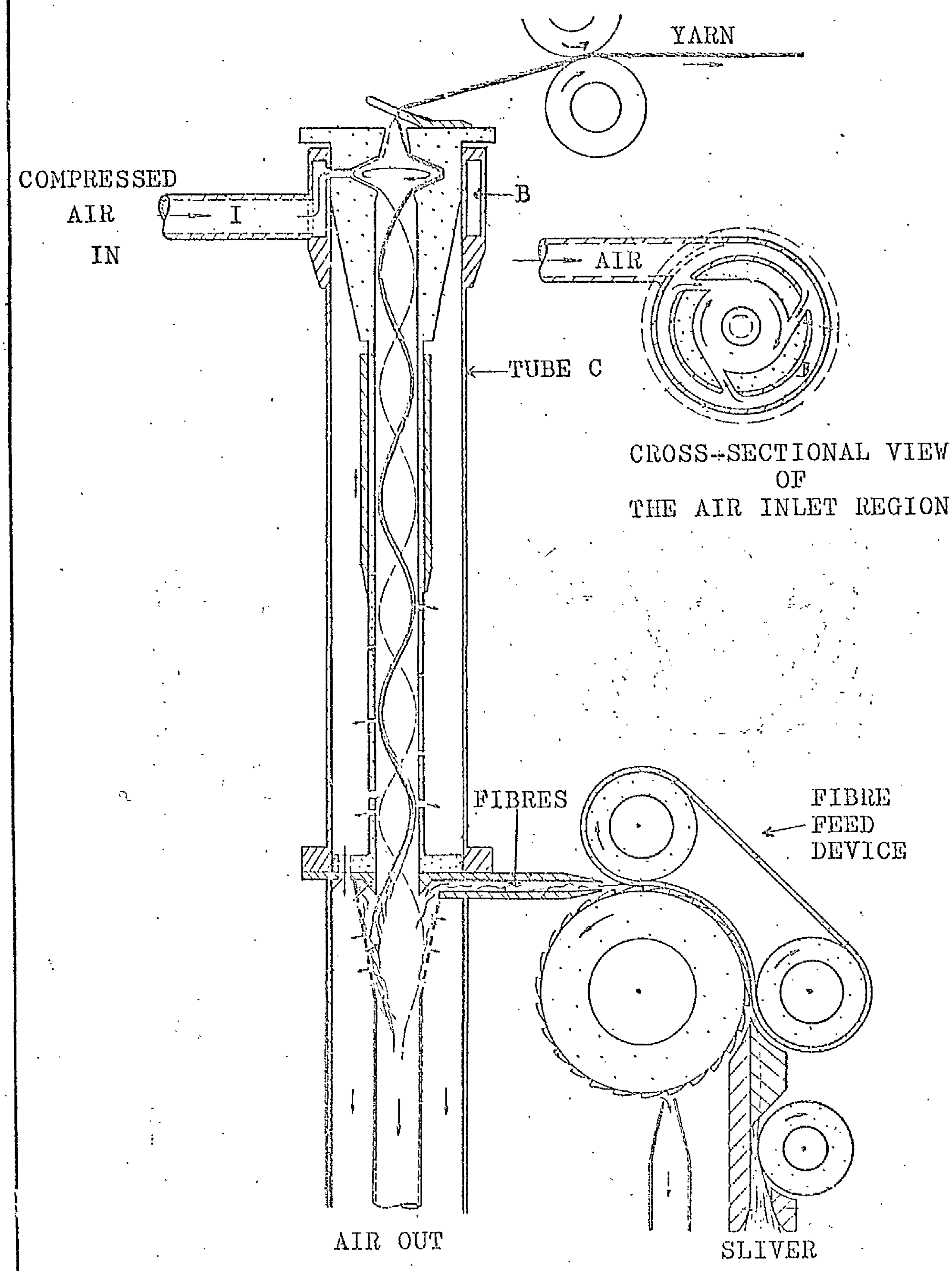



Fig. 2.27.

GOTZFRIED'S AIR VORTEX SPINNER

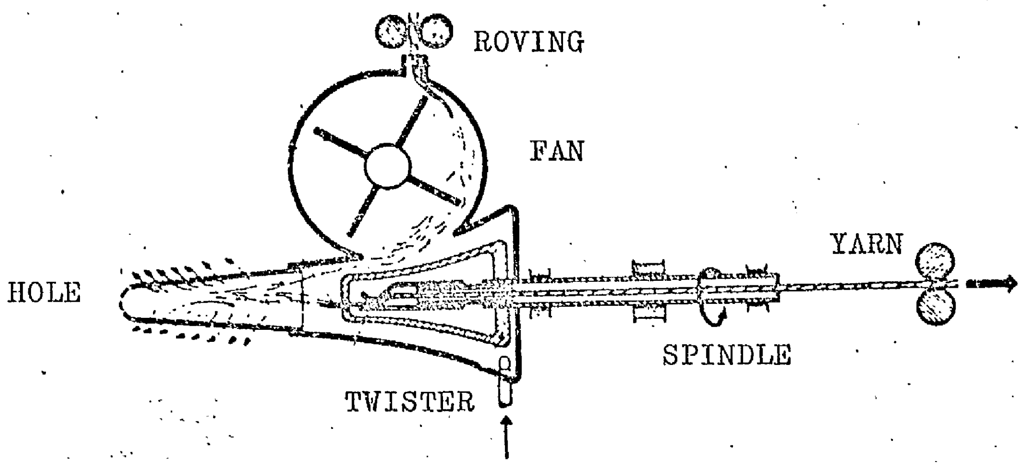



Fig. 2.28.

URANO'S SPINNER

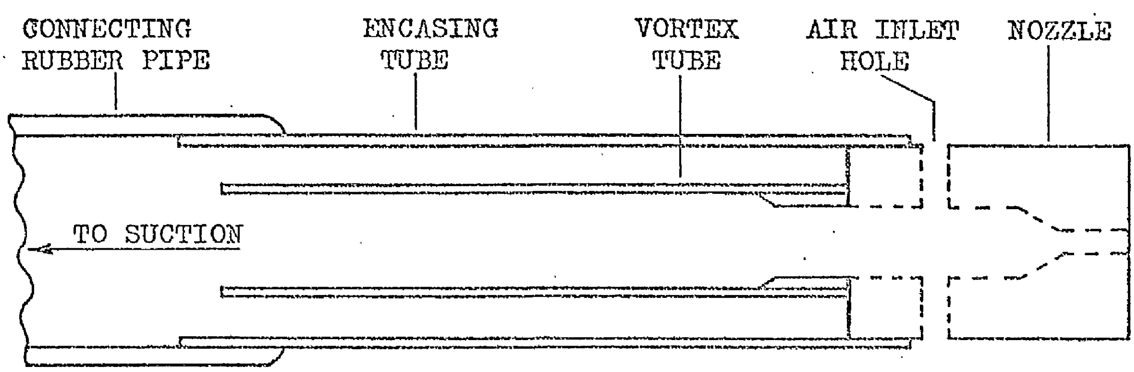



Fig. 2.29

HIRWAY'S VORTEX SPINNER

holes. The air suction created by the pump caused the air to flow in a tangential direction inside the tube. The air vortex thus created rotated the fibres and enabled them to attach themselves to a seed yarn. Twist was inserted into yarn by the vortex. The spun yarn was wound directly on a wooden drum.

2.6.7. Burkhardt[65] (1966)

This method consisted of a vortex tube one end of which had four tangential air inlets spread equally around the circumference of the tube. The other end of the tube was left open. Fibres were fed through a separate inlet placed about midway along the length of the vortex tube. Two throats were formed with the intention of obtaining an increased rotational speed of yarn. Compressed air was blown through the four air inlets. The fibres introduced into the tube became attached to a seed yarn. The continuous feeding of fibres and withdrawing of formed yarn made spinning a continuous operation.

2.6.8. General comment on pneumatic methods

Among the pneumatic methods mentioned before, Gotzfried's apparatus merits some consideration. Although this method has not yet reached the stage of full development, nevertheless, it seems very interesting because of its extreme simplicity of operation and the complete absence of mechanically moving parts. The idea of simplification was taken a step forward when the vortex tube was applied directly to the cylinder of a card. The spinning tube requires little space and, therefore, it was thought a bank of vortex tubes, about 40 in number, might directly spin yarns from the card(the doffer and coiler of the card might become redundant).

It has been possible to produce reasonably even yarns. The yarn is full and soft to handle. An advantage is the use of air which is freely and abundantly available. The capital cost per spinning unit may work out to be considerably less than that of the conventional spindle. Thus this system offers the prospect of a low cost machine capable of producing a reasonably good quality yarn.

In spite of the advantages mentioned, this method has some drawbacks. The yarn strength has still a long way to go before it can equal the strength of a ring spun yarn. The most serious disadvantage of this method is that the fibres which are not assembled into yarn are collected as waste. This waste can, however, be reprocessed. Although air is available in plenty, it becomes expensive to pump it. It has not been possible yet to exercise a precise control over yarn twist. At very high air flow speeds, turbulence may be created inside the tube and this may impair yarn formation. The yarn structure is rather unorthodox and it may not be particularly suitable for certain end uses and textile processes, especially as warp in weaving.

Striking a balance between the merits and demerits of this method, it appears that this system has great potentials for further development and the disadvantages may, at least to a certain extent, be overcome if a detailed study were to be conducted. With this end in view, a further study of Hirway's method (which was a modification of Gotzfried's device) was taken up as the subject for the present research.

## 2.7. THE PRESENT SITUATION OF BREAK SPINNING

### 2.7.1. Machinery developments

In addition to the BD 200 machine offered by V.U.B. of Czechoslovakia, three more companies have joined the race for the manufacture of break spinning machines and they are expected to release their machines soon. These companies are:-

(1) Societe alsacienne de Constructions Mecaniques(S.A.C.M.) of France,

(2) Toyo Rayon Co. Ltd.,-Howa Machinery Ltd., of Japan,

(3) Toyoda Automatic Loom Production Company of Japan.

Few details of these machines have so far been published. Of these known particulars, only the essential ones are given below:-

The spinning drum of the S.A.C.M. machine, named as the 'Integrator', is based on the patent described in section 2.3.2.6. Unlike the BD 200 machine, the fibres are opened by means of double apron drafting units. Draw frame sliver from a can feeds each drafting unit. The Integrator which is a single-sided machine is claimed to spin yarns from 4s to 14s c.c.(150 to 42 tex) from carded cotton and man-made fibres of staple length up to 1 9/16 in. The drum can be driven at speeds up to 30,000 r.p.m.

The Toyo-Howa MS400 machine is double-sided and has 200 spinning units. Presumably, MS 400 denotes the maximum speed of the drum which is about 40,000 r.p.m. Sliver from a can passes through a 3 zone, double apron drafting unit. The drafted fibres are carried by an air stream into the spinning unit. This machine is fitted with an automatic piecing device. The power requirement for one machine is about 18.5 kW. It is reported that the MS400 will spin cotton, man-made fibres and blends of staple lengths from $\frac{3}{4}$ in. to 2 in. in a count range from 10s to 50s c.c. (60 to 12 tex).

The Toyoda TX type machine is also a double-sided machine with a total of 200 spinning units.

2.7.2. Publications

During the last few years, a number of papers, mostly of a documentary nature, have been published. A number of authors have documented well the various devices and patents in break spinning. Among them may be mentioned Catling(7), Lord(8), Grossman(66), Heimeran(67), Liebscher(68), Anon(69), Stiepel(70), Keller(71), Anon(78) and several others.

The reviews of break spinning devices written by different authors seem to differ from each other mainly in their method of classification of the various devices.

Catling(28) divided the break spinning systems into the following four groups based on their distinctive features of fibre assembly:-

(a) vortex assembly system, typified by Gotzfried spinning tube,
(b) axial assembly system which includes Pavek's basket spinner,
(c) intermittent assembly system, such as, Barker's spinner and
(d) continuous circumferential assembly system; this includes drum type spinners.

Grossman and Liebscher grouped the various devices according to the means used for imparting twist and the procedure for gathering the fibres. Their classification fell into three groups, viz., mechanical, pneumatic and electro-static. In this grouping, it is impossible to make a distinct division between the groups because different means are often combined, viz., pneumatic and mechanical forces are present in drum spinners.

Lord(72) categorised the break spinners by the way in which the fibres travelled to the collecting surface and grouped them as radial, tangential, spiral and axial. A further classification was made on the basis of the major intentional forces involved in twist insertion and this consisted of four divisions, viz., mechanical, aero-mechanical, fluid and electro-static. Fig. 2.30 shows this classification.

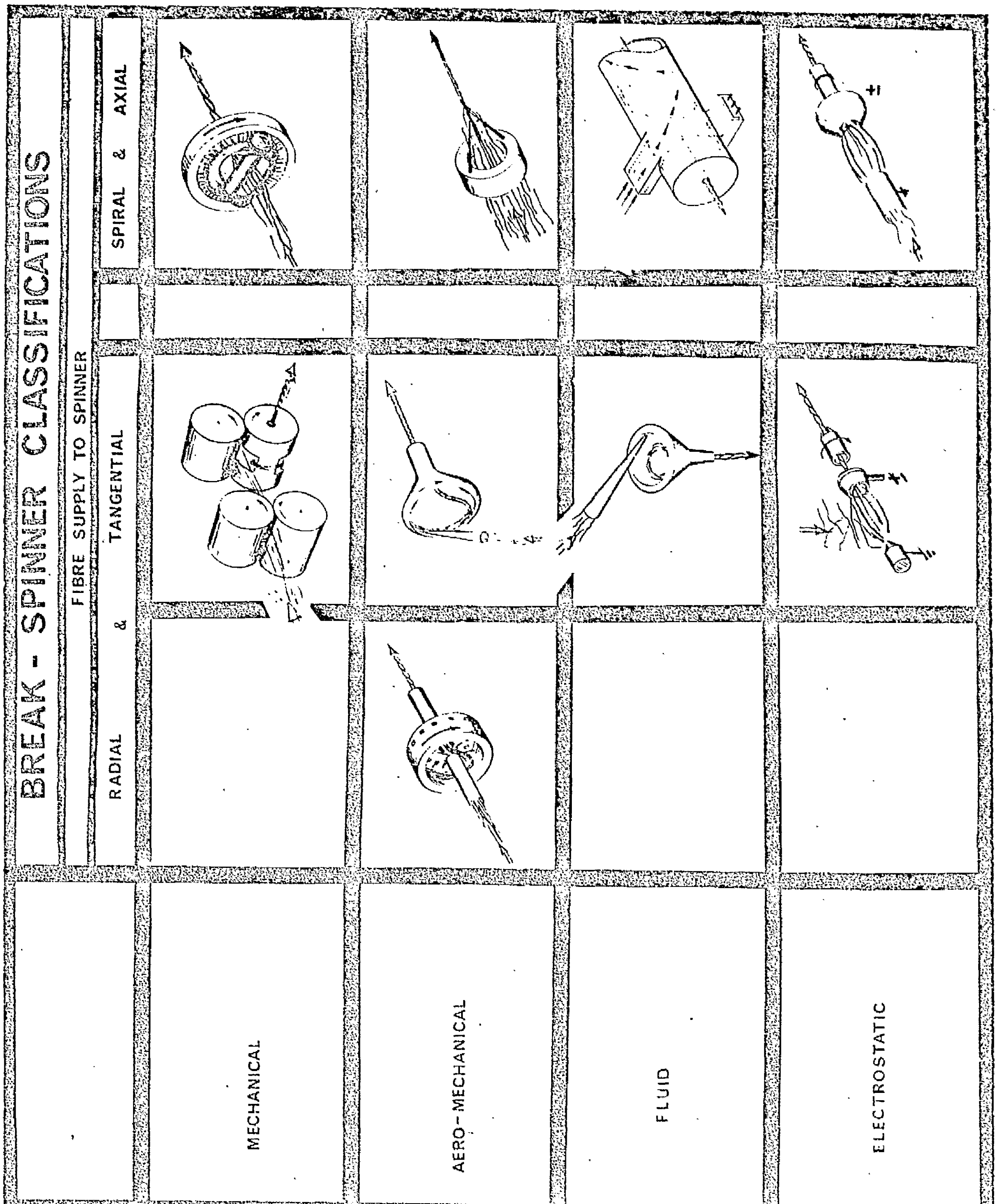
Catling(73) and Lord(72) have discussed the economics of break spinning. With the present capital cost of the BD 200 machine, the economical operating speed of drum would be around 50,000 r.p.m. and this machine would give the maximum financial returns when spinning coarse yarns.

The recent release of the report(74) on break spinning conducted by the Shirley Institute is a substantial contribution to this new technology. This gives a detailed study of the potentials and limitations of the different break spinning devices.

A few conferences have been held on this subject in this country and abroad. These have contributed considerably to the advancement of the knowledge in the developing technology of break spinning.

Fig. 2.30.

LORD'S CLASSIFICATION OF BREAK SPINNERS



# CHAPTER 3

## A BRIEF REVIEW OF FIBRE FEED DEVICES

# CHAPTER 3

## A BRIEF REVIEW OF FIBRE FEED DEVICES

### 3.1. INTRODUCTION

The quality of break spun yarn may be greatly influenced by the method adopted to feed the fibres into the spinning element. It was, therefore, felt that it would be relevant to mention briefly the various methods of fibre presentation to the spinning element of a break spinner.

The one important quality of yarn(i.e., the yarn evenness) which influences the other characteristics depends, to a large extent, on the nature and efficiency of the fibre feeding device used. An ideal fibre feed device would be expected to fulfill the following conditions:-

(a) The fibres must be separated from each other and they must be presented to the fibre inlet of a spinner one by one rather than as clumps or tufts.

(b) Fibres must be well-oriented and lie parallel to each other on the collecting surface.

(c) The rate of fibre input into the spinner must be maintained constant during the spinning operation.

Many methods of fibre feed have been suggested and some have been experimented upon. These methods often form a part of the break spinning device. Amongst these methods, only a few of them seem to partly satisfy the desired objectives. One of these feed systems has been already incorporated in the Czechoslovakian break spinning machine of the drum type. However it appears that a break spinner of the future would necessarily need a fibre feed system capable of not only satisfying the essential conditions of fibre individualisation and parallelisation mentioned above, but also be capable of coping with extremely high speeds of fibre input that might be called for in the not too distant future. Fibre feed systems of the present day require further improvements in order to attain these objectives. In the light of the future trend, it is even considered that it would be a worthwhile and rewarding project to take up the subject of fibre presentation on its own as a topic for immediate research.

A brief outline of the various methods of fibre feed classified under the headings of the type of raw materials used in these systems is given below.

3.2. BALE FEED

A bale is subjected to a number of high pressure air jets issuing out of nozzles. The force of impinge of air slowly disintegrates the bales into tufts. These fibre tufts float in the chamber and are carried through a series of chambers where the tufts are broken down still further into small sizes by the action of the high velocity air streams. The small tufts are finally led to a cyclone separator and are subjected once again to the action of high velocity air jets. The fibres from the bottom of the cyclone separator are taken directly into a break spinner. Mayo's method, outlined in section 2.6.2., employed this feed system.

It is not known to what extent a complete separation of fibres could be effected by the use of air jets alone and without any mechanical means. This is because it is quite difficult to break down fibre tufts into individual fibres by pneumatic means alone. This belief is confirmed by Edberg[79] who worked on a method similar to the one mentioned above and finally arrived at the conclusion that it was not possible to disentangle the tufts and separate them into individual fibres by means of pneumatic methods alone. Even assuming that fibre individualisation occurs, it would be highly unlikely that the fibres would lie parallel to each other. The random arrangement of fibres during the feeding of a spinner is most likely to result in the formation of an irregular or weak yarn. Considering this feed system as a whole, it is doubtful if this method would be economic to use, because of the large quantities of air needed to achieve fibre separation.

It may be mentioned, purely as a matter of subject interest only, that instead of the air the fibres may also be dispersed in a liquid medium, such as, water. The use of a liquid medium would have far too many disadvantages(please refer to section 2.5.).

3.3. LAP FEED

A lap is passed through a taker-in and cylinder of a card. The lap is broken down into fibre tufts by the action of the taker-in roller. These tufts are then combed (or carded) between the wire points of the cylinder and the flats. Fibres stand a good chance of being individually separated. At the zone of the front plate of the card, these fibres are removed by air suction and finally conveyed into the fibre inlet of a break spinner.

Chandarana[10] used this method with a slight variation when spinning by air vortex from a card. Slivers were used instead of a lap as the backstuff. Simplicity, the ready availability of slivers and the need to feed only one nozzle were probably the main reasons for his choice. Alternatively, a lap feed would necessitate the use of a number of nozzles on the card to cover the lap width. Furthermore it is important that the lap must be very even in its cross-section across its width and also along its length, if uniformity in the rate of fibre feed is desired not only for all the nozzles but also for any one nozzle over a length of time.

The yarns spun by Chandarana[10] were quite regular and this suggested that apart from the good performance of air vortex spinner, the fibre feed arrangement was also partly responsible for this result. However there appears to be still room for further improvements. The periodicity of slub formation in these yarns might be a reflection of the periodic nature of fibre plucking by the taker-in roller. This periodicity may be greatly reduced by evening out the periodic fluctuations in fibre supply to the cylinder by interposing a fast rotating roller with fine wire points between the taker-in and the cylinder of the card.
On carding, the fibres may not be fully separated and they may be still in tuft form. According to Rahman[80], of the total fibres on the cylinder surface of a card, clumped fibres formed about 15% when sliver was fed and about 30% when lap was used as the backstuff material. The continuous stripping of fibres from the cylinder surface will tend to reduce the carding action on fibres. Although the orientation of fibres on the cylinder surface leaves much to be desired, the use of air stripping can give a sort of 'gilling' action. This will tend to straighten out the fibres. However it seems likely that a part of this orientation may be lost during the fibre condensation on the tube wall of an air vortex spinner. Moreover the rate of fibre input into the spinner will tend to vary on a long term transient basis due to the

loading up of the cylinder with fibres, when the stripping efficiency is not 100%.

3.4. FIBRE STRAND FEED

The drafting of fibres may be achieved either by

(a) the conventional roller/apron drafting apparatus

or (b) miniature taker-in type opening device.

3.4.1. Conventional drafting system

In this type of feed system, sliver or roving is used as the backstuff material. In its simplest form, a sliver or roving is drafted in a conventional roller/apron drafting system and the fibres emerging from the front roller nip are presented to the break spinner. This method was employed by many workers in the field of break spinning because of its simplicity and the reasonably efficient way in which fibres are presented.

The fibres are made almost parallel to each other by the drafting system. Under normal working speeds, the rate of fibre flow can be maintained almost at a uniform level. The drafting mechanism is usually simple and robust in construction. Nevertheless, in spite of these apparent advantages, there are some drawbacks too. The fibres are not completely separated from each other and they tend to lie in groups. There is a limit to the range of staple lengths that can be processed. At very high speeds, the efficiency of the mechanical means used for control of the fibre movements in the drafting zone may be seriously affected. Irregularities, such as drafting waves, may occur at these speeds and these will be detrimental to the maintenance of a uniform rate of fibre feed into the break spinner. Very high draft ratios which are essential for feeding fibres as individuals cannot be achieved in this system.

3.4.2. Miniature taker-in type opening device

The limitations of conventional drafting apparatus lead the inventors to seek alternative means of fibre feed devices. Most of these opening devices are modified versions of the taker-in used in the card.

3.4.2.1. Meimberg's opening device

In Meimberg's(81) device, there are three rollers A,B and C, all of taker-in type covered with fine wire points. The surface speed of the roller B is faster than that of A, and that of C much higher than that of B. The progressive increase in the surface speeds of the rollers assist in the transfer of fibres from the roller A to the roller C. During this process of fibre transfer, the fibres are subjected to very high opening drafts which tend to separate the fibres into individuals. The individual fibres from the roller C are conveyed into the break spinner by the air suction created by it. This device is shown in Fig. 3.1.

3.4.2.2. Pavek's opening device

This device consists of a fibre opening roller covered with taker-in type wire. A sliver passes between a feed roller and a curved dish plate, as shown in Fig. 3.2. The dish plate presses on the feed roller by means of compressed springs. There is a gradual divergent taper in the clearance between the wire points and the roller cover up to the region almost diametrically opposite to the feed roller. A stripping blade assists in the removal of fibres from the roller surface. The roller speed is around 7,000 r.p.m.

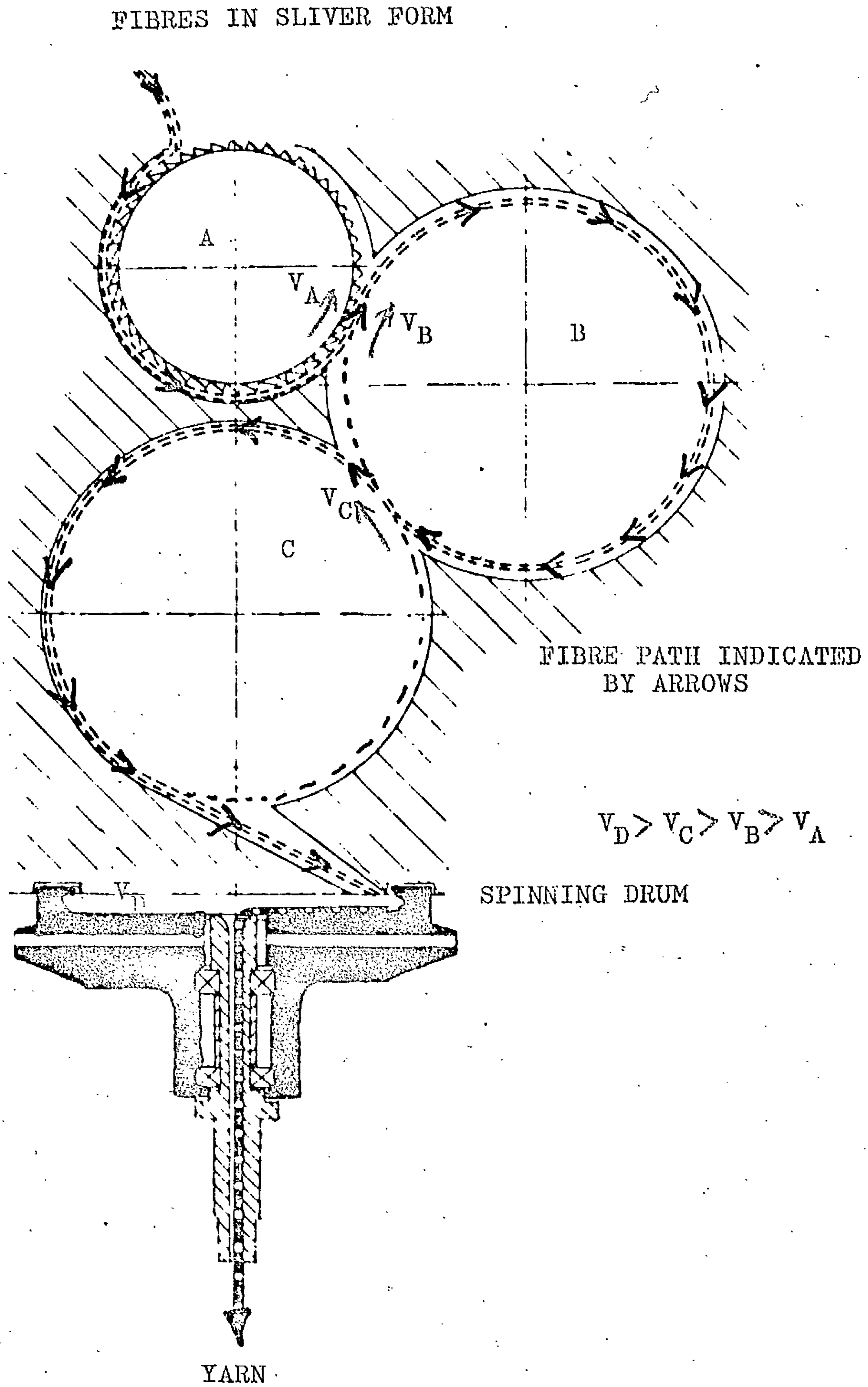



Fig. 3.1.

MEIMBERG'S OPENING DEVICE

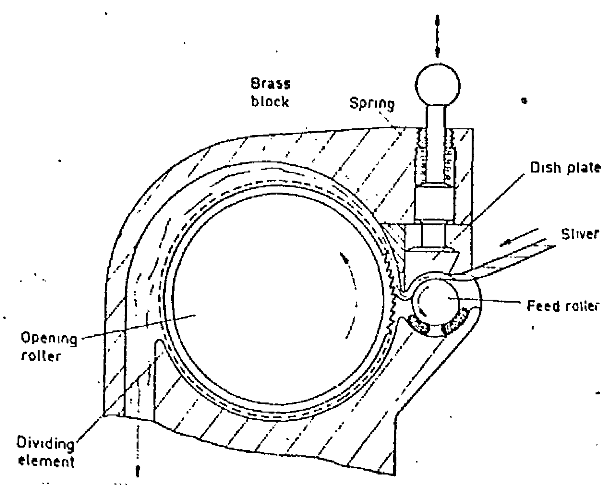



Fig. 3.2.

PAVEK'S OPENING DEVICE

<u>3.4.2.3. V.U.B. opening device(as used in BD 200 machine)</u>

A variation of Pavek's opening device is the one used in the Czechoslovakian BD 200 drum spinner. Rohlena(50) was perhaps the first to give the details about this opening device. The fibre separating device is shown in Fig. 3.3.

This device consists essentially of a feed roller A and an opening roller B covered with fine wire points. A spring loaded pressure shoe S compresses the sliver and presents this fibre mass to the combing action of the opening roller B. The roller B is about $2\frac{1}{4}$ in. in diameter and rotates at about 8,000 r.p.m. Very high draft ratios of about 10,000 to 15,000 can be obtained during the opening process. Such high draft ratios will tend to separate the fibres almost completely. The combined action of the high velocity air stream(generated by the air suction of the spinning drum) flowing across the wire points and the centrifugal force of the fibres tending to throw them out of the roller surface remove the fibres from the roller surface. The individual fibres are then carried into the tangentially placed fibre inlet tube D by the air current passing through the air inlet tube C which is more or less an extension of the fibre inlet tube D. Finally the fibres deposit on the collecting surface of the drum.

Let $V_1$ be the surface speed of the feed roller A,
$V_2$ be the surface speed of the opening roller B,
$V_3$ be the velocity of air passing through the air inlet C at the region where the fibres are removed from the roller B,
$V_4$ be the air velocity in the fibre inlet D and
$V_5$ be the surface speed of the collecting surface of the spinning drum E.

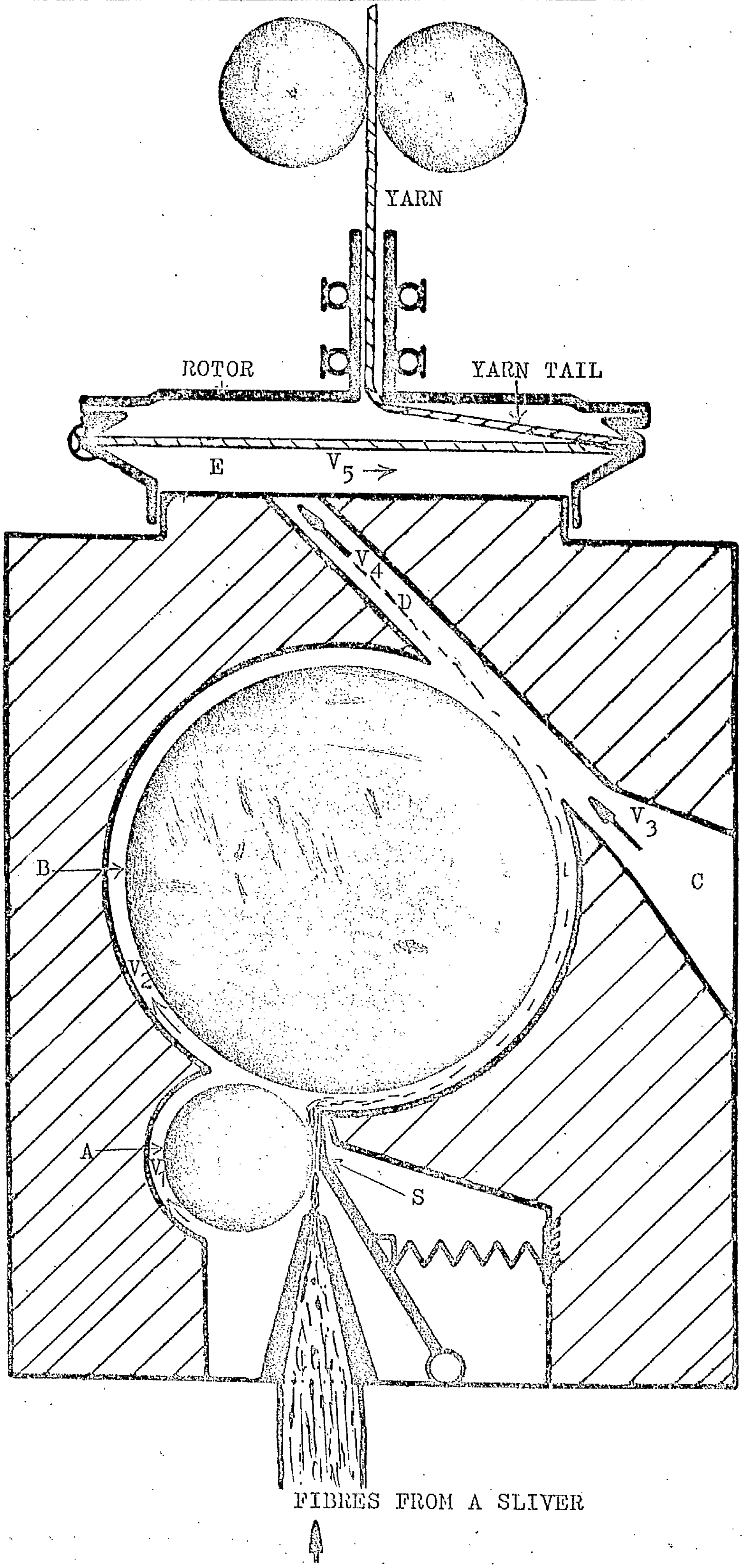



Fig. 3.3. V.U.B. OPENING DEVICE

It might be reasonable to expect that the fibres will tend to attain the velocities of the medium in which they are present.

In order that an effective opening and stretching of the fibres is to be achieved from the time the fibres enter the opening device until they are deposited on the collecting surface of the spinning drum, it is essential that

$$V_5 > V_4 > V_3 > V_2 > V_1$$

3.5. LIMITATIONS ON YARN COUNT IMPOSED BY FIBRE SUPPLY SPEED

The following calculation is worked out in order to obtain an idea of the speed of fibre supply that will be necessary to fulfill the ideal condition of feeding the fibres one by one into the spinning tube.

Assumptions:

(a) During the spinning process, all the fibres supplied into the spinner are assembled into yarn and, therefore, there is no fibre wastage.

(b) The spun yarn is uniform in thickness along its length, i.e., the yarn contains exactly the same number of fibres in its cross-section throughout its length.

Let the linear density of yarn be 20 tex and let the linear density of fibre used for spinning this yarn be 1.5 denier, i.e., $(\frac{1.5}{9})$ tex.

The number of fibres in a cross-section of the yarn will be $\frac{20}{\frac{1.5}{9}}$, i.e., 120.

If the fibres are supplied one by one into the spinner so that the leading end of one fibre just touches and follows the trailing end of the previous fibre, then the fibre supply may be said to contain one fibre in its cross-section. Suppose a small break is introduced into the fibre flow such that the fibre ends are placed at a given distance apart. Let such a fibre supply contain 0.8 fibre in its cross-section.

In order to produce a yarn of 20 tex at a withdrawal rate of 120 m/min, the fibre supply speed must be $\frac{120 \times 120}{0.8}$ m/min, i.e., 18,000 m/min. or 300 m/sec .

This fibre speed is too high to be normally attained by the conventional means of fibre feed devices, such as, the roller drafting unit. Even if the yarn withdrawal rate is halved to 60 m/min , the correspondingly reduced fibre supply speed of 150 m/sec is still very high. A satisfactory performance of fibre feed will tend to be seriously affected because the efficiency of the mechanical means for controlling the fibre movements in the drafting zone will tend to decrease to abnormally low values as the roller speeds are increased above certain limits. Drafting waves will be introduced and this will affect the uniformity of fibre feed.

Since the coarser the yarn, the greater are the number of fibres present in its cross-section(with a given linear density of fibre), it becomes necessary to increase the fibre supply rate to phenomenally high speeds in order to spin coarser yarn counts. The mechanical limitations in speed of the fibre supply system will tend to limit the coarsest count of yarn spinnable under given conditions of yarn withdrawal rate and fibre linear density. This seems to suggest that it may be easier to achieve an ideal fibre supply for spinning a fine yarn rather than a coarse yarn, at high take-off rates of yarn.

Let $V_f$ be the limiting velocity of fibre feed,

$V_y$ be the yarn withdrawal rate,

$tex_f$ be the linear density of fibre in tex,

$tex_y$ be the linear density of yarn in tex.

and 0.8 be the number of fibre in a cross-section of fibre feed.

The coarsest count of yarn that can be spun is given by the expression $tex_y = \frac{V_f \times tex_f \times 0.8}{V_y}$.

From this expression, it may be inferred that, for any given fibre feed velocity, the limiting coarse count of yarn is influenced directly by the coarseness of fibre. Again the lower the yarn withdrawal rate, the coarser the yarn that can be spun.

$$tex_y = \text{Constant} \times \frac{tex_f}{V_y},$$

$$\text{or} \quad tex_y \propto \frac{tex_f}{V_y}.$$

Thus, for a given limiting velocity of fibre feed, the linear density of yarn $\simeq \frac{\text{linear density of fibre}}{\text{yarn withdrawal rate}}$.

Thus there appears to be some practical difficulties involved in the fulfillment of the ideal condition of fibre supply at high speeds, especially when spinning coarse counts. Alternatively, it may be said that an ideal fibre supply system will tend to impose a limit on the coarseness of the yarn that can be spun.

The fibre supply speeds may, however, be reduced either by half or one third by feeding 2 or 3 fibres together at a time rather than as individuals but this method of feeding will be at the expense of an ideal fibre supply arrangement.

The following tabulation gives in brief the essential requirements at each stage of air vortex spinning and the implications involved for the requirements to be attained.

| STAGE | REQUIREMENTS | IMPLICATIONS |
|---|---|---|
| Fibre drafting | Draft to single fibres | Very high draft ratio in the region of 20,000 to 30,000 might be needed. |
| Fibre transport | Fibres to be carried without disturbing their order or shape | No fibre deceleration. No air turbulence. |
| Fibre condensation | Fibres to be layered without deceleration. Fibres to be straight and perfectly aligned on collecting surface(s) | Fibre speed in tube > fibre arrival speed to give straightening effect. Ideally there will be as many doublings as there are fibres in the yarn cross-section. |
| Yarn formation | Yarn should remove all fibres from the stationary collecting surface; yarn to contain as little wrap twist as possible. | Yarn tail must be sufficiently strong and of constant length; the fibre should migrate from one layer to another to prevent 'onion skin' effect. |

| | | |
|---|---|---|
| Yarn take-up | Constant velocity | Take-up is continuous and linear; therefore any continuous process can be inserted. |

# SECTION II

# P R E L I M I N A R Y  T H E O R Y  A N D  T E S T S

## CHAPTER 4

## A BRIEF REVIEW OF PRELIMINARY THEORY AND TESTS ON AIR VORTEX SPINNING BY HIRWAY

# CHAPTER 4

## A BRIEF REVIEW OF PRELIMINARY THEORY AND TESTS ON AIR VORTEX SPINNING BY HIRWAY

### 4.1. INTRODUCTION

Since the present research is concerned with furthering the studies conducted by Hirway on the air vortex method of spinning yarns, it was considered necessary to give a brief review of Hirway's theoretical and experimental work in a separate chapter.

Hirway explained the mechanism of fibre assembly and twist insertion in his theory on air vortex spinning. The basic theory seems to hold good still and, in fact, this theory formed a foundation for the building up of the subsequent theory. Nevertheless a critical assessment of Hirway's theory showed that modifications were needed to bring this theory up to date and it became evident that there was ample scope for development of his theory. The further development of Hirway's theory is dealt with in detail in Section III.

Hirway's experimental study may be considered as a preliminary exploration in the then new field of vortex spinning and this formed a good basis for future work. The experiments conducted by the author in the present research is a continuation of Hirway's practical investigations. A critical assessment of Hirway's experimental investigations pointed to the various ways and means by which improvements in spinning performance might be effected to produce reasonably good yarns.

Hirway's study may be broadly divided into two sections. They are as follows:-

(a) the theoretical aspects of vortex spinning and (b) the experimental work.

## 4.2. HIRWAY'S THEORY OF VORTEX SPINNING

### 4.2.1. Yarn behaviour in a vortex tube

Hirway considered separately the behaviours of a yarn in a forced and a free vortex.

In the case of a yarn introduced into a vortex tube and subjected to a forced vortex (Fig. 4.1.), the twist is inserted by the translational drag imposed on the yarn due to rotational velocity of the vortex. However the lack of restraint at the open end allowed most of the twist to leak away. The resultant twist in the yarn was thus said to be inserted by the torque due to torsional drag only.

Again a yarn introduced into a free vortex would be also subjected to the torsional effects mentioned above. Since the angular velocity of air stream varies with radius there would be a torsional shear between radially adjacent streamlines. Hirway assumed, therefore, that in addition to torsional drag effects the yarn would undergo a torsional shear due to its thickness and this would impose a torque on the yarn. This torsional shear would, however, tend to untwist the yarn. This effect is shown in Fig. 4.2. The net result would be that the final twist in a yarn subjected to a free vortex would be less than that in a forced vortex.

A yarn inserted in a vortex tube is thrown against the tube wall because of the centrifugal forces exerted by the rotating yarn. There are solid friction effects between the yarn and the tube wall and this frictional effect also tends to untwist the yarn. Please see Fig. 4.3.

Hirway, therefore, envisaged the possibility of obtaining a significant loss of twist by these means.

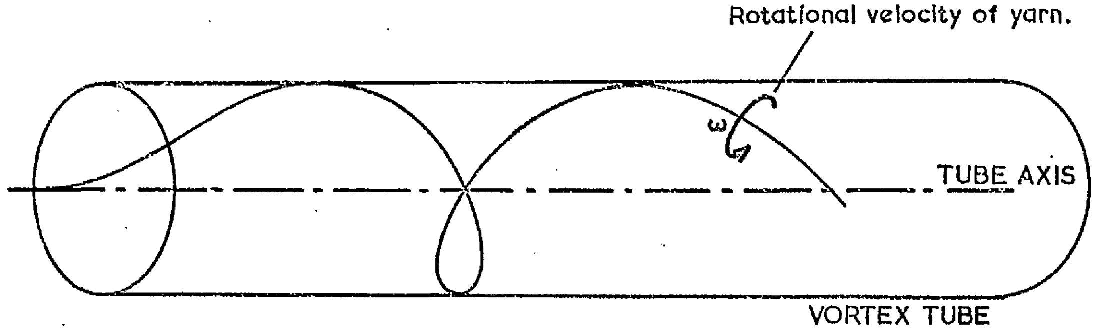



FIG. 4·1

BEHAVIOUR OF YARN IN A FORCED VORTEX.

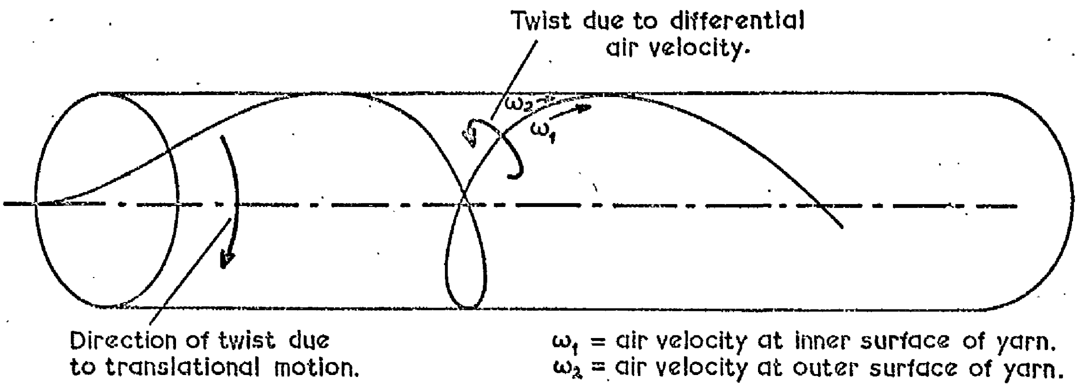



FIG. 4·2

BEHAVIOUR OF YARN IN A FREE VORTEX.

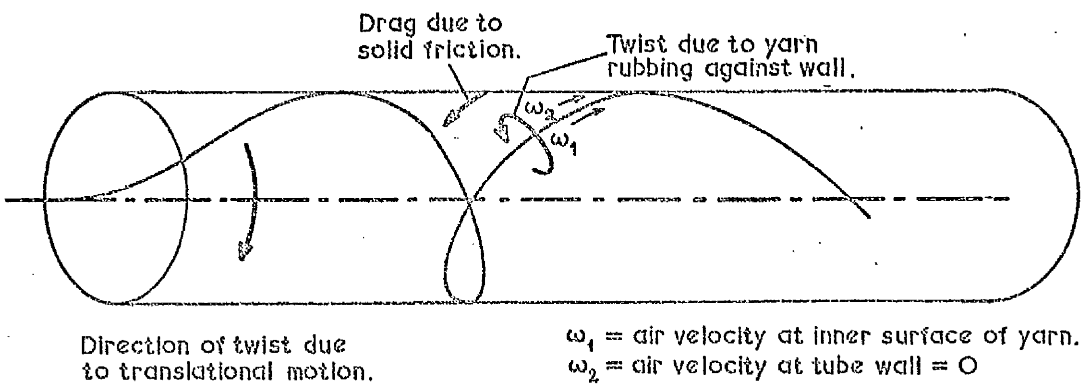



FIG. 4·3

EFFECT OF YARN RUBBING AGAINST INSIDE WALL.

During a preliminary study of vortex spinning, the author obtained yarns with a twist opposed in direction to that of vortex flow. This was as a result of varying the nozzle design parameters. The yarn produced then had, however, a low twist. The yarn was S-twisted with the vortex flow in an anti-clockwise direction when viewed from the suction end. Chandarana[10] confirmed this behaviour of reversed twisting in his work on the application of vortex spinning to the card. The yarns produced by him contained a relatively large number of twists per unit length. However no theoretical explanation to this observed phenomenon was put forward by Chandarana.

Thus it may be said that Hirway's prediction of twist loss due to solid friction and torsional shear effects was found to be true in practice. In fact, the results obtained in spinning during the course of the present research pointed to the fact that under certain conditions of nozzle parameter design it was possible to experience a substantial net twist gain in the reverse direction.

4.2.2. Twist estimation in yarn

Hirway ignored the effects of torsional shear and wall friction on the yarn merely for the sake of simplicity and, therefore, assumed the yarn movement inside the tube to be similar in effect to that which would be obtained if the yarn were rotated about its own axis in still air. Thus he took into account only the yarn rotation about its own axis for estimating the amount of twist insertion.

The yarn twist is proportional to

$$\frac{\text{torque applied on the yarn}}{\text{torsional rigidity of the yarn}}.$$

Here the torque inserts the twist into the yarn and because of the torsional rigidity the elastic torque opposes the twisting of yarn. The resultant twist in yarn would depend to a large extent on the torsional rigidity of yarn and any twist insertions beyond a certain limit would tend to leak away through the free end.

Hirway calculated theoretically the value of torque due to the torsional drag and obtained experimentally the torsional rigidity of a given smooth yarn. Thus for a given yarn of 0.124 inch diameter (the count of yarn is not mentioned in the text) rotating at about 17,800 revolutions per minute, the twist per centimetre was estimated to be $6.56 \times 10^{-6}$. This is an extremely low figure.

On the other hand, while considering the effects of hairiness on the net twist inserted Hirway estimated the twist for a hairy yarn as 9.25 twists per centimetre. This value seems to be quite high.

However it might be expected that the actual number of twist insertions in such a yarn would lie somewhere between these two extremes.

<u>4.2.3. Fibre assembly</u>

Fibres introduced into the tangential inlet of a vortex tube will tend to follow the air streamlines closely because the mass of fibres is relatively small.

A seed yarn inserted in a vortex tube is subjected to a rotational force and a translational force. As a result of these two, the yarn follows a helical path but the yarn helix rotates as a whole whereas the fibre helix remains stationary. The solid frictional forces between the yarn and the tube wall introduce drag forces and because of this, the helical shape of the yarn is different from that of the air streamlines. The fibres and the yarn travel along different paths and there are periodic intersections between their paths.

It is only at these intersections that assembly of fibres on a yarn is possible.

The fibre assembly is shown in Fig. 4.4. The circumferential surface of the vortex tube is developed into a single plane. The trajectory of the air streamline is represented by AZ. The trajectory of the individual fibres subject to friction is AZ'. The yarn trajectory is represented by a series of parallel lines, OB', AY etc.

The fibres have their first intersection point at the fibre supply point A. Some of them attach themselves to the seed yarn at A. Those fibres that are not attached to the seed yarn at A proceed on to B' at which point some fibres will be again attached to the seed yarn. This assemblage of fibres on the seed yarn proceeds at each subsequent intersection point. The variation in the distance between two intersection points, termed as the "assembly distance", is important because if this distance is too great then the forming yarn might not extend to the second (or subsequent) assembly point. The fibres will then have no chances of attachment and will be, therefore, collected as waste. The amount of waste seems to depend upon the number of times the fibre and yarn trajectories intersect and upon the efficiency of attachment at each intersection point. Possibly the length of yarn in the vortex tube may give an indication of the waste to be expected.

## 4.3. HIRWAY'S EXPERIMENTAL WORK

Hirway experimented with various sizes of vortex tubes ($\frac{1}{8}$ in., $\frac{1}{4}$ in., $\frac{3}{8}$ in., $\frac{1}{2}$ in. diameter Perspex and $\frac{1}{2}$ in. metal tubes) and different sizes of tangential inlet holes. He also varied the take-up speed of yarn from 2.2 yards per minute to 7.4 yards per minute and the air pressure difference

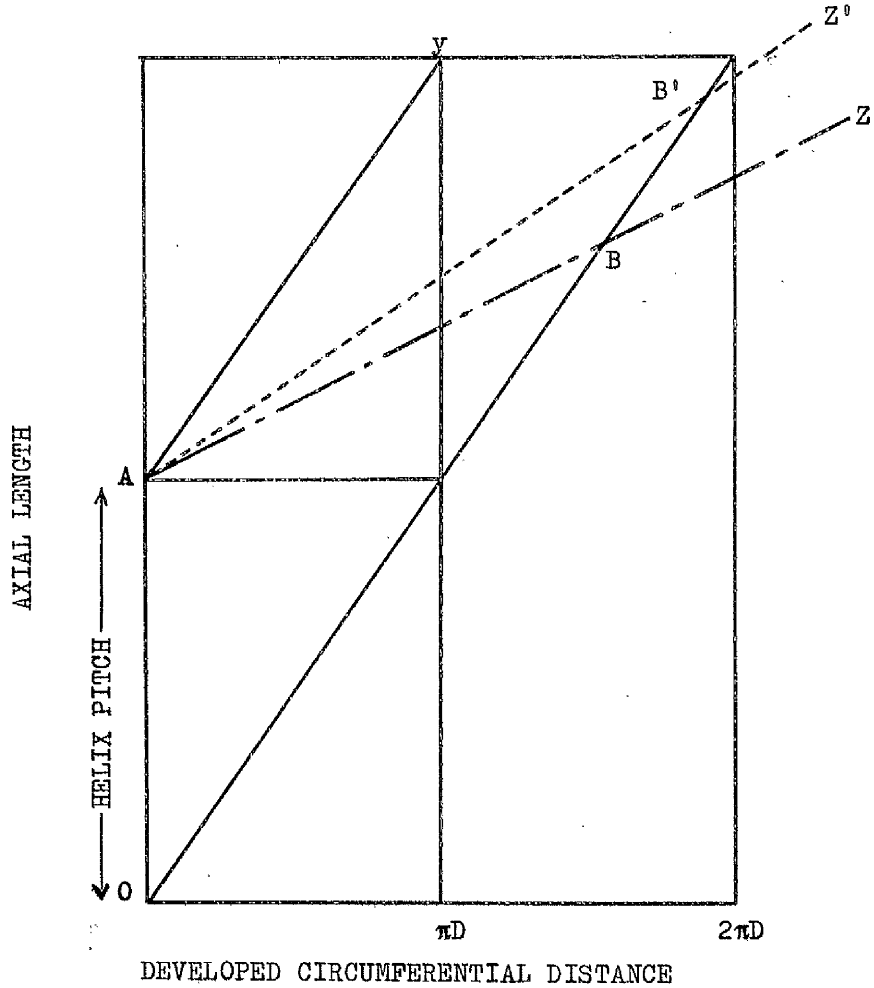



Fig. 4.4

ASSEMBLY OF FIBRES ON TO A SEED YARN

in the tube from about 5 in. to about 24 in. of water below atmospheric pressure. From all these experiments, the following processing condition was found to be the optimum for producing a yarn with a reasonably good breaking tenacity and evenness as well as yielding low waste and a relatively small number of yarn breaks per hour of spinning production.

(a) A $\frac{1}{2}$ in. diameter Perspex tube with 2 X $\frac{1}{4}$ in. diameter tangential inlet holes in the nozzle,

(b) An air pressure inside the tube of about 10 in. of water below atmospheric pressure, and

(c) A yarn take-up speed of 2.2 yards per minute.

It is interesting to note the variations of some yarn properties and the processing results obtained by Hirway during his series of experiments. This information was used later as a guide for comparison with the results achieved by the author in his own experiments. The maximum yarn breaking tenacity was 4 gf/tex, although this value was around 2 gf/tex in the majority of the tests. The percentage mean deviation of yarn irregularity varied between 17 and 27. The calculated fibre waste percentage was, in certain cases, as high as 80% but the average figure might be taken as around 60%. One other point that seemed to play an important role in Hirway's tests was the number of yarn breaks per hour of spinning production. The figure for this factor varied between 8 and 80.

The spinning draft ratio (which is equal to $\frac{\text{rate of yarn take-up, in./min.}}{\text{rate of fibre supply roller, in./min.}}$) in Hirway's experiments was maintained at about 3.5.

Photographs were taken showing the slub-like assemblies attached at intervals along a seed yarn when a tuft of fibres was fed into the vortex spinning tube. This seemed to prove the basic theory of fibre assembly. The average value of the actual assembly distance was found to be in close agreement with the theoretical value obtained.

It was particularly important to note an observation made by Hirway that the electro-static forces generated in the Perspex tube were not significant. This is questionable.

## 4.4. A CRITICAL ASSESSMENT OF HIRWAY'S WORK

### 4.4.1. Theoretical aspects

The yarn behaviour inside a vortex tube was explained in a general way by Hirway without going into details of the various mechanisms present. One noticeable omission was the frictional effect due to electro-static charges caused by the movement of fibres and yarn in tube.

The estimated twist value for a vortex spun yarn was extremely low. However, the yarns spun by Hirway gave breaking tenacity values around 2 gf/tex. This would suggest that the number of twists should have been much higher than the estimated value. On the other hand, the theoretically calculated value of 9.25 twists per centimetre for a hairy yarn is too high to be consistent with the breaking tenacity values obtained. Perhaps this high value of twist indicates that there is still a good scope for further improvement in twist insertion rate in actual spinning. The amount of hairiness during the formation of a yarn ( as distinct from the hairiness in the final yarn) might affect the actual number of twists introduced. The greater the hairiness of the forming yarn, the larger might be the amount of twist inserted per unit length of yarn.

The basic theory proposed by Hirway for fibre assembly is not correct in so far as the trajectories of air and fibre are concerned. From the fibre assembly diagram given by Hirway and shown in Fig. 4.4., it is evident that even though the yarn helix follows a different path to that of the fibre helix, these two helices still lie in the same direction. However during the present work it was observed with a stroboscope that the yarn helix was in fact of the opposite hand to that of the fibre helix. Hence modifications are needed to the basic theory of fibre assembly. The observed spirals were not uniform and the so called "fibre helix" opened up with the axial distance, i.e., the helical pitch increased with axial distance measured towards the suction end. On the other hand, the "yarn helix" tightened up towards the open end of yarn. With sufficiently long lengths of yarn in the tube, the free end of yarn was observed to lie in a plane almost perpendicular to that of the tube axis. This behaviour of fibre path and yarn helical shape will necessitate alterations in the theoretical trajectories of the fibres and yarn. The developed trajectories will no longer be straight lines as shown by Hirway but instead they will follow curved paths similar to those represented in Fig 4.5.

It was found in the present work that the length of forming yarn in the vortex tube did not have much influence on the amount of waste produced during spinning. It is thought that the fibre capture efficiency at each assembly point might have a relationship with the amount of fibre waste.

4.4.2. Experimental work

It was rather unfortunate that the sizes of vortex tubes experimented by Hirway were limited to a maximum of ½ inch diameter only. In the present research, it was observed that ¾ in. and 1 in. bore tubes were better suited for spinning than the ½ inch bore tube, especially when the fibres used

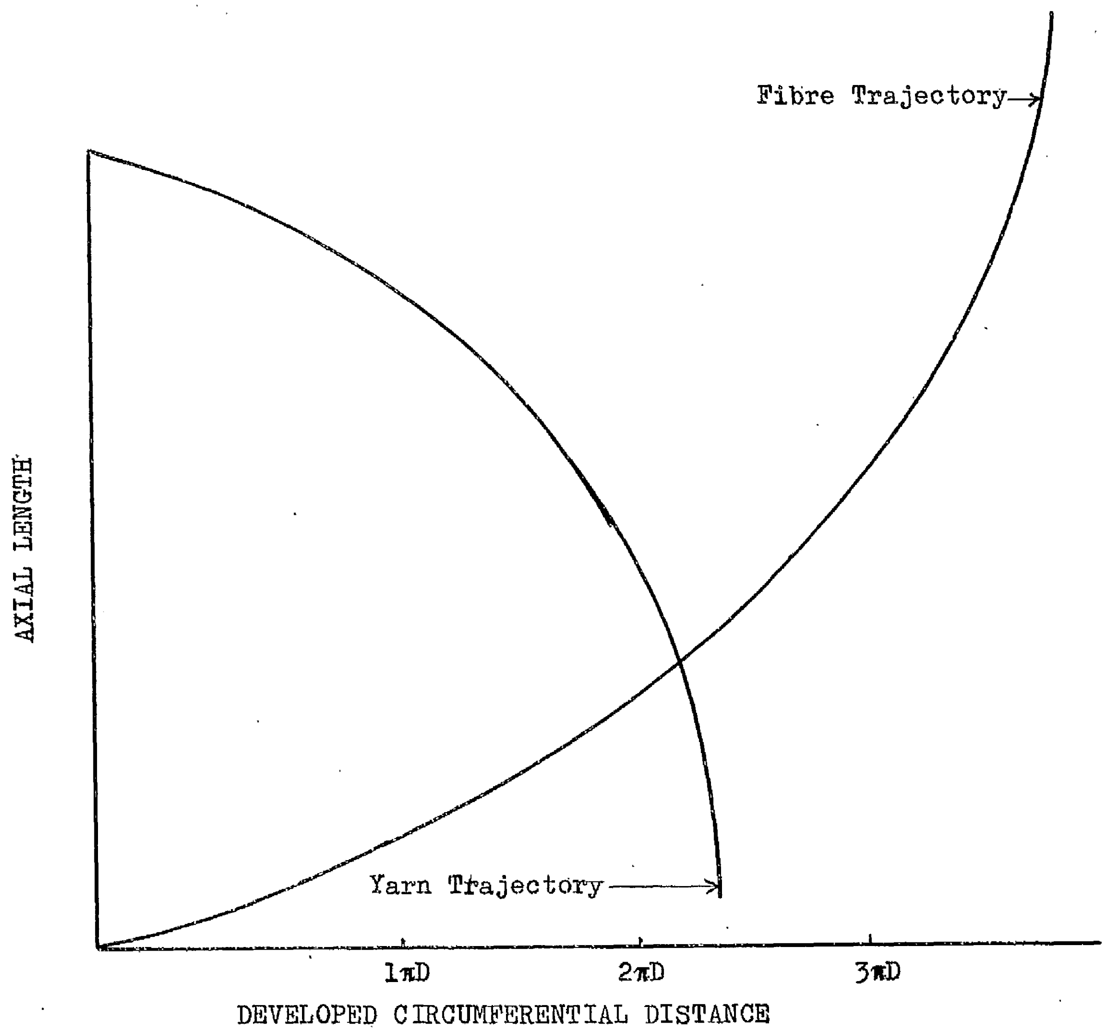



Fig. 4.5

MODIFIED PATH OF FIBRE AND YARN IN THE VORTEX TUBE for spinning were of a staple length of about $1\frac{1}{2}$ in. Perhaps the size of the vortex tube ($\frac{1}{2}$in. bore) used by Hirway restricted the rate of spinning and imposed limitations on yarn quality.

The essential conditions for a break spinner to be successful(and these apply equally well to air vortex spinning too) are:-

(a) the fibres must be sufficiently opened into small clumps (or better still into individual fibres) and

(b) the fibres must condense at the collecting surface so that the forming yarn will gather them in a more or less uniform thickness.

This condensation or doubling of fibre layers is a pre-requisite for the production of yarns of good evenness.

In vortex spinning there are two drafting stages; one is the draft that takes place in the feed system and the other in the vortex spinning tube itself. The latter may be termed as the "spinning draft ratio"(please refer to section5.3.4.)

Hirway used a single apron drafting unit with a draft of 4. This was too low to permit a proper fibre separation especially when the material used for drafting was in the sliver form. Remedial measures adopted to improve the fibre presentation consisted of a high drafting unit and the use of roving feed.

The second condition of fibre condensation needs a little modification when it is applied to vortex spinning. It would be to advantage if the fibre condensation occurred on the forming yarn rather than on the collecting surface. In order to achieve this, it seems essential to keep the spinning draft ratio to less than unity. Draft ratios over unity might not afford sufficient chances for the fibres to condense on the forming yarn and this would tend to result in a poor quality yarn. This is discussed in detail in the next chapter.

The most important point that Hirway seemed to have completely neglected is the spinning draft ratio. A draft ratio of about 3.5 was used in his apparatus and this draft ratio seemed too high. When spinning with such high draft ratios the forming yarn was not sufficiently long to assemble the fibres properly and, therefore, this might have been the cause for the poor assembly of fibres and the frequent breaks in yarn during spinning. Almost the first major change that was effected in Hirway's apparatus was the reduction of draft ratio from 3.5 to about unity.

It was anticipated that (a) with a 1 inch diameter vortex tube, (b) with a spinning draft ratio of about unity and (c) with a reasonably good presentation of fibres to the spinning tube, a reasonably good yarn might be produced yielding fairly low waste. Experiments on these lines were performed and these are included in the next chapter.

Contrary to Hirway's findings, the generation of static charges in the spinning tube were found to be quite significant. Too great a charge caused fibre lapping at the feed rollers and this caused an uneven fibre delivery to the spinning tube. On the other hand, a complete absence of static charges might not be conducive to spinning because the presence of static would alter the frictional characteristics of the fibres and yarn. This might be essential to produce reversed twisting in yarn. It might be, therefore, expected that the presence of static charges within reasonable limits would tend to assist in an improvement of spinning performance of the tube.

In spite of the above criticisms, it was appreciated that, in the limited time available to carry out the research, Hirway made substantial contributions to the knowledge of this method of spinning yarns. It was also realised that the work involved was of a pioneering nature.

# CHAPTER 5

## FURTHER PRELIMINARY TESTS ON STANDARD VORTEX TUBE

# CHAPTER 5

## FURTHER PRELIMINARY TESTS ON STANDARD VORTEX TUBE

### 5.1. INTRODUCTION

In order to gain an insight into the design parameters of the then existing Hirway apparatus, it seemed necessary to conduct a preliminary study of the performance of the apparatus with particular reference to the various design parameters. This study was also needed because the general spinning performance of the apparatus was very poor. Indeed it was observed that during the running of the unit, even for a short period, there were frequent yarn breakages occurring inside the vortex tube. The short lengths of yarn produced were far from even and the amount of twist in yarn was low although sometimes the yarn appeared to be quite lively. The strength of the yarn was low. Moreover, a considerable proportion of fibres supplied to the spinning system were not collected and spun into yarn but passed into the exhaust system as waste.

From the foregoing observations, it was obvious that although the new concept of spinning yarn by means of air vortex only was feasible, the general spinning performance needed to be toned up. It was thought that changes in the design parameters of the apparatus might improve the yarn quality and reduce the fibre loss. Hence a critical examination of the design parameters was made and this led to some modifications to Hirway's apparatus. As a result of this, an overall improvement in the spinning performance was noticed. Before going into the various modifications, it is felt that the next logical step should be to give a brief description of Hirway's apparatus.

## 5.2. A BRIEF DESCRIPTION OF HIRWAY APPARATUS

The apparatus used by Hirway consisted essentially of a conventional drafting unit supplying fibres to a vortex tube with a nozzle at one end and a suction pump at the other end.

The drafting system had only one zone of drafting which was the front zone of a conventional drafting system. It employed the cradles and aprons of a Casablanca GX2 drafting unit. The top rollers were weighted by compressed springs. The gearing of the rollers were so arranged as to give a draft of four between the two lines of rollers.

A vortex tube, made of Perspex and of $\frac{1}{2}$ inch bore, was encased in another Perspex tube of 1 inch bore. One end of the outer encasing tube was connected to a domestic vacuum pump by means of a long flexible rubber hose. The other end was closed by a nozzle which carried the vortex tube. The nozzle was also made of Perspex and it had two $\frac{1}{4}$ inch diameter air inlet holes tangential to the $\frac{1}{2}$ inch diameter tube and an axial hole of 3/32 inch for the yarn exit as shown in Fig. 5.1. These dimensions of the vortex tube and nozzle were arrived at by Hirway after a series of tests performed on various sizes and designs of spinning tubes. Fibres were fed through one of the tangential holes in the nozzle block.

The spun yarn was wound on a 5 in. diameter take-up drum. This drum was driven by a $\frac{1}{4}$ horse power motor, through a variator and a reduction gear box. The drafting unit was mechanically coupled to the winding drum.

The draft ratio between the front roller of the drafting unit and the winding drum was arbitrarily chosen as 3.53.

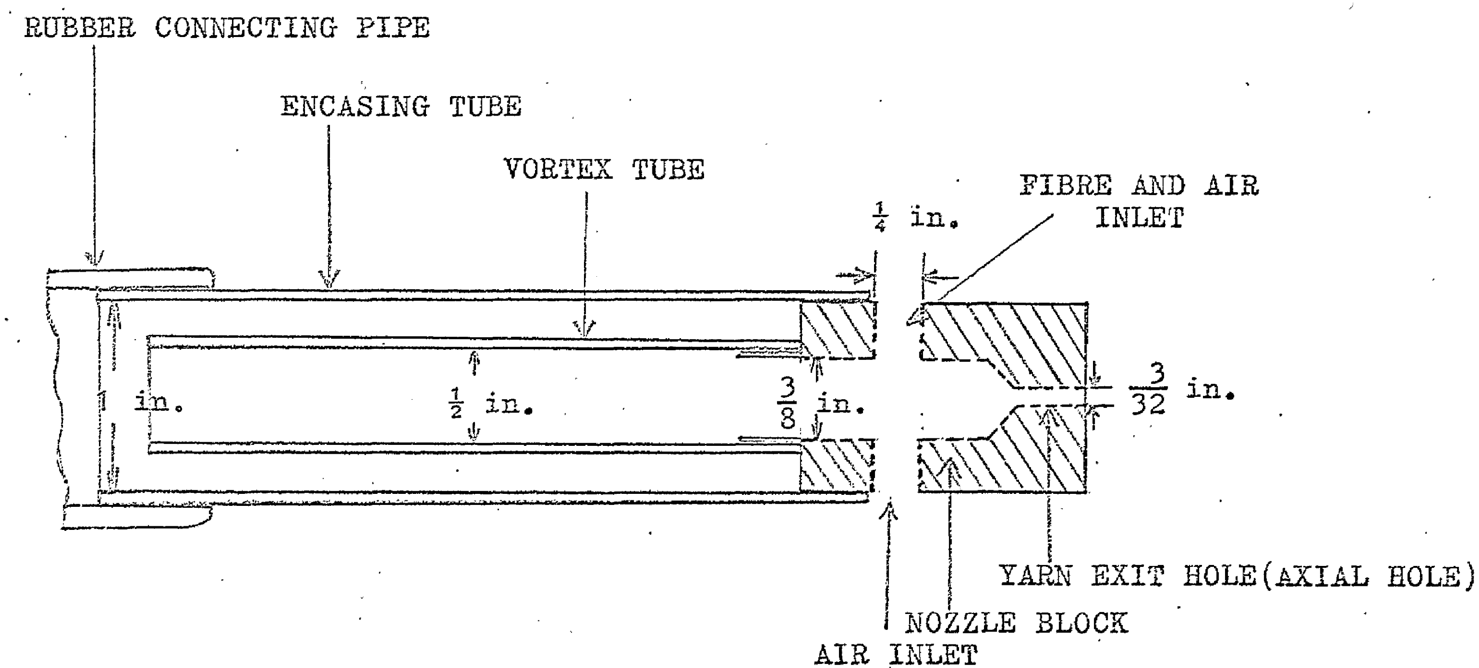



Fig. 5.1.

HIRWAY'S SPINNING TUBE

Fig. 5.2. shows the photograph of the essential parts of the Hirway apparatus.

## 5.3. MODIFICATIONS MADE TO HIRWAY APPARATUS

In the first few trials of the Hirway apparatus, a roving of Egyptian cotton of 1.25 hank (0.472 ktex) was fed to the drafting mechanism. This roving was not drafted properly and this resulted in an uneven drafting of the fibres with some undrafted ends emerging from the front roller nip. This behaviour appeared to be due to the absence of a break draft zone in the drafting unit employed and also possibly due to the low draft. These limitations imposed by the drafting unit made it necessary to change the backstuff material. With a drawn sliver a proper drafting was achieved. It was thought that the backstuff material should be kept standard during this preliminary study and, therefore, a finisher head draw frame sliver of about 1.25 hank (about 0.472 ktex) made from Egyptian combed cotton was used throughout this test series. The staple length of the fibres was 1 7/16 in.

The preliminary analysis was based mainly on the careful observations made of the various design parameters of the spinning tube and their influence on the spinning performance. As a result of this critical examination, certain modifications were made on the apparatus. These are described below in a chronological sequence.

### 5.3.1. Nozzle

It may be true to say that the nozzle forms the heart of this spinning tube. It was felt that an improved performance of the system as a whole might be attained by a proper design of this part of the spinner. Hence the nozzle design was considered first. Perspective drawings of

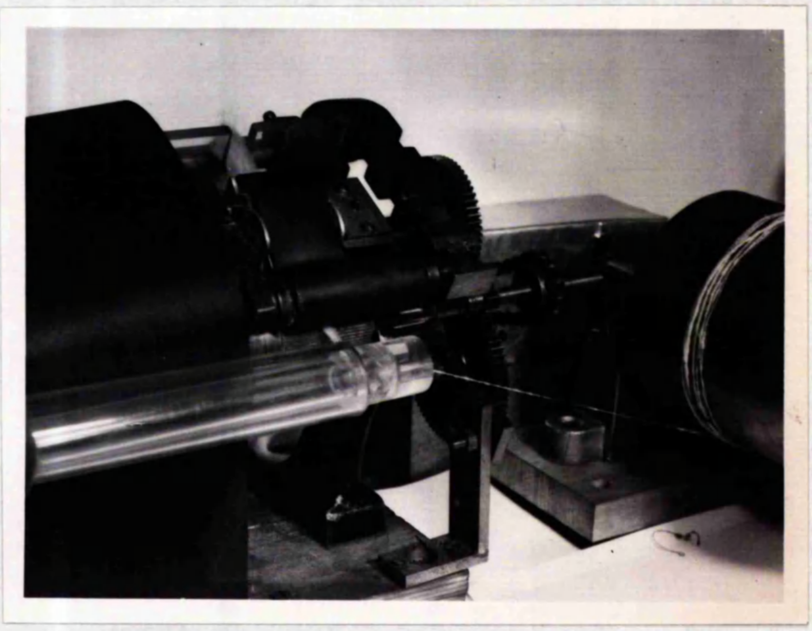


Fig. 5.2.

PHOTOGRAPH OF HIRWAY'S SPINNING APPARATUS the nozzle used by Hirway and the modified nozzle based on this study are given in Figs. 5.3. and 5.4. respectively. These figures might assist in a proper understanding of the discussions concerning the various parameters of the vortex spinner.

5.3.1.1. Nozzle bore

The importance of this dimension was possibly overlooked by Hirway as there appears to be no mention of change in this dimension in his work.

The inner diameter of the nozzle used by Hirway was $\frac{3}{8}$ in. A close visual observation of the fibre flow and subsequent assembly of the fibres showed that the formation of slubs was possibly due to fibre lumps attaching to the forming yarn at certain intervals of time. It was also noticed that these slub attachments usually took place in the fibre inlet region. Moreover the movement of the forming yarn appeared to be greatly restricted. Perhaps this might be due to the interaction of the fibre motion on that of the yarn. This suggested that the space within the main bore of the nozzle was inadequate for free, unrestricted movement of both the fibres and the yarn, especially when the fibres used were long. stapled ones. The inner diameter of the nozzle was, therefore, changed from $\frac{3}{8}$ in. to $\frac{3}{4}$ in. The dimensions of the tangential holes were, however, not altered.

There was another reason for enlarging the nozzle bore. With a $\frac{3}{8}$ in. bore, the chances of a fibre wrapping around itself are great because the nozzle circumference is less than the staple length of the fibre used. In a $\frac{3}{4}$ in. bore nozzle, fibre wrappings are unlikely to occur with the fibre used for spinning. Both possibilities suggested that

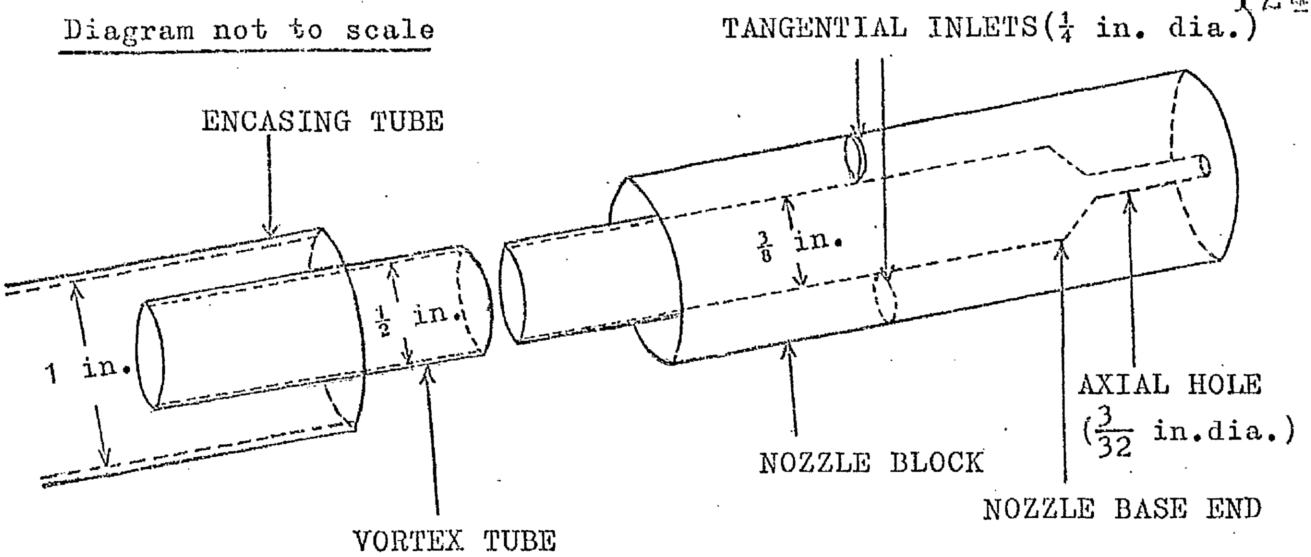



Fig. 5.3.

EXPLODED VIEW OF HIRWAY'S SPINNING TUBE

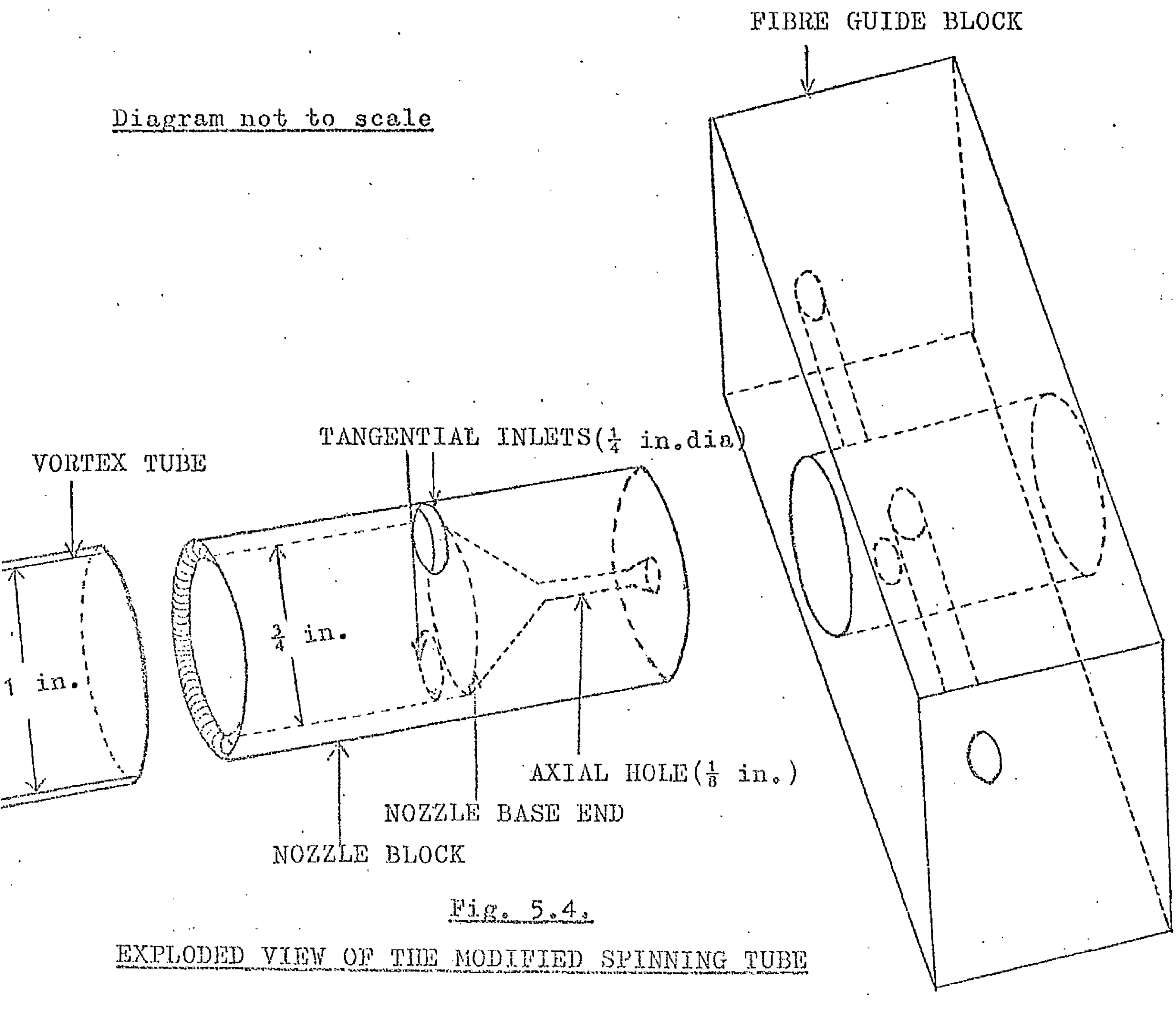



Fig. 5.4.

EXPLODED VIEW OF THE MODIFIED SPINNING TUBE there might exist a relationship between the nozzle bore and the staple length of the fibres used for spinning.

5.3.1.2. Position of tangential air inlet ports

Hirway performed a number of tests to determine the optimum size of the tangential air-cum-fibre entry ports in the nozzle and showed that a nozzle with two holes of $\frac{1}{4}$ in. diameter was the best. However, the positioning of these ports with respect to the nozzle base end was not investigated by him.

It was noticed that the port placement played an important role with regard to slub formation in the yarn. A close observation of the fibre flow from the front roller nip to the nozzle revealed that it divided itself into two portions on reaching the tangential inlet. One portion followed the main air streamlines in the vortex tube. Of this portion some fibres were assembled to form a yarn and the rest were collected as waste in the suction pump. The other portion, at certain intervals of time, attached itself directly on to the already formed yarn. These attachments usually took place at or near the nozzle base end. It was observed from tests performed by varying the positioning of inlets that the further away these tangential ports were from the base end of the nozzle, the greater was the accumulation of fibres in yarn resulting in thick slubs.

This peculiar behaviour was probably due to the formation of a subsidiary vortex in that region of the nozzle. In fact some fibres were observed to rotate as a fibre mass at the nozzle base end region. This fibre mass was gradually built up and attached itself to the yarn moving past it. This building up of fibre mass and its eventual attachment to the yarn was an almost continuous process. By placing the air-cum-fibre entry holes as near as possible to the nozzle base end, the formation of large slubs in the yarn was greatly reduced and the evenness of yarn was thereby considerably improved.

5.3.1.3. Setting of the nozzle with respect to the front roller nip

The setting of the nozzle may be defined as the distance between the front roller nip of the drafting unit (or fibre release point from an opening device) and the fibre inlet measured along the tangential line from the nearest point on the inner surface of the nozzle. This setting was found to have a considerable effect on the performance of the spinning unit.

Too close a setting caused the twist to run up to the nip of the front rollers. The fibres were twisted around themselves in the region between the nozzle and the roller nip. They were, therefore, not detached from the body of the drafted sliver as is required for break spinning. However, after entering the nozzle, short lengths of this fibre assembly were intermittently drawn off in tufts by the suction created by the pump. This was so because of the absence of a standing break in the fibre flow. Under these conditions the twist imparted by the vortex was of a false nature rather than a true one. The untwisted fibre mass was unable to resist the pull exerted by the air stream and so the mass was broken up into tufts. It was, therefore, difficult to produce even short lengths of yarn. Moreover the withdrawal of the fibre assembly through the axial hole in the nozzle also resulted in false twisting because of the connections with material issuing from the front roller nip. It was not possible to produce yarn in this way. Thus spinning of yarn by the air vortex method which is based on the principle of break spinning could not be achieved with too close a setting.

Too wide a setting did not allow all the fibres to be gathered up and transported from the roller nip to the vortex tube since the influence of suction did not extend far enough. This resulted in fibre lapping at the front rollers. It was noticed that sometimes the fibres were removed in tufts from the roller nip. Also short fibres were released and conveyed into the vortex stream a little earlier than the longer ones. So it appeared that drafting waves were also formed during the movement of the fibres from the roller nip to the nozzle inlet. Nevertheless, unlike the previous case, spinning of yarn was possible although the yarn quality was poor indeed. However frequent yarn breakages occurred during spinning due to lack of a regular supply of fibres caused by intermittent roller lapping.

A setting of 1 7/16 in. made possible both break spinning and a reasonably good control on transportation of fibres. This setting was arrived at by trial and error, the yarn appearance being used to judge the yarn quality. This optimum setting was, in this particular case, equal to the staple length of the cotton used and was analogous to the settings employed in the conventional roller drafting system. It may be pointed out here that Hirway, after conducting a few tests, concluded that the optimum setting was $\frac{1}{4}$ in. This differed very much from the setting arrived at in the present work although the staple length and the quality of cotton were exactly the same in both cases. This was probably because at the distance of 1 7/16 in. Hirway could not induce fibres to enter the spinning tube nozzle.

5.3.2. Vortex tube

5.3.2.1. Tube bore

As mentioned earlier, the vortex tube used by Hirway was one of $\frac{1}{2}$ in. bore. Earlier he experimented with four different sizes of vortex tubes, varying from $\frac{1}{8}$ in. to $\frac{1}{2}$ in. bore in steps of $\frac{1}{8}$ in. and showed that the $\frac{1}{2}$ in. bore tube gave the best results. It is to be noted in this connection that the maximum bore of vortex tube experimented by Hirway was $\frac{1}{2}$ in. and this factor seemed to have limited the spinning performance attained by his tube.

Once again, it was observed that during spinning with the $\frac{1}{2}$ in. bore vortex tube the fibres attached themselves in tufts on to the forming yarn. This suggested that the tube might not have afforded adequate space for the free movement of the fibres and the yarn. This was possibly because of the long stapled fibres that were used in spinning. So it was thought that a vortex tube of a diameter larger than the present one might afford better assembly conditions and thus improve the working performance of the tube. When the vortex tube was changed from $\frac{1}{2}$ in. bore to 1 in. bore an improvement in yarn regularity was noticed. This size of tube was arbitrarily chosen. However the modified nozzle fitted well into this vortex tube.

In a vortex tube with too large a diameter, it was observed that fibres agglomerated and rotated in a plane at an angle to the axis of the tube. After some time the mass of fibres moved in lumps towards the suction pump and were collected as waste. The presence of a subsidiary vortex (or vortices) might be the cause of this phenomenon.

It appears, therefore, that a relationship may exist between the bore of the vortex tube and the staple length of fibres used for spinning.

5.3.2.2. Length of vortex tube

In Hirway's work, the yarn tail was nearly always short and there appeared to be no need to vary the length of the tube. However the length of the vortex tube seemed as if it might have some influence on yarn evenness as well as on the amount of waste produced.

In the present series of tests, it was observed that the free end of yarn rotating inside the tube extended throughout the length of the 6 in. long X 1 in. diameter vortex tube. It was quite likely then that any extra length in yarn tail end formation was limited by the length of this tube because any additional length in tail end would be prevented from being formed at the place where the tube opened out into the rubber pipe. It was thought that a longer yarn tail might allow the moving fibres a greater chance of becoming attached to the forming yarn and this, in turn, might produce less waste. So it was decided to experiment with longer vortex tubes which would enable longer tail ends to be accomodated well inside the tube length.

Two tubes of one foot and two feet length were tried. It was found that, for all practical purposes, the two foot tube accomodated sufficiently long lengths of forming yarn and there was always adequate space left free in the tube. So it was decided to use two foot long tubes in the rest of the preliminary experiments.

With the two foot vortex tube, there was an appreciable drop in the percentage of waste collected. An improvement in yarn evenness was also noticeable.

5.3.3. Connection of vortex tube and suction pump

The long flexible hose pipe connecting the vortex tube and the suction pump, as used by Hirway, was discarded for two reasons.

Firstly, a greater length of pipe would result in a reduction of the effective pressure drop available at the nozzle ports. This, in turn, would reduce the effective suction on the fibres supplied from the roller nip and there would be also a drop in the vortex speed.

Secondly, a large proportion of waste fibres flowing towards the pump from the vortex tube became attached to the walls of the hose pipe. This affected the total amount of waste collected for any particular experiment. The accumulated waste inside the pipe also reduced the effective suction at the nozzle. Therefore, it was decided to use a short, smooth rubber pipe in all the subsequent experiments.

5.3.4. Spinning draft ratio

Apart from the draft in the drafting system, there can be also a draft in the vortex spinner itself. This drafting inside the vortex tube is referred to in this work as the "spinning draft ratio". It may be explained in the following way:-

Let a seed yarn be inserted into a vortex tube. Let the end lying outside the tube be anchored firmly and the end inside the tube be free to rotate. When fibres moving with the air stream become added to the rotating seed yarn, the linear density of yarn inside will soon increase due to the build up of fibres on it. If the yarn is withdrawn at a suitable rate, then the linear density of yarn can be maintained at any desired level. If the yarn is taken up at a faster rate than the given fibre supply rate, the resultant yarn will be finer than if the fibre supply had been twisted without passing through the vortex spinner. Conversely, if the rate of yarn withdrawal is slower than the given fibre supply rate, the yarn produced will be coarser. This latter effect is due to the "condensing" of the fibres on the forming yarn. Thus there exists drafting(or condensing which is fractional drafting) in the vortex spinner. The term "spinning draft ratio", therefore, denotes the draft existing between yarn withdrawal rate from the spinner and the fibre supply rate to the spinner.

An alternate explanation is given below:-

When drafted fibres are released from the nip of the rollers, they come under the direct influence of the air stream. They are subjected to sudden acceleration and, therefore, tend to approach the air stream velocity. This sudden acceleration may open out the fibre tufts into individual fibres and thus very high drafts can be obtained. This opening draft is considered essential for proper fibre presentation to any form of break spinner. When the fibres subjected to this opening draft become assembled on to the seed yarn(or forming yarn), a process of fibre condensation occurs. This fibre condensation is referred to as "condensation fraction" because it is merely, in effect, fractional drafting. Thus spinning draft ratio may be expressed as follows:-

spinning draft ratio = opening draft X condensation fraction.

As a drafting system was employed during the preliminary study, the "supply draft" refers only to the draft used in the drafting unit. Thus in air vortex spinning-as possibly in other break spinning methods too- a control over the linear density of yarn is obtained by not only changing the draft in the fibre supply system but also by means of varying the yarn withdrawal rate.

The spinning draft ratio maintained in all the tests conducted by Hirway was 3.53. This draft ratio was considered to be too high on the grounds that a considerably faster take-off rate of yarn formed, as compared to fibre input rate, would probably give less chances for the moving fibres to attach themselves to the forming yarn. This might adversely affect yarn evenness and waste produced. It was observed that the length of the forming yarn was very short possibly for the same reasons as mentioned above.

A draft ratio of about unity seemed to be a reasonable choice. To obtain these spinning draft ratios, the size of the take-up drum was changed and the intervening gears between the drum and the front roller were properly manipulated. The diameter of the drum was kept constant at 1.59 inches.

Draft ratios of 0.83, 0.91, 1.00 and 1.12 were used and their effect on yarn parameters as well as on waste percentage was studied.

The preliminary tests showed that the draft ratio of 0.91 produced a reasonably good yarn with low fibre loss.

<u>5.3.5. Method of yarn winding</u>

The method of winding the spun yarn directly on to the winding drum, as was followed by Hirway, had two disadvantages. Firstly, the draft ratio of the spinning tube increased gradually with the build-up of yarn on the drum. Secondly, the wound yarn had to be rewound manually after each test on to a package to facilitate yarn handling during subsequent evaluation of the yarn properties. Manual rewinding not only involved a considerable loss of time but also damaged the yarn.

Consequently, a cheese winder with its associated traverse mechanism was made and fitted to the apparatus. The paper tube was driven by frictional contact with the take-up drum and the yarn was wound directly on to the paper tube. The wooden take-up drum was covered with flannel to prevent slippage of yarn during withdrawal from the spinning tube.

### 5.3.6. General effect on yarn quality due to modifications to Hirway apparatus

The modifications mentioned above were carried out during the early stages of this research. A few more modifications were tried afterwards and these will be discussed at later stages. Even with these preliminary modifications, the yarn produced was of an appreciably better quality than the best yarn produced by Hirway. It was quite evident that the yarn evenness had considerably improved. The rate of yarn withdrawal had been increased too. As regards the waste percentage, there was definitely a substantial drop and there was a moderate improvement in the strength of the yarn. The most important outcome of these modifications was the complete absence of yarn breaks during spinning for a period of even up to 10 minutes. It was, therefore, possible to spin continuous lengths of yarn.

It was quite obvious that the changes in the design parameters had greatly improved the general performance of the apparatus. Nevertheless it was felt that there was still an ample scope for further improvement. In fact, much remained yet to be done to bring the yarn quality of air vortex spun yarns to the standards that are normally attained by conventionally spun yarns.

## 5.4. PRELIMINARY INVESTIGATIONS OF THE EFFECTS OF PROCESSING VARIABLES ON YARN PARAMETERS

Experiments were performed to study the effects of the processing variables on some of the properties of the yarns spun by the air vortex method.

### 5.4.1. Processing conditions

The following apparatus working under the stated processing conditions were maintained almost unchanged throughout this series of tests:-

(a) A 1 in. diameter Perspex tube of 2 foot length was used.

(b) A Perspex nozzle block with a bore of $\frac{3}{4}$ in. and with 2 X $\frac{1}{4}$ in. diameter tangential air inlet holes and an axial hole of 3/32 in. diameter was fitted to one end of the Perspex tube. The rest of the apparatus was as described earlier.

(c) Egyptian cotton of 1 7/16 in. staple length was used.

(d) The hank of drawn sliver supplied to the drafting unit was about 1.25 (0.472 ktex).

(e) The air pressure inside the tube was maintained nearly at 16 in. of water below atmospheric pressure.

(f) The atmospheric conditions of the room in which the tests were performed were maintained at $70^\circ \pm 2^\circ$F and 55% ± 1% relative humidity.

### 5.4.2. Processing variables

The processing variables during the tests were as follows:-

(a) The spinning draft ratio between the front roller and the take-up drum was varied. The four draft ratios experimented upon were 0.83, 0.91, 1.00 and 1.12.

(b) The yarn take-up rate was varied from about 0.5 metres per minute to about 12 metres per minute at each of the four draft ratios.

5.4.3. Measurement of air pressure

The air pressure was measured by connecting one arm of a U-tube water manometer to the suction end of the vortex tube and leaving the other arm open to the atmosphere. The difference in the levels of the water columns in the two arms of the manometer gave the air under pressure in inches of water.

5.4.4. Conditions of yarn testing

The yarn samples obtained by air vortex spinning were conditioned and all the following tests were conducted at standard atmospheric conditions of 65% ± 1% relative humidity and a temperature of $20^{\circ} \pm 1^{\circ}$ C. The yarn samples were kept in this conditioned atmosphere for a minimum period of 24 hours before being tested.

5.4.5. Evaluation of the yarn properties

In the preliminary study of the present research it was considered adequate to measure the count, evenness and tenacity of the yarn along with the waste produced under the various processing variables. One of the yarn parameters, the twists per unit length, could not be exactly determined. This was because of the complex and unorthodox nature of the twist formation with the number of twists varying from layer to layer of the yarn. It appeared that the twist per unit length increased from the outer to the inner layers. Hence it was difficult to estimate the twist by the conventional methods which usually employed the principle of untwisting the yarn. It was, however, envisaged that it might be possible to study the nature of twist in the yarn by the use of "tracer fibre" technique. This technique is dealt with in Chapter 14.

5.4.5.1. Measurement of the yarn count

In general, about 50 metres of yarn was spun under each condition of test. The total length of the yarn produced excluding the length of the forming yarn lying inside the vortex tube was accurately weighed on a sensitive balance and the count was determined.

5.4.5.2. Measurement of the evenness of yarn

The Uster evenness tester, Model B, was used to measure the irregularity of the vortex spun yarns. The Integrator and the Recorder were also used along with the tester. The Integrator indicated the average irregularity of yarn as percentage mean deviation (P.M.D.) and the Recorder registered the irregularity graph on a chart paper.

The yarns were tested on this apparatus at a material feed rate of 8 yards per minute. A chart speed of 4 in. per minute was used in the Recorder. Yarn was passed through the measuring capacitor marked 6. Readings on the Integrator were taken at intervals of 30 seconds. A total of 10 readings was taken for each sample.

Since this evenness tester is highly sensitive to moisture content in the material being tested, it was thought necessary to condition the yarn properly. Hence the yarn samples were kept in the conditioned atmosphere for about four days.

The Uster Spectrograph was operated in conjunction with the tester. It produced an irregularity spectrum or "spectrogram" of material tested in the evenness tester. Thus any periodic variation occurring in the yarn could be easily known.

5.4.5.3. Measurement of the tenacity of yarn

The strength of the air vortex spun yarns was much less than that of the conventionally spun yarns. In fact, in certain cases, the strength of the vortex yarn was very low. It even appeared that yarn breaks which occurred during testing were due more to fibre slippage than fibre breakage. Hence it was considered necessary to use a highly sensitive instrument not only to measure the strength of these yarns but also to register on graph paper the exact nature of their breaks.

The Instron constant rate of extension tensile testing machine was selected for this purpose. This instrument incorporated a highly sensitive electronic weighting system with load cells employing bonded wire strain gauges for detecting the tensile load applied to the sample under test.

The specimen length was chosen as 10 cm. in view of the limited lengths of yarn available for testing purposes. In order to allow the specimen to break in 20 ± 3 seconds, it was desirable to use a cross head speed of 2 cm./min. The chart speed was maintained at 20 cm./min. The load cell used was the CTM type cell and it was adjusted for high sensitivity.

Particular care was taken while mounting the yarn length in the two jaws so that no extra twist was inserted or removed from the test specimen.

The breaking load of yarn in grammes was calculated from the graphs obtained on the chart paper. The count of the yarn under test was determined by weighing the broken test lengths on a sensitive balance. The breaking tenacity of yarn was obtained by dividing the breaking load by the yarn count and this was expressed in grammes force per tex (gf/tex). The percentage breaking elongation was also determined from the graph.

5.4.5.4. Measurement of twist in the yarn

Lord[8], while commenting on the nature of twist in the air vortex spun yarns, stated that,

> "The vortex spun yarns have the characteristic of indefinable twist by the virtue of the fact that fibres are looped together as well as being twisted, and the amount of twist in the core is very different from that at the outside of the yarn. Because of this construction the yarn is rather difficult to analyse, and it is very soft and open in structure, which probably accounts for some of its weakness".

It was, therefore, not possible to measure the twist by the conventional methods of twist measurement. Hence, as mentioned earlier, the twist was not measured in this preliminary study. However it needs to be mentioned here that at the later stages of this research, the 'twist to break' method was adopted for twist measurement. This method is explained in Chapter 11.

5.4.5.5. Measurement of waste (fibre loss)

Fibres in the suction pump were carefully collected at the end of each test and then accurately weighed. Special care was taken not to allow fibres to adhere to the inner walls of the rubber connecting pipe or collecting bag. The waste percentage was the ratio of the weight of the collected waste fibres to the weight of total input of fibres (weight of collected waste fibres + net weight of yarn spun) expressed as a percentage. At each test, the actual waste percentage was recorded.

Instead of the term "waste percentage", the term "percent fibre assembly efficiency" has been used in the later chapters. These two terms are complementary to each other.

Hirway used the terms - 'measured waste percentage' and 'calculated waste percentage' - in his work and these were necessary because there were quite large differences in these values. The discrepancy was traced to the accumulation of fibres on the inner walls of the hose pipe. In the present work, the need for the two different waste percentages did not arise because the actual waste percentage and the calculated waste percentage were almost equal.

5.4.6. An analysis of the results of the preliminary tests

At each of the spinning draft ratios, the effect of the yarn take-up rate on the yarn parameters mentioned above and on the amount of waste produced was studied.

The results of the above tests are shown in Tables A1, A2, A3 and A4 in Appendix A. Graphs were drawn showing the relationships between the yarn take-up rates and (a) evenness, (b) tenacity and (c) waste produced, at the various spinning draft ratios. Another set of graphs were drawn showing the relationships between the spinning draft ratios and (a) evenness, (b) tenacity and (c) waste produced, with different yarn take-up rates.

It might be mentioned that when the fibre supply rate was maintained constant, the linear density of yarn (tex) was found to vary inversely with waste percentage. This relationship is shown in Fig. 5.5.

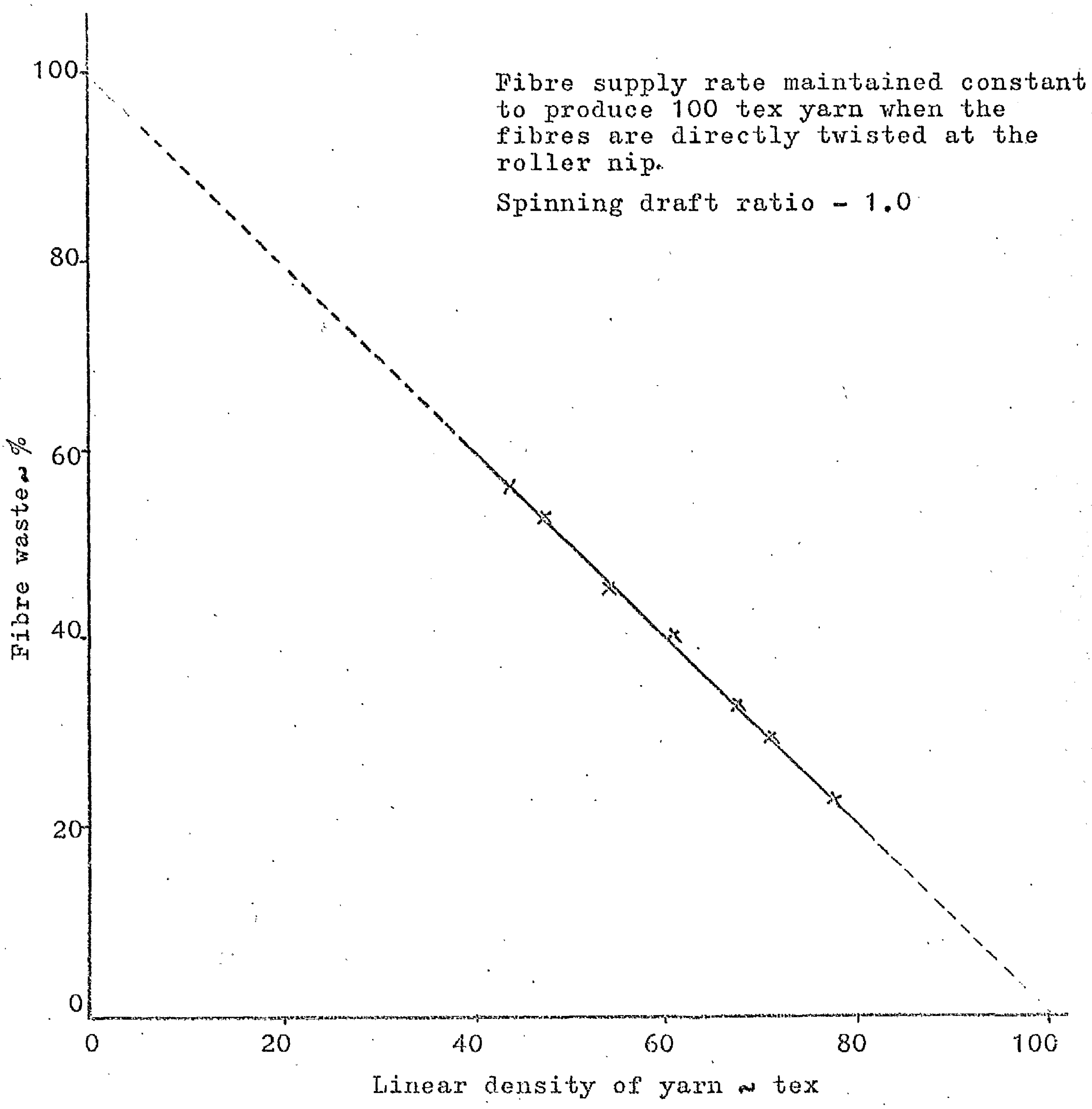



Fig. 5.5.

RELATIONSHIP BETWEEN LINEAR DENSITY OF YARN AND FIBRE WASTE WITH CONSTANT FIBRE SUPPLY RATE

5.4.6.1. Relationship between draft ratio and waste percentage

Figs. 5.6. and 5.7. show the relationship between the yarn take-up rate and waste percentage at the four draft ratios of 0.8, 0.9, 1.0 and 1.1.

Let the yarn take-up rate be considered to consist of two regions; the 'low speed region' comprising speeds from 0 to 4 m/min. and the 'medium speed region' from 4 m/min. to 13 m/min.

It may be said that at the low speed region, the waste tended to decrease with increase in speed till a minimum waste was reached at speeds which varied with the draft ratios; the maximum waste percentages were usually attained at speeds which decreased with increase in draft ratios. After the minimum waste was reached and when the yarn speeds were in the medium speed region, the waste percentage in almost all the cases tended to increase with yarn withdrawal speed.

In the low speed region, the decrease in waste with increase in yarn speed suggested that if the forming yarn were allowed to remain in the vortex tube for long periods of time, then some fibres already attached to the forming yarn might tend to be detached due to the force of suction acting on them and these might then find their way into the pump and be collected as additional waste. On the other hand, in the medium speed region, the waste percentage tended to increase with yarn withdrawal rate. This behaviour might be due to a gradual lowering of the fibre capture efficiency as the rate of yarn withdrawal was increased.

It ought to be pointed that it was only as a matter of purely theoretical interest that the low speed region was considered as these speeds are too low to be of any practical value.

Fig. 5.6

ATIONSHIP BETWEEN YARN TAKE-UP E AND THE WASTE WITH FERENT SPINNING DRAFT RATIOS

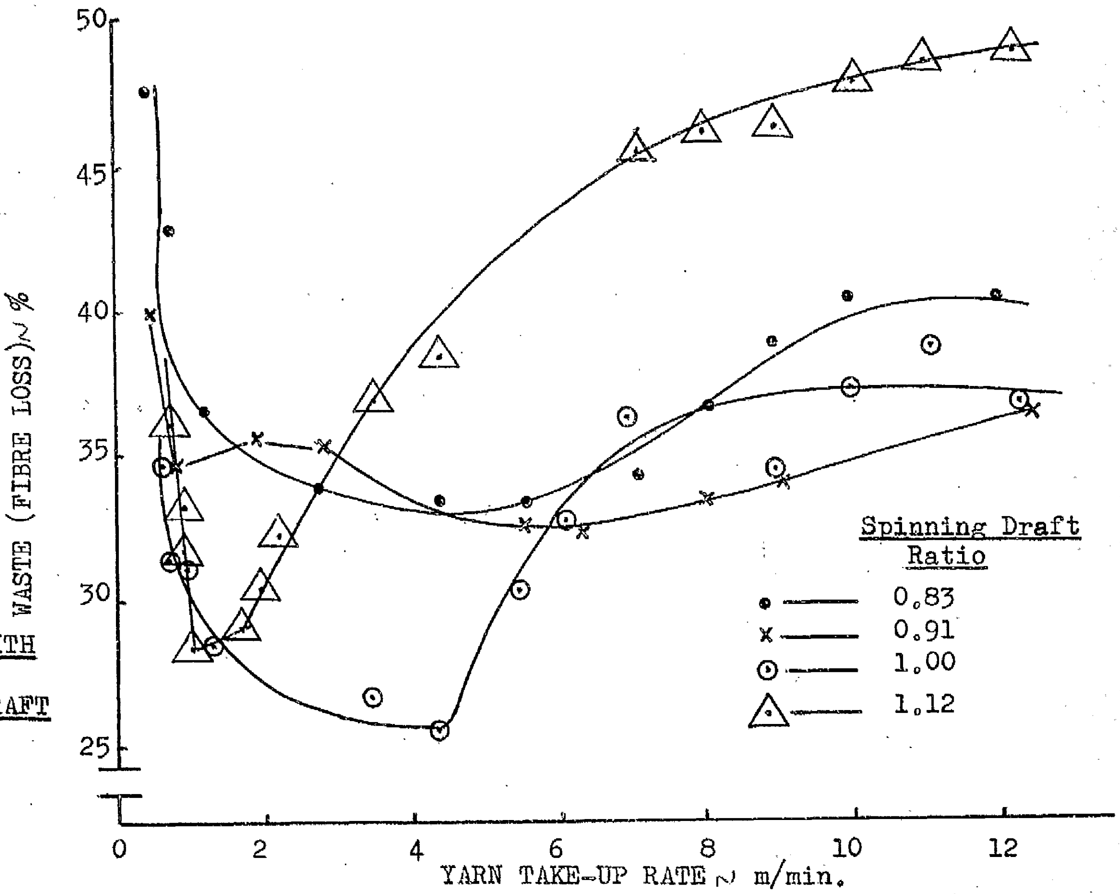
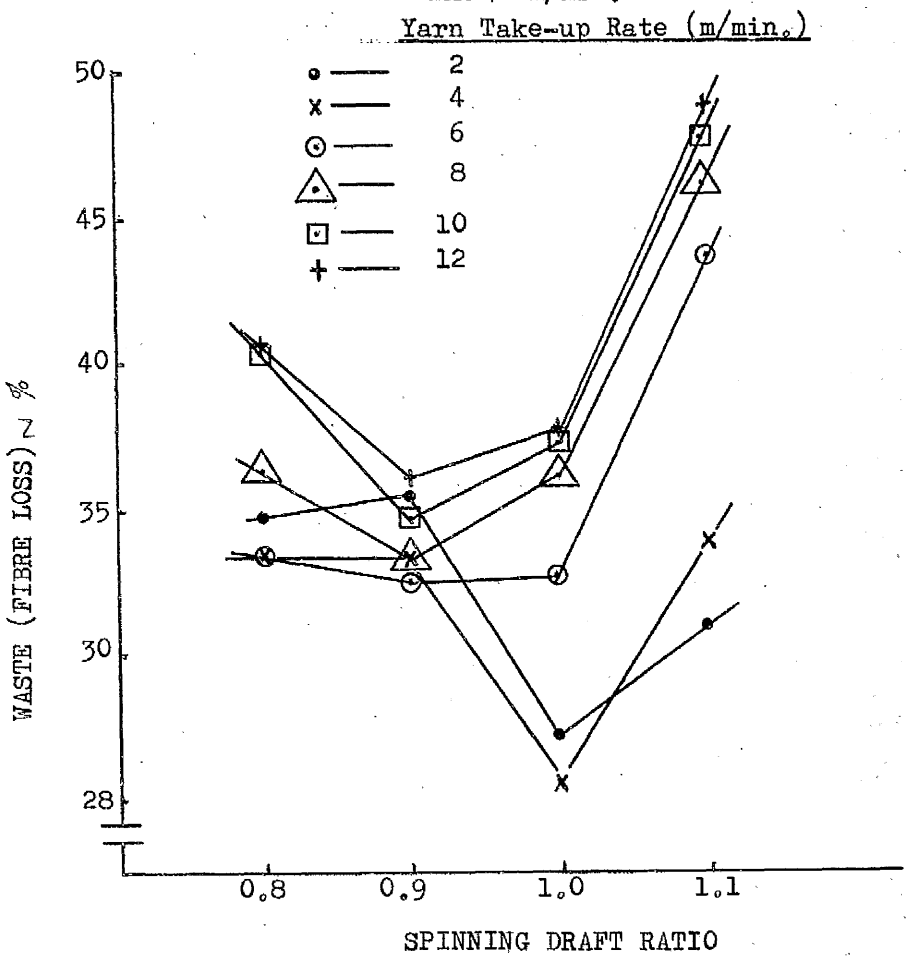



Fig. 5.7

ATIONSHIP BETWEEN SPINNING FT RATIO AND WASTE WITH FERENT YARN TAKE-UP RATES



Spinning draft ratios of 1.1 gave rise to high fibre loss figures whilst the draft ratios of 0.8, 0.9 and 1.0 yielded comparatively low wastes.

When the spinning draft ratios were below unity, the lengths of forming yarn were more or less constant within each test. These low draft ratios will tend to allow layering of fibres to take place. Thus when the fibres are captured by the yarn, the yarn mass is increased without there necessarily being any sudden deceleration and this can be achieved without any great unevenness. In fact, this may even assist in a reduction of the short term irregularities in the final yarn. This layering is probably an important factor in the control of yarn regularity. On the other hand, a fibre entering the tube may or may not be materially decelerated before being captured by the yarn. A deceleration must be associated with a condensation of the fibres and such a condensation may be very uneven. Thus the smaller the chance of the fibres being caught by the yarn, the greater will be the deceleration mode of condensation and thence the unevenness and the greater will be the waste.

At draft ratios above unity, it was observed with the help of a stroboscope that the lengths of the forming yarns fluctuated much during the course of each test. This was the reason for not registering the lengths of the forming yarns in Tables A3 and A4 for draft ratios of 1.0 and 1.1. These fluctuations were possibly due to the following reasons:-

When the forming yarn was withdrawn at a faster rate than the fibre input, the chances of the forming yarn capturing the fibres would tend to be reduced. This would tend to lead to reduced fibre layerings on the yarn. Any reduction in the number of fibre layers might seriously increase the short term irregularities of the forming yarn. This might lead to not only an irregular yarn but also to varying lengths of the forming yarn during spinning. The fluctuations in yarn lengths are likely to be due to fibre tufts breaking off from the main body of the forming yarn at the very thin places. There was also another possibility that the length of the forming yarn might not be ~~quite~~ sufficiently long to gather the fibres supplied into the tube.

It was thought appropriate to point out that the very high values of waste percentages obtained by Hirway were most probably due to the excessive draft ratio employed (the draft ratio was about 3.5). The measured waste percentage in Hirway's work usually ranged between 65% to 75%. In the preliminary tests of the present work, the waste percentages, at draft ratios below unity, varied between 30% and 40%.

From all the foregoing, it was quite clear that draft ratios below unity were certainly to be preferred to draft ratios above unity.

It ought to be pointed out that the lowest figure for waste percentage was recorded at a draft ratio of 1.0 for a yarn delivery speed of about 4 metres per minute. However this was not consistent with the other results obtained at the same draft ratio. In the case of 0.9 draft ratio, the minimum waste was recorded at about 7 m/min.

From a comparison of the draft ratio-waste relationship, shown in Fig. 5.7., it might be observed that the scatter of fibre loss values was least at the spinning draft ratio of 0.9. The waste figures were consistently lowest at 0.9 draft ratio, especially at high yarn take-up rates of 10 and 12 m/min. This suggested that the optimum draft ratio with respect to fibre loss was 0.9.

5.4.6.2. Relationship between draft ratio and yarn irregularity

Figs. 5.8. and 5.9. show the relationship between the yarn take-up rate and yarn irregularity at the four draft ratios.

The yarn regularity at the low speeds was thought to be of no practical importance. It might be, therefore, sufficient just to mention that the irregularity was rather unstable in the speed range of about 1 to 4 m/min. In the range of speeds lying between 4 and 10 m/min., the irregularity tended to remain fairly constant with speed for all the draft ratios excepting 1.1, in which case, it tended to increase with speed. However there was a sharp rise in unevenness at all the draft ratios when speeds were raised above 10 m/min.

In general, the yarn regularity tended to deteriorate when the draft ratio was increased above 0.9. This is evident from Fig. 5.9. where the scatter of irregularity values for the different speeds is found to be minimum at 0.9 spinning draft ratio.

It is considered relevant to include at this stage an idea of the different mechanisms of fibre assemblies into yarn and their influence on yarn evenness. In section 5.3.4., it was stated that the sudden acceleration imposed on the drafted fibres entering into the air stream at the nozzle produced very high drafts which tended to make the fibre assemblies separates into individual fibres. On entering the tube, these fibres would tend to be subjected to the condensation mechanism. The term "condensation" is used in the sense opposite to that of drafting, i.e., it denotes "fractional drafting".

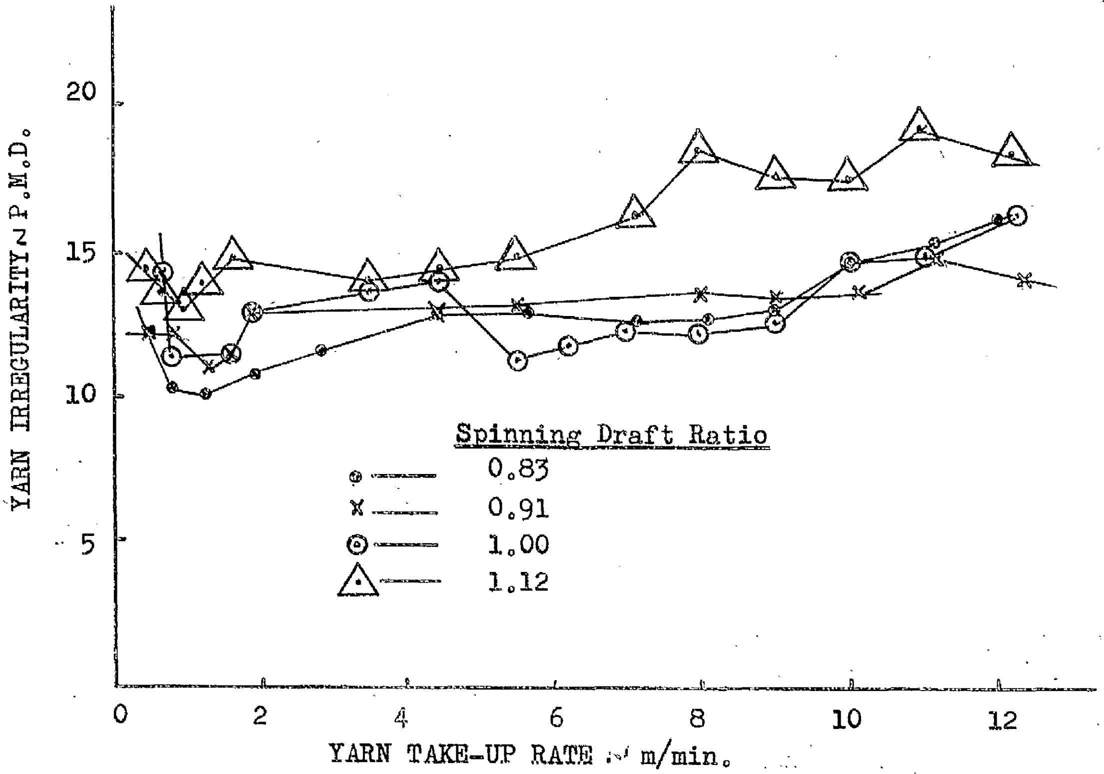



Fig.5.8

RELATIONSHIP BETWEEN YARN TAKE-UP RATE AND YARN IRREGULARITY WITH DIFFERENT SPINNING DRAFT RATIOS

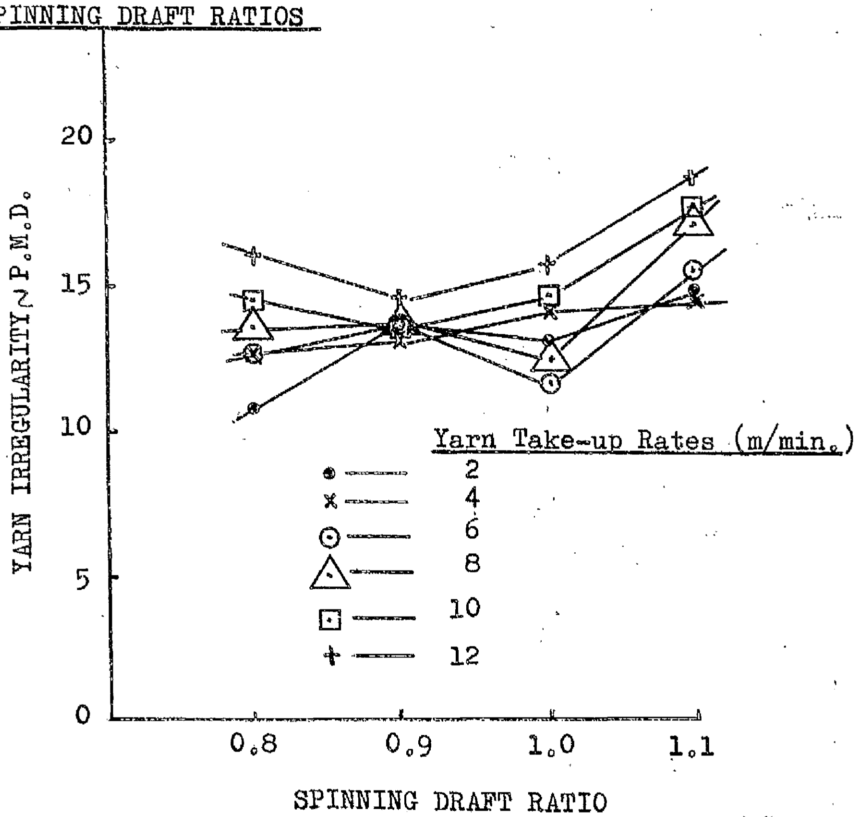



Fig.5.9

RELATIONSHIP BETWEEN SPINNING DRAFT RATIO AND YARN IRREGULARITY WITH DIFFERENT YARN TAKE-UP RATES

This "condensation" might happen either

(a) on the walls of the vortex tube, or

(b) on the forming yarn.

These two forms of condensation mechanisms need to be distinguished from each other.

Firstly, the presence of both solid friction and static charges will tend to retard the fibre flow inside the tube. Since mass flow must be conserved, the product of fibre velocity and linear density must remain constant and hence this retardation must cause the fibres to telescopically condense on the tube wall. Such condensation is not likely to be an even process and it is likely that fibres will tend to clump together. The attachment of these fibre clumps to the forming yarn will tend to result in an irregular yarn. This mode of fibre condensation will tend to be independent of draft ratios.

Secondly, a layering or doubling of fibres might be obtained by the "condensation" of fibres on the forming yarn. By a proper manipulation of the yarn withdrawal rate, it might be possible to allow the forming yarn to stay in the tube for a length of time sufficient to permit a reasonably large number of fibre layers to be built up on it. The process of doubling a number of fibre layers will tend to even out the short term irregularities in yarn. At draft ratios below unity, the layering mechanism seems to become more prominent and this is advantageous to yarn evenness.

In addition to the fibre layering mechanism described above, there is another one which might be caused by the uniform oscillating movement of the fibre assembly points during yarn formation. Assuming that at each assembly point the fibres tend to be uniformly peeled away and attached to the forming yarn, it is conceivable that the uniform oscillation of the assembly points along the circumference of the tube will tend to take off many thin and fairly uniform fibre layers. The overlapping of fibre layers produced by the mechanisms described above will, in its turn, tend to even out the thick and thin places and produce a uniform density of fibre layers. The addition of this uniform fibre layers on to the forming yarn would tend to improve the short term evenness of the final product. By extending this line of thought, it would seem that if the amount of fibre layering were to be progressively increased by decreasing the draft ratio, the short term regularity of the final yarn should show progressive improvements.

The irregularity of the yarns produced by Hirway ranged between 20 and 25 percent mean deviation, whereas in the preliminary tests conducted so far, an average irregularity of about 12.5 P.M.D. was obtained at draft ratios below unity over a wide range of yarn take-up speeds. Thus the yarn evenness had shown a remarkable improvement and this might be largely attributed to the changes effected in the draft ratios used in the apparatus.

#### 5.4.6.3. Relationship between draft ratio and breaking tenacity of yarn

Figs. 5.10 and 5.11. show the relationship between the yarn take-up rate and breaking tenacity of yarn at the various draft ratios.

The values of tenacity were obtained with only 10 tests for each sample. Hence the results were not statistically significant and only trends could be observed.

Fig. 5.10

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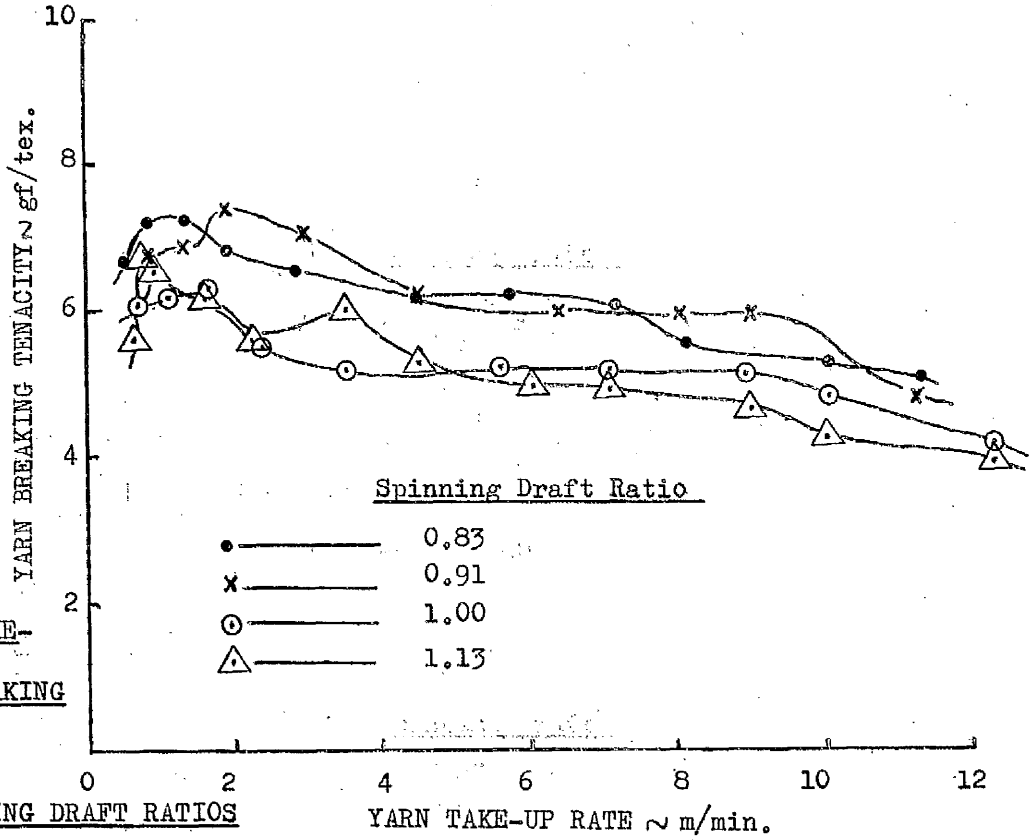
ERENT SPINNING DRAFT RATIOS



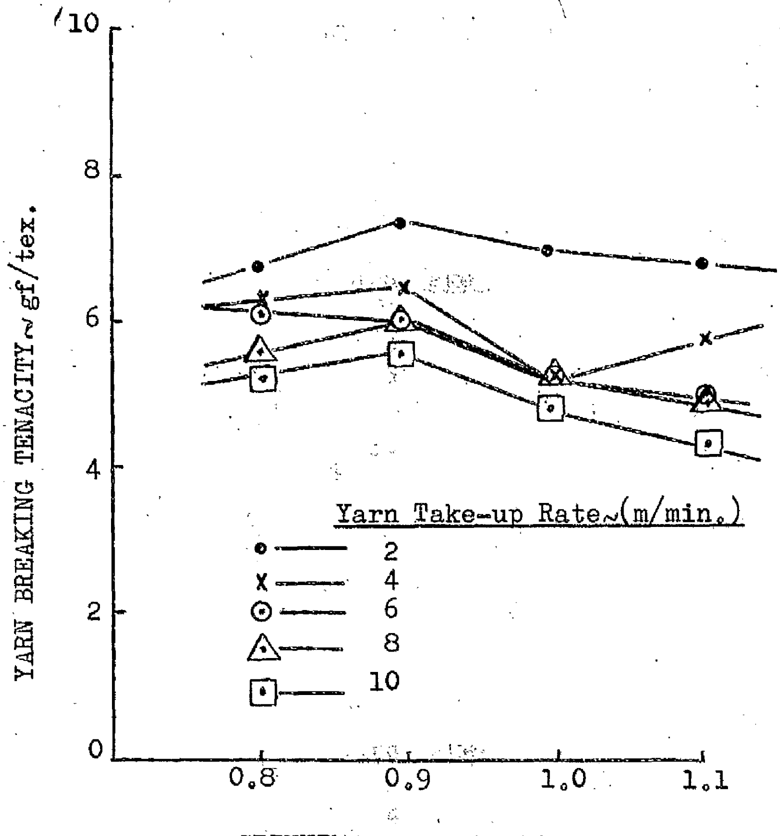




Fig. 5.11

RELATIONSHIP BETWEEN SPINNING DRAFT RATIO AND BREAKING TENACITY WITH DIFFERENT YARN TAKE-UP RATES .

However it was felt that the running averages of three consecutive tests might probably better indicate the trend of the behaviour of tenacity with draft ratios. Neglecting the tenacity values at low yarn take-up speeds, it was observed from Fig. 5.12. that in the speed range of 4 to 10 m/min. there were 'humps' or 'local maxima' in each of the curves obtained with the running averages. These 'local maxima' were attained at different speeds for the various draft ratios and these are given below:-

| Spinning draft ratio | | Yarn take-up rate at the 'local maxima' (m/min.) |
|---|---|---|
| 0.83 | - | 8.1 |
| 0.91 | - | 7.1 |
| 1.00 | - | 6.2 |
| 1.12 | - | 4.5 |

The yarn take-up rates at which these 'local maxima' occurred usually decreased as the draft ratio was increased. Perhaps a linear relationship existed between the parameters mentioned above.

Referring back to Fig. 5.11., it might be noted that for any given yarn take-up speed, the tenacity in most cases tended to be maximum at 0.9 draft ratio. The tenacities of yarns obtained at 0.8 and 1.0 draft ratios were generally less than those with 0.9 draft ratio at any corresponding yarn take-up speed. With 0.9 draft ratio, a yarn delivery speed of about 8 m/min. gave a breaking tenacity value of 6 gf/tex. It was rather difficult to know the exact reasons for the relatively high breaking tenacity values of yarn at 0.9 draft ratio. However a possible explanation is given below:-

Draft ratios above unity produced rather more irregular yarns than those below unity. These high irreguig. 5.12

IONSHIP
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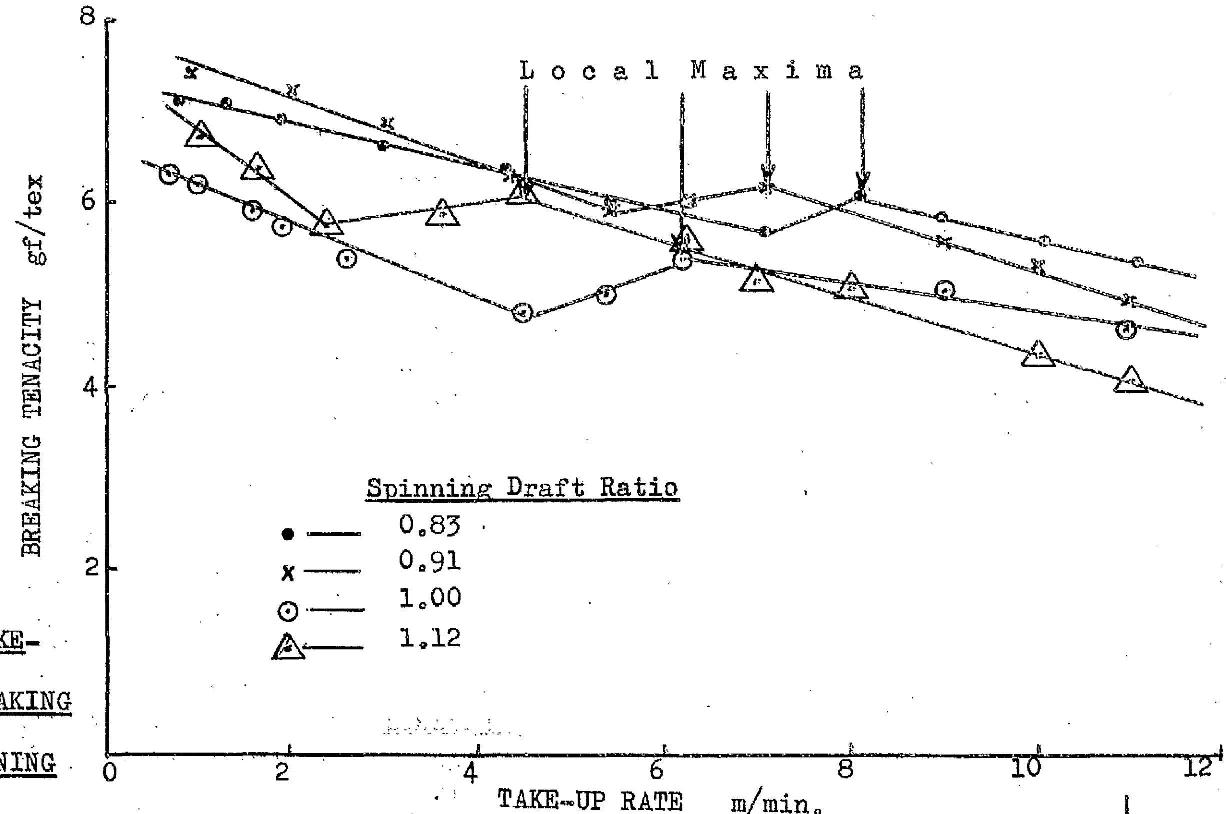
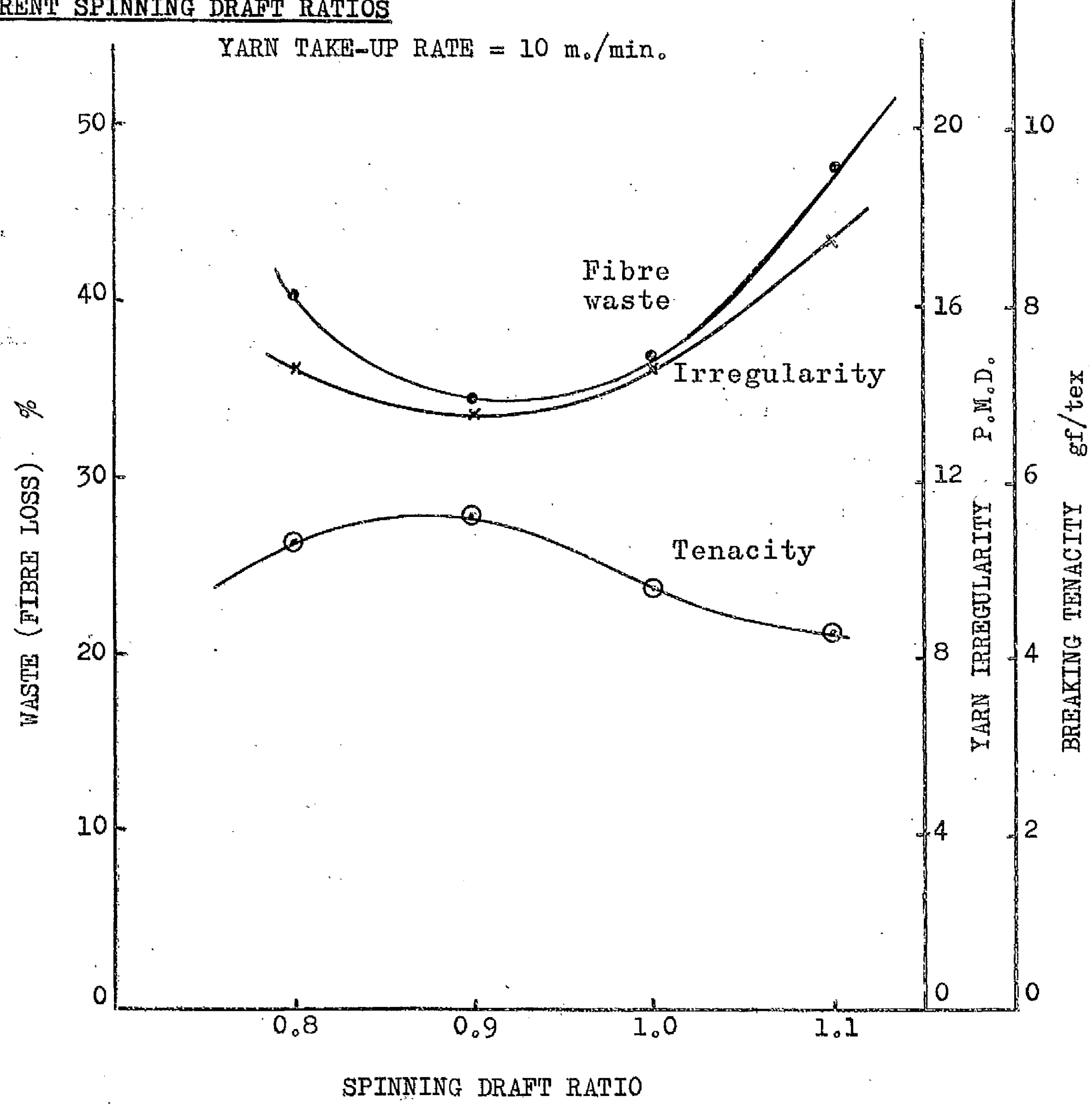
ITY - (RUNNING
GES) WITH DIFFERENT SPINNING DRAFT RATIOS




ig. 5.14

T OF SPINNING
RATIO ON THE
RMANCE OF THE
TUBE



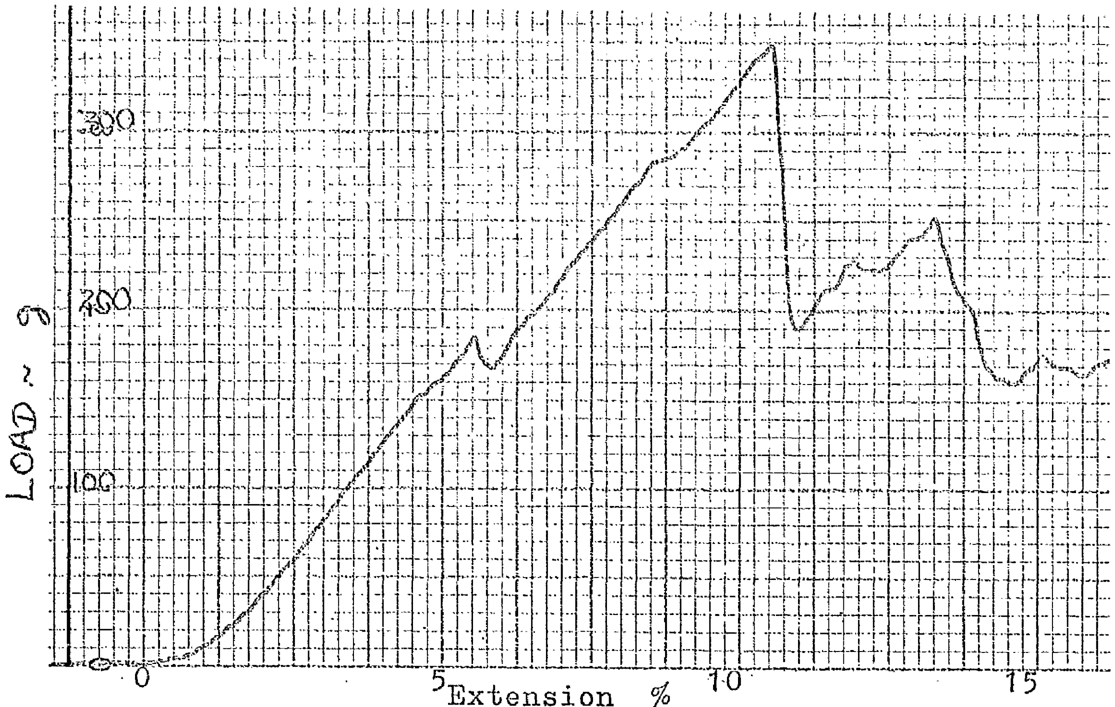
larities would probably be reflected on the low values of breaking tenacities. On the other hand, the higher tenacity of yarn spun at 0.9 draft ratio as compared to that at 0.8 draft ratio might be due to better fibre migration in the yarn structure.

It is of interest to note that yarns with low breaking tenacities usually exhibited a stick-and-slip relationship during their breakages. Fig. 5.13. shows a record taken at random from samples of low breaking tenacities. It may be noticed that there were also intermediary yarn breakage points, as shown by the different peaks. The stick-and-slip behaviour indicated that the yarn breakages occurred more due to fibre slippage rather than fibre breakage. However, most of the yarns tested showed the normal one point breakage of yarn. For the sake of comparison, a chart showing the normal breakage of a vortex spun yarn is shown alongside in the same figure.

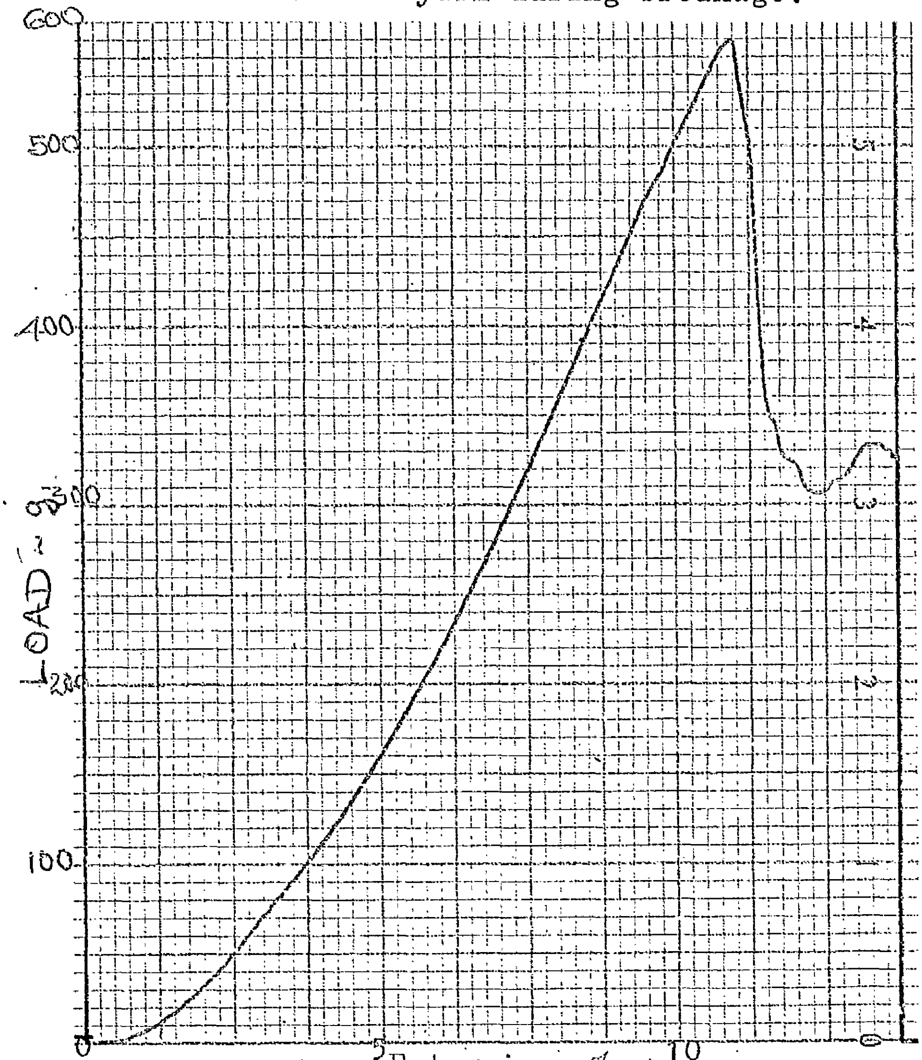
The tenacity values of Hirway's yarns were generally very low and they usually ranged between 0.5 and 1.5 gf/tex. In the preliminary tests, yarns of tenacity values in the range of 5 to 6 gf/tex were obtained. It might be interesting to note that the breaking tenacity of a conventionally spun yarn (equivalent count and twist to that of the vortex spun yarn) with a twist factor of 2.0 was found to be 12 gf/tex.

5.4.6.4. The optimum draft ratio

The optimum draft ratio was arrived at after taking into account all the foregoing considerations. Draft ratios above unity tended to produce bad yarns in terms of both yarn regularity and breaking tenacity. The waste figures




(a) Stick and slip behaviour exhibited by a soft spun vortex yarn during breakage.




(b) One point breakage of a normal twisted vortex yarn

Fig. 5.13.

RECORDS OF BREAKAGES OF VORTEX YARNS IN THE INSTRON TESTER were also high. When draft ratios were reduced below unity, the spinning performance improved quite dramatically. The yarn tended to be more regular and also of higher breaking tenacity. The waste too had shown a considerable improvement.

The effect of draft ratios on the overall spinning performance might be made more clear from Fig. 5.14. This figure shows the effect of draft ratio on yarn irregularity, tenacity and waste percentage at a yarn take-up speed of 10 m/min. From the curves in the figure, it was evident that the best draft ratio was around 0.9. Incidentally, it might be pointed out that the curves for yarn irregularity and the waste percentage tended to go together. It might be reasonable to infer from this tendency that a good fibre assembly efficiency would be obtained at low waste and good yarn regularity.

From all the above considerations, it was evident that the optimum condition for spinning a reasonably even yarn with a fairly good tenacity was obtained at a draft ratio of 0.9. It was, therefore, decided to conduct all the subsequent tests with such a draft ratio.

## 5.5. STATIC ELECTRIFICATION IN VORTEX SPINNING

During the preliminary study of air vortex spinning, only cotton fibres were used. The fibres always tended to move along the inner walls of the vortex tube. The material of the tube - 'Perspex' - was highly prone to static electrification. So, unlike the case of the conventional spinning where the cotton fibres do not normally produce static charges during processing, it was found in air vortex spinning that the fibre movement in the tube created charges the effects of which were quite noticeable. This static charge formation seemed to affect the general spinning performance of the tube.

Thus, quite contrary to Hirway's findings, wherein he states, "... the electro-static forces in the Perspex tube did not appear to have been very significant", it was found that the static electricity generated during vortex spinning had an influence not only on the amount of waste produced but also on other yarn parameters.

Static electricity was generated in the vortex tube by the movement of fibres against the inner walls of the tube. The amount of static appeared to increase with the rate of flow of fibres. After running some time, say, for about 10 minutes, the fibres emerging from the front roller nip were observed to be influenced by the static created in the tube. The fibres were electrically charged and they repelled each other producing the familiar "ballooning" effect. This ballooning effect combined with the rather poor control of the emerging fibres by the air suction caused frequent roller lapping both at the top and bottom rollers. Roller lapping occurred especially frequently with high fibre input speeds. A partial lapping of fibres resulted in an irregular yarn being spun. A full lapping, as is obvious, prevented the fibres from being fed into the spinning system and this caused breaks in the yarn spun with the result that it became quite difficult to spin continuous lengths of reasonably regular yarn. The use of clearer rollers improved the lapping only to a small extent.

It was also observed that the presence of large static charges impeded the fibre flow and caused a reduction in the speed of yarn rotation in the tube. If the static formation in the tube was left uncontrolled, then a stage was reached when the fibres started clinging to the tube wall.

The attached fibres formed an obstruction to the smooth flow of the subsequent fibres supplied to the tube. Since static charges build up with time, the fibre flow after spinning for a certain time became impeded because of the number of fibres adhering to the tube wall. This led to the formation of fibre tufts which resulted in a non-uniform flow of fibres. The presence of the fibre tufts attached to the wall also caused the speed of yarn rotation to be considerably slowed down. Those fibre tufts which were assembled on to the yarn caused large slubs in the yarn but more often these tufts found their way into the suction pump bag. Thus not only was the yarn spun very uneven but the waste was also greatly increased. It was, therefore, quite obvious that the generation and presence of large amounts of static charges during spinning had a significant influence on the spinning performance. Whilst the possibility that small amounts of static charges might be conducive to good spinning was not ruled out, it was clear from the above that the presence of large charges caused serious deterioration in the spinning performance. Consequently, it was thought that if proper means were adopted to control the amount of static created in the tube, then the general performance of the spinning tube might be improved.

### 5.5.1. Choice of the methods of static elimination

It is unnecessary to go into the variety of mechanisms which might cause static charge formation. However it is felt important to explore in the present study the various methods available to reduce or prevent the charge formation.

It appeared that there was no completely successful method of fully preventing the separation of charges that caused static. Therefore a reduction in the static formation rather than a complete elimination of it was aimed at. Attempts were, therefore, made to prevent the build up of large static charges by dissipating as far as possible the charges as soon as they were formed.

The static may be made to leak through the tube itself or through the air. (Strictly speaking, ions do not pass from the tube to the air but oppositely charged ions come from the air to neutralise those on the tube). Various methods were tried to achieve a reduction in static charge formation.

5.5.1.1. Control of relative humidity

Apart from the nature of the fibre used, the other factor which affects the conductivity of the textile material is the moisture content. The moisture content, in turn, is controlled by the relative humidity and, to a lesser extent, by the temperature of air surrounding the material.

With low relative humidity - about 45% - it was observed that the static built up quickly. Raising the humidity of the air might, therefore, be sufficient to reduce the static formation. In fact, relative humidities around 65% seemed to greatly improve the spinning performance but maintaining the humidity at such a level for long periods in the spinning room was not possible. High humidity also presented problems in the feeding of fibres. Roller lapping occurred and there was uneven drafting too.

When the humidity of the air surrounding the tube was raised by a jet of steam, it was found that the fibres stuck to the tube wall because the steam condensed on the tube surface. It was rather difficult to exercise reasonable control over relative humidity with the crude apparatus used. The fibre flow and assembly of yarn were greatly hampered.

Yarn rotation in the tube was also affected.

It was rather unfortunate that research could not be carried out to establish the relationship between the spinning performance and the variation in relative humidity in view of the limitations imposed by the humidification plant in the spinning room. This was especially so because it was felt that a proper relative humidity could be arrived at consistent with both the spinning performance as well as the fibre feed arrangement.

5.5.1.2. Application of static polishes

A thin coating of Perspex Polish No.3 (recommended by ICI for static prevention on Perspex surfaces) was applied to the inside surface of the vortex tube. This was allowed to dry for about 10 minutes. During the first few minutes of spinning, the static in the tube was dissipated almost as soon as it was formed. However on continuation of the spinning process the fine coating was slowly removed by the moving fibres and the rotating yarn. Static charges started building up again gradually with time until the effect of charges became detrimental to good spinning. Moreover this polish is not always effective on occasions where particularly low humidities are experienced. The use of this anti-static polish was, therefore, discarded.

Next liquid Arquad* 18-50% which was claimed to possess good anti-static properties was tried. The inside of the vortex tube was uniformly wetted with a 1% solution of this liquid(diluted with distilled water). The tube was allowed to dry. The liquid evaporated leaving a fine uniform

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*-supplied by Armour Hess Chemicals Ltd,Leeds 1. Arquad 18-50% is a quaternary ammonium salt supplied as a 50% solution of the salt in isopropyl alcohol.

coating on the tube wall. The spinning performance of this tube seemed to be only marginally better than the previous case (where the anti-static polish was applied). This liquid anti-static polish had the same drawbacks as the creamy Perspex Polish No.3. Hence the use of this liquid was discontinued.

5.5.1.3. Application of static eliminators

It was thought that the dissipation of static should be brought about by ionizing the air either by a radio active substance or by means of silent electric discharges from pointed electrodes. The radio active method is only suitable in those cases where a comparatively slow discharge is required. This slow discharge would not be able to bring about the neutralisation of large static charge rates. Another point against the use of radio active type of elimination was the physical health hazard involved due to emission of radio active rays.

The ionizing type of static eliminators generally finds a favour for static elimination. The Shirley static eliminator which belongs to this type was finally chosen because of the ease of operation, the comparatively safety in use, the fast discharge rate of ions and its ready availability in the laboratory. In the Shirley static eliminator, a high direct current voltage was applied via a protective resistance to a double pole electrode which provided a continuous output of ions of both positive and negative sign. The outputs were approximately ± 12,000 volts with respect to earth.

In experiments conducted during the spinning of yarns, a reduction of static charges was brought about by lowering the resistance of the surrounding air by ionizing it with the static eliminator. On the first observation, it was noticed that the use of this eliminator ensured a smooth flow of fibres in the tube. However regular experiments were conducted to confirm the validity of the use of this eliminator by relating the working of the eliminator with the various spinning parameters of the tube.

5.5.2. Condition of tests with the application of the Shirley static eliminator

The effect of varying the distance of the electrode of the static eliminator from the tube was examined in order to arrive at the optimum distance between the two. Tests were carried out by placing the electrode about 6 in. and 12 in. away from the nozzle end of the tobe. A draft ratio of 0.9 was employed throughout these tests. Furthermore, a nozzle fibre guide, explained in section 5.6., was used with the nozzle in all the tests.

5.5.2.1. Effect of static elimination on the waste produced

The results of the tests conducted with the static eliminator electrode placed at 6 in. and 12 in. away from the vortex tube and also with the static eliminator switched off are shown in Tables A.5., A.6., and A.7. respectively.

Fig. 5.15. shows the effects of static electrification on waste percentage obtained at the different yarn take-up speeds. Fig. 5.16. also shows the same relationship but here the inverse distance of the electrode from the tube was used so that '0' (zero) meant that the static eliminator was off.

From these figures, it may be seen that the application of static eliminator had a pronounced beneficial effect on the amount of fibres collected as waste. The nearer the electrode was to the vortex tube, the less was the waste.

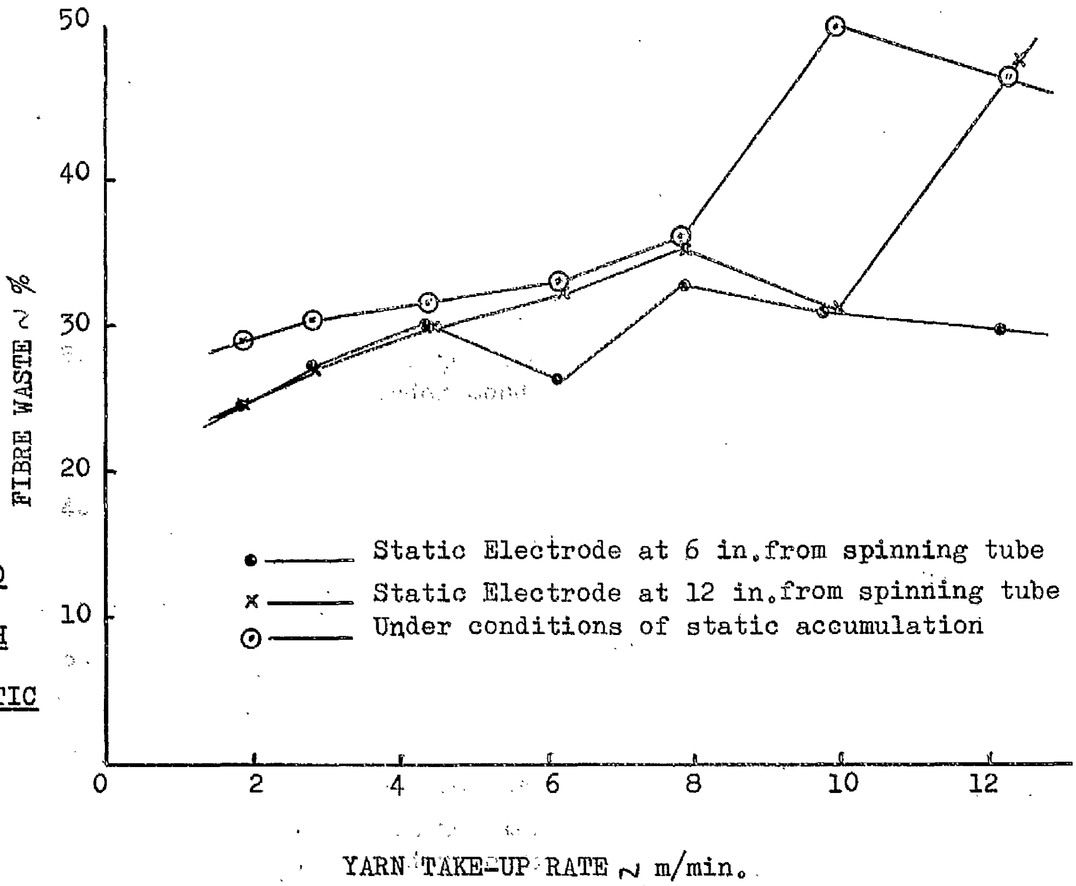



Fig. 5.15

ATIONSHIP
VEEN YARN
E-UP RATE AND
RE WASTE WITH
WITHOUT STATIC
LIMINATION

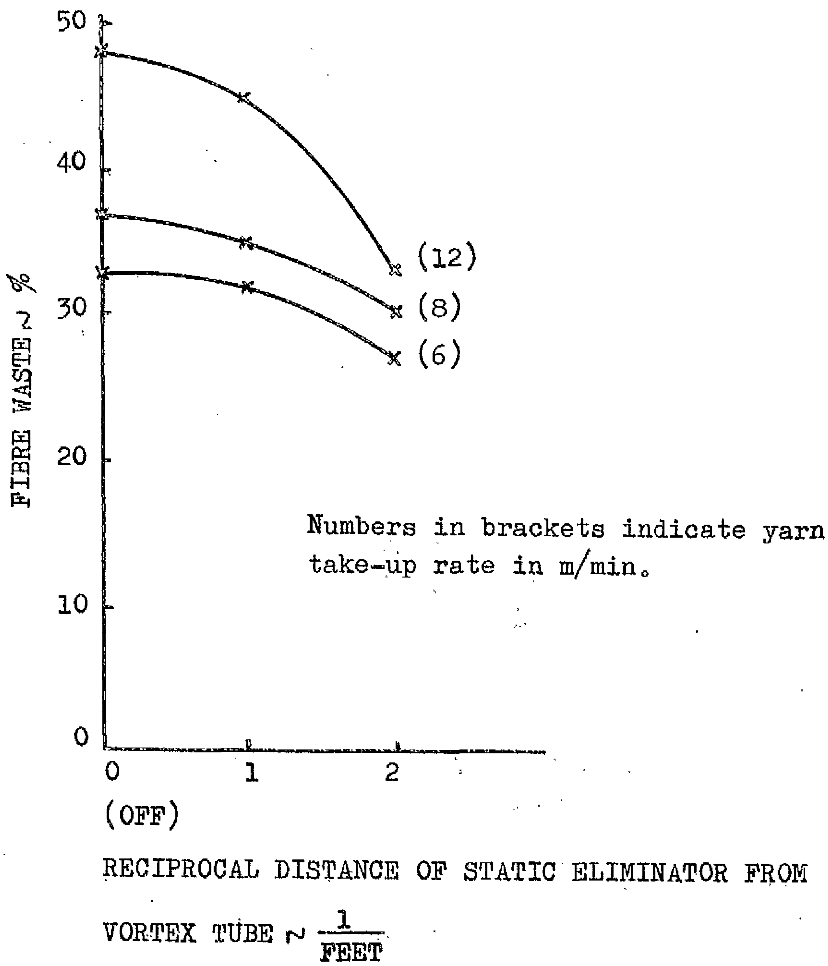



Fig. 5.16

ECT OF STATIC ELIMINATION ON
TE AT DIFFERENT YARN TAKE-UP RATES

The percentage of fibre loss was definitely less with the static eliminator working than without. Thus it seemed that a reduction of static generated was beneficial in minimising the waste produced during the spinning process.

5.5.2.2. Effect of static elimination on yarn regularity

The yarn regularity improved with the control of static generated in the tube. The irregularity was the least with the electrode placed close to the tube (6 in. away) and teneded to increase with the distance between the electrode and the spinning tube. This is shown in Figs. 5.17. and 5.18. There was a sharp deterioration in the evenness of the yarn when the static eliminator was switched off. So it appeared that the presence of large static forces was probably one of the causes of the production of irregularity in yarns and that the application of the static eliminator improved the yarn regularity. It might be pointed out that under conditions of electrification the deceleration mode of fibre condensation is encouraged and this will tend to lead to the production of poor yarn.

5.5.2.3. Effect of static elimination on breaking tenacity

Paradoxically, the more regular yarns obtained with the electrode placed close to the vortex tube apparently gave poorer tenacities as compared to the less regular yarns produced with either the electrode placed farther away or with the static eliminator switched off. Please see Fig. 5.19.

However it was not rigidly established that the regular yarns were always of low breaking tenacity because the number of tests performed to evaluate the tenacity values were not sufficient to give results that were statistically significant.

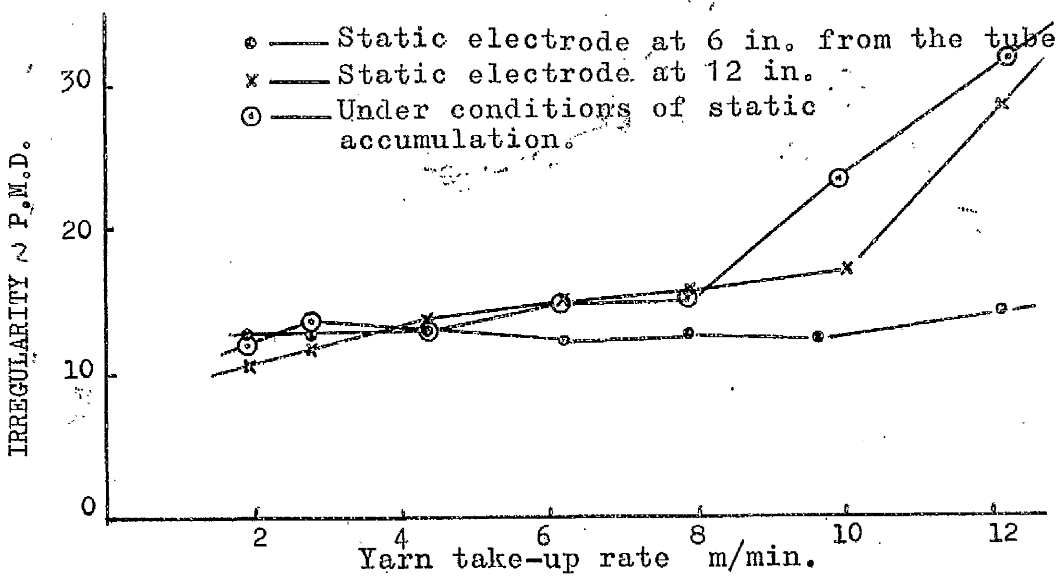



Fig. 5.17

RELATIONSHIP BETWEEN YARN TAKE-UP RATE AND YARN IRREGULARITY WITH AND WITHOUT STATIC ELIMINATION

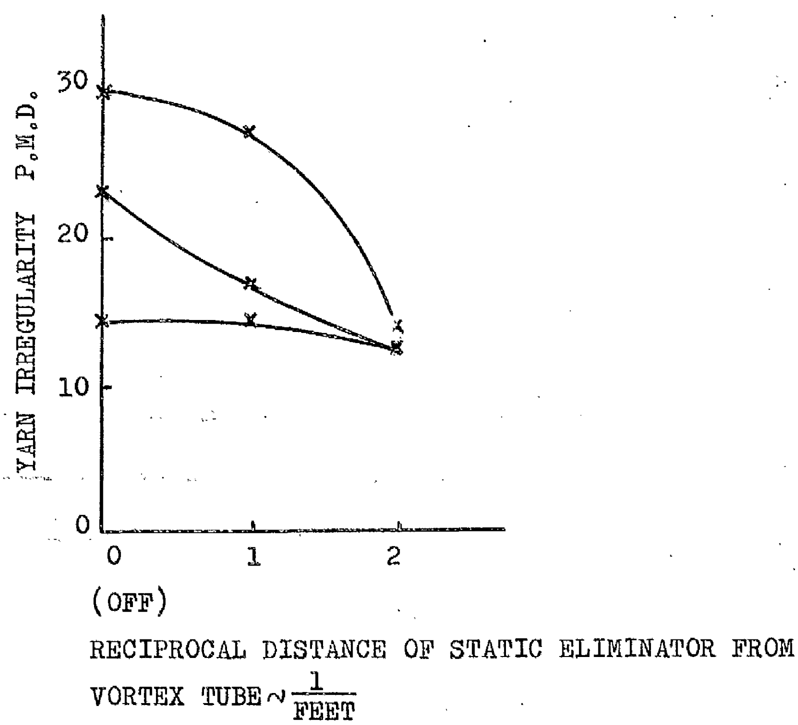



Fig. 5.18

T OF STATIC ELIMINATION ON YARN ULARITY AT DIFFERENT YARN TAKE-UP RATES

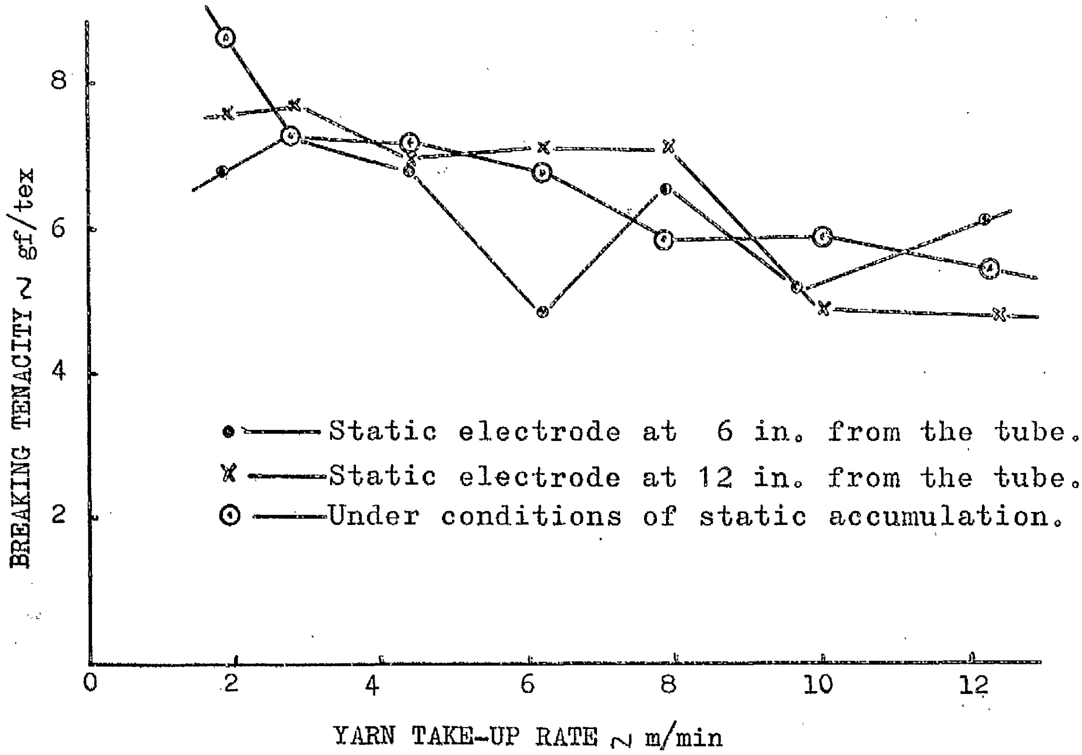



Fig. 5.19

RELATIONSHIP BETWEEN YARN TAKE-UP RATE AND BREAKING TENACITY OF YARN WITH AND WITHOUT STATIC ELIMINATION

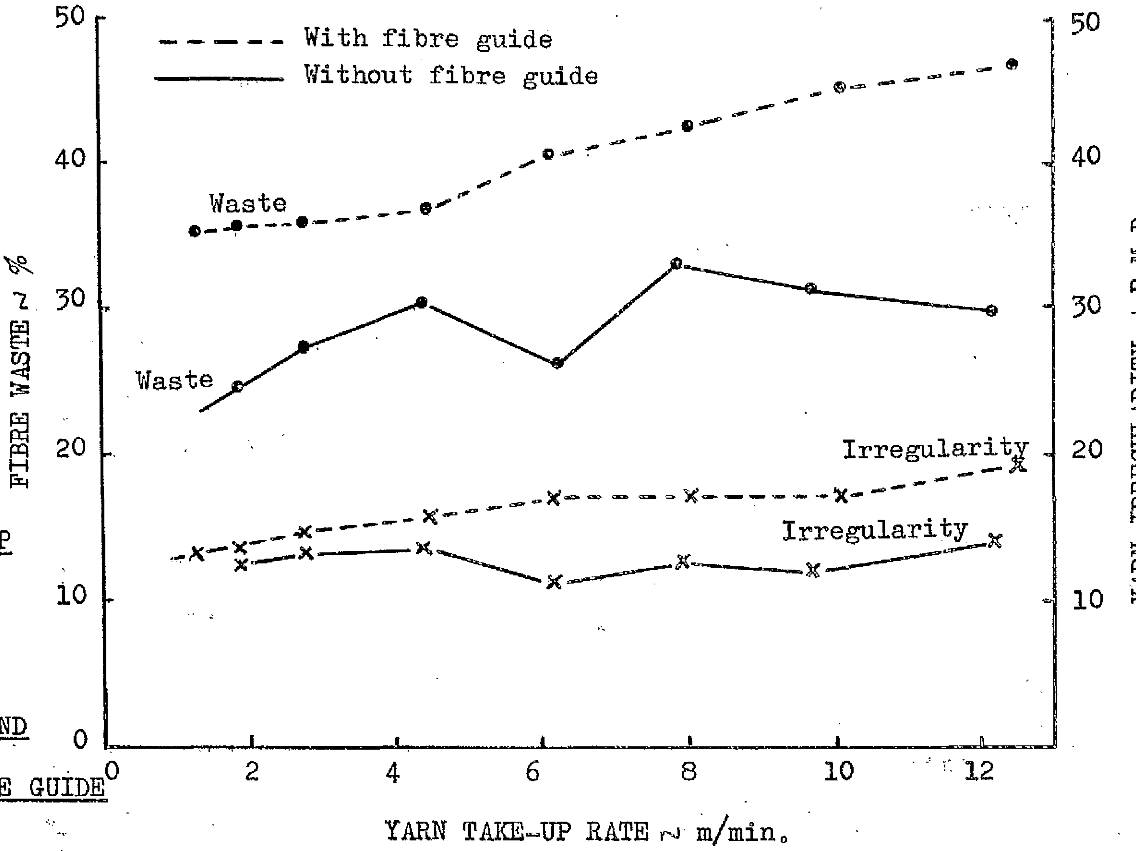



Fig. 5.21

TIONSHIP EEN YARN TAKE-UP AND a) FIBRE E AND b) YARN GULARITY WITH AND OUT USE OF FIBRE GUIDE

### 5.5.2.4. General conclusions on the application of static elimination to vortex spinning

Judging from the above analysis of results obtained with and without the static eliminator working, it was evident that a reasonably good yarn could be produced together with small amounts of waste when the electrode was placed about 6 in. away from the spinning tube. Thus it appeared that the amount of electrification was an important parameter which must be taken into consideration in all the subsequent tests.

It was noticed that when working the electrode even as close as 6 in. from the tube a small residual static charge was left in the tube. It was not definitely known at this stage whether this residual charge was conducive to good spinning or not. However it might be worth mentioning that when a metal tube was used for spinning, the yarn assembly was extremely poor. The metal tube being a good conductor of electricity helped to dissipate the charges as soon as they were formed and so it is probable that all the static charges produced leaked away. This suggested a relationship existing between residual static charge and yarn formation. It might well be that a certain amount of charge might be essential for good fibre assembly and improved yarn quality.

From the foregoing, it seemed that, as far as vortex spinning was concerned, the static charges generated in the tube need to be controlled rather than completely eliminated.

## 5.6. NOZZLE FIBRE GUIDE

Even with the best setting employed between the front roller and the nozzle, as described in section 5.3.1.3., it was observed that at high front roller speeds the air suction through the nozzle was not sufficiently strong enough to transport all the fibres from the roller nip into the tube. Better control over the fibres was essential if high yarn delivery speeds were to be achieved. So it was considered necessary to take the air suction of the nozzle as near as possible to the front roller nip. Not only was it necessary to allow the suction to be applied where it was needed but at the same time it was desirable to obtain a correct setting distance. It was, therefore, decided to make fibre guides of about one fibre length. (In the present case, it measured about $1\frac{1}{2}$ in.) Since the fibre guide was made as a separate piece, the long entries of the fibre guide were fitted to coincide well with the tangential inlet holes of the nozzle. A photograph of the fibre guide and nozzle is shown in Fig. 5.20.

With the fibre guide fitted to the nozzle, the control over the fibres emerging from the front roller nip was greatly improved and roller lapping was practically eliminated even at very high front roller speeds of fibre input. It might be mentioned that the arrangement of fibre guides for both the tangential inlets was made merely to balance the air flow through them.

Experiments conducted with and without the fibre guide, at a draft ratio of 0.9, indicated that considerably higher rates of yarn withdrawal could be attained with the use of the fibre guide. From Fig. 5.21., it might be noted that the tenacity of yarns produced with the fibre guide in the nozzle was higher than those spun without it. The fibre loss and yarn quality also showed improvements.

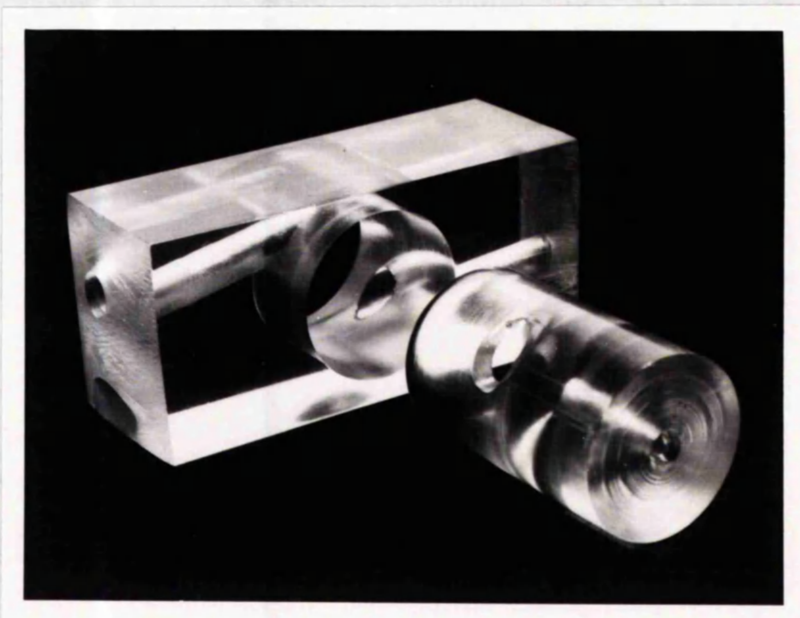


Fig. 5.20.

PHOTOGRAPH OF THE NOZZLE WITH THE FIBRE GUIDE

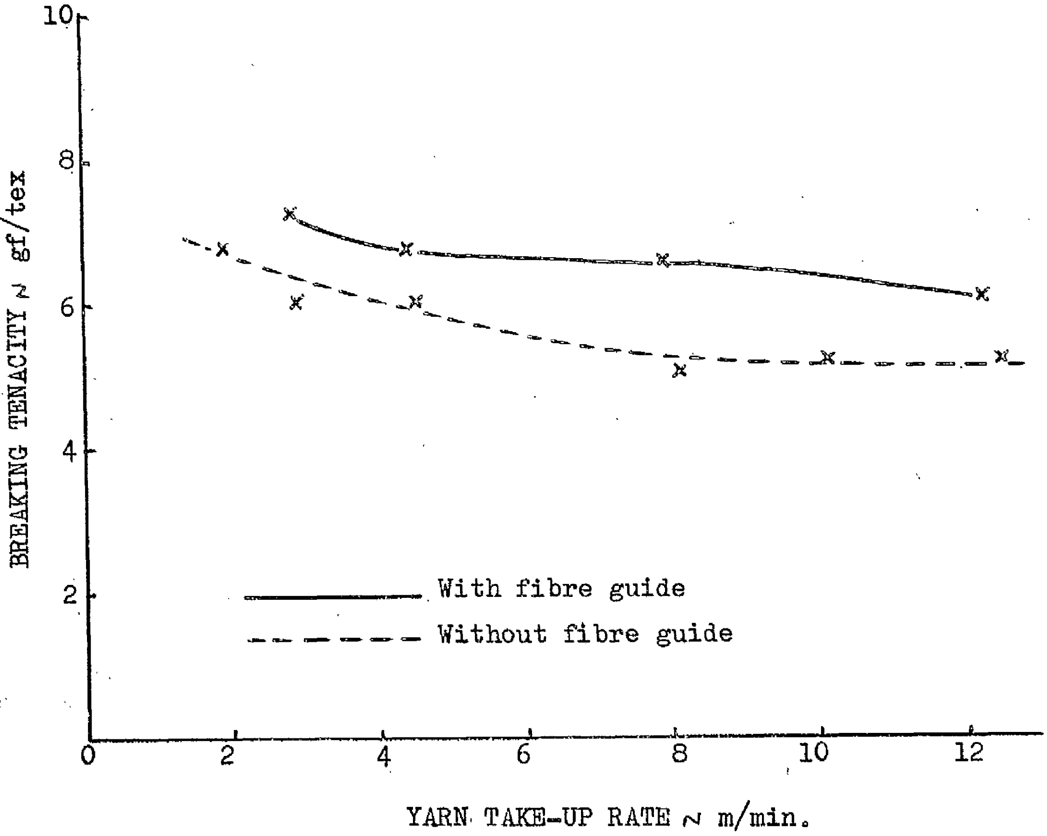
## 5.7. EFFECT OF STATIC ELIMINATION ON DRAFT RATIO

It was thought desirable to find out, under the conditions of static elimination and the use of fibre guide, if the optimum draft ratio arrived at earlier still remained the same or had altered. So a comparison was made between the spinning draft ratios of 0.9 and 1.0 in respect of the yarn parameters and the amount of waste obtained.

Fig. 5.22. shows the relationship between the yarn take-up rate and yarn irregularity, tenacity and waste percentage at the two draft ratios. It was found that the draft ratio of 0.9 still produced a more even yarn with a higher tenacity and less waste in spite of the change in the working conditions.

## 5.8. FLOW TRANSITION BETWEEN NOZZLE BLOCK AND TUBE

During the course of the above tests, it was observed that a draft ratio of 1.0 produced abnormally irregular yarns at speeds in excess of 8 m/min. In these cases, the length of forming yarn was very short. It was noticed that a deterioration in yarn evenness was usually associated with the short length of the forming yarn. Also the yarn spun was finer than usual indicating that a large proportion of fibres had been collected as waste. A peculiar sound was heard during spinning on such occasions. When the source of this sound was investigated, it was found that the noise was made by the end of the forming yarn whipping around the plain edge of the nozzle at the transition between the nozzle block and the vortex tube. It might be recalled that the nozzle bore was $\frac{3}{4}$ in. but the tube bore was 1 in. At the transition zone, there was an abrupt step from $\frac{3}{4}$ in. to 1 in. diameter. The end of the forming yarn rotated and rubbed the edge of this step and this probably gave rise to the noise.




g. 5.21(a)

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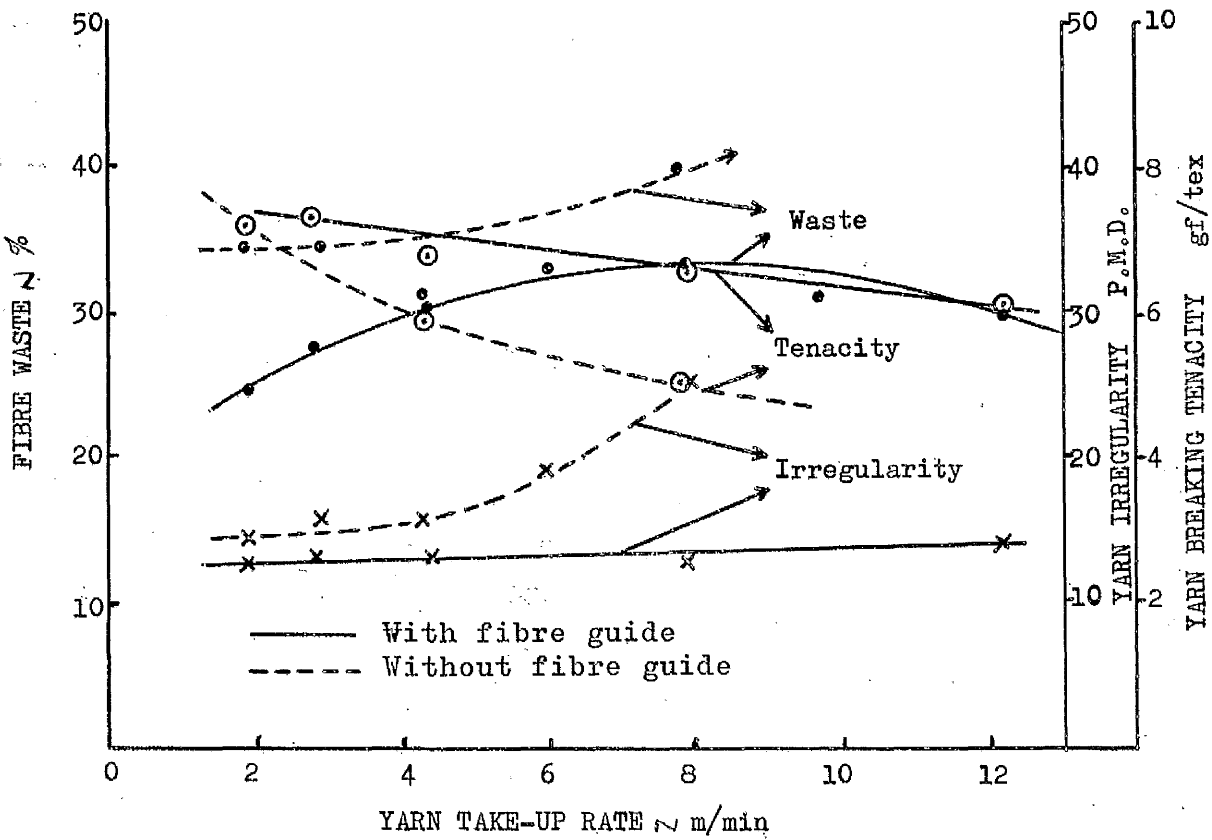



Fig. 5.22

RELATIONSHIP BETWEEN YARN TAKE-UP RATE AND YARN PROPERTIES WITH SPINNING DRAFT OF 0.9 AND 1.0 (SPINNING TUBE FITTED WITH FIBRE GUIDE)

It was felt that the smooth flow of the helical vortex might have been affected by this step in the path of air flow. In fact, when only fibres were fed into the spinning system, it was observed that at the step region the fibres built up and rotated along the edge of the step until they gradually built up into a large tuft which was eventually carried into the pump. This process of tuft formation was continuously repeated. The abnormal behaviour of fibres during their movement in the tube suggested that a subsidiary vortex might have been formed at the step region. The presence of this subsidiary vortex might be a reason for the peculiar behaviour of the forming yarn. Flow transition at a sudden enlargement is discussed in Part II of Chapter 6.

Since the fibres and yarn tend to travel along the inner surface of the tube, any sudden step might cause them to travel on different imaginary surfaces away from the tube wall in the zone near the step. This would then result in a bad assembly. There was also the possibility that at least some of the fibres rotating in the step region might be picked up by the forming yarn. The attachment of these fibre tufts would form slubs on the yarn and a periodic attachment of these tufts would increase the yarn irregularity.

Whatever the exact nature of the cause may be, the fact that there was a bad fibre assembly and high yarn irregularity when spinning with a stepped bore seemed to prove that the intervention of a step in fibre flow and yarn path was definitely detrimental to good spinning performance. It was thought, therefore, that a smooth transfer of both material and fluid flow from the nozzle block to the tube might avoid these undesirable effects. With this object in mind, it was decided to make a smooth chamfer to prevent the step as shown in Fig. 5.23.

5.8.1. Effect of using a smoothed flow surface on the spinning performance

Experiments performed with the chamfered nozzle showed the immense beneficial effect that this modification had on the amount of waste produced and on the regularity of yarn. This is clearly shown in Figs. 5.24. and 5.25. Tests were conducted at spinning draft ratios of 0.9 and 1.0. The yarns obtained after chamfering seemed to be better than those produced before at both the draft ratios. It was also noticed that the yarns spun with a chamfered nozzle at the draft ratio of 1.0 compared favourably with those produced at the best (0.9) draft ratio before chamfering. It was rather surprising to note that after chamfering, the waste percentage tended to decrease with speed at both the draft ratios. With a draft ratio of 0.9, the waste was about 16% at a yarn take-up speed of about 10 m/min.

The yarn regularity showed remarkable improvement but, strangely enough, the tenacity appeared to have been lowered. This slight reduction in tenacity was noticed only at the draft ratio of 0.9 but not with the draft ratio of 1.0.

In general, it might be said that the effect of chamfering the nozzle end and thereby smoothening the flow transition between nozzle block and the tube resulted in an overall improvement of the spinning performance of the tube.

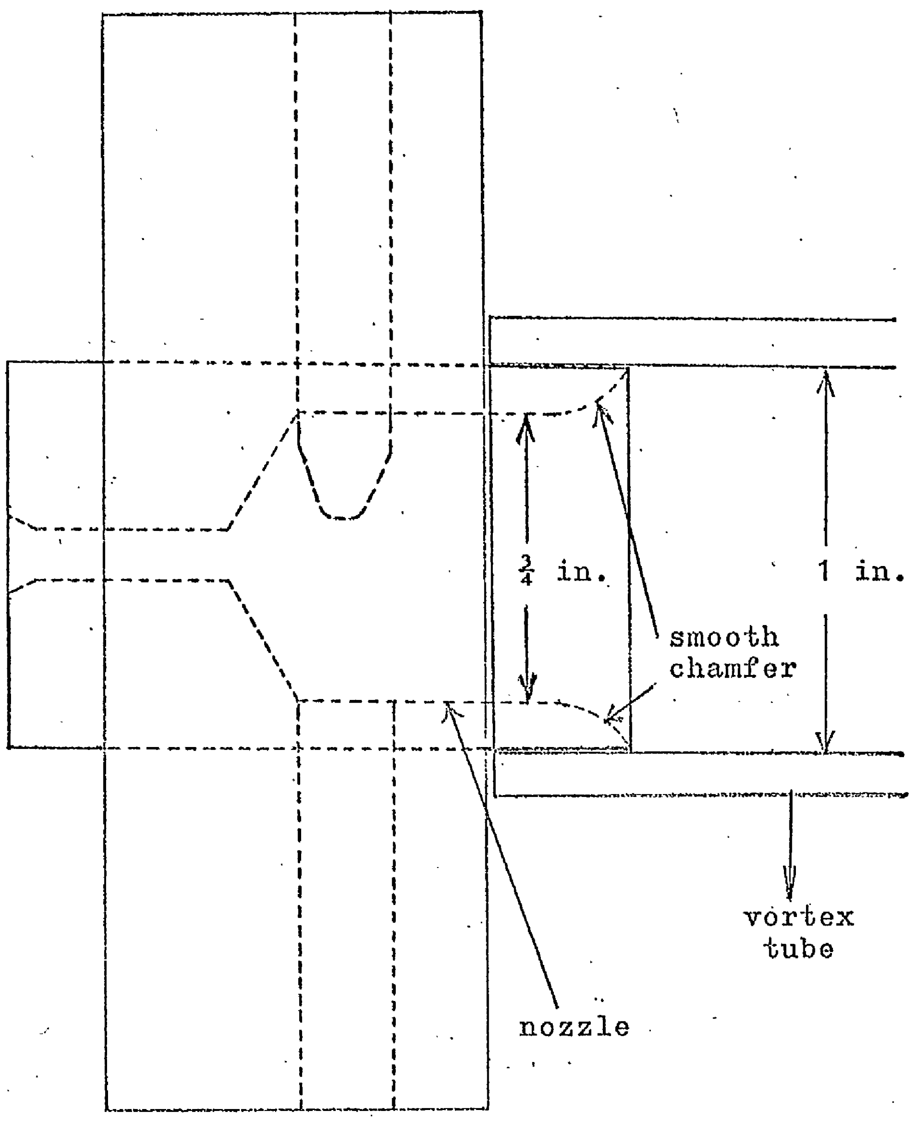
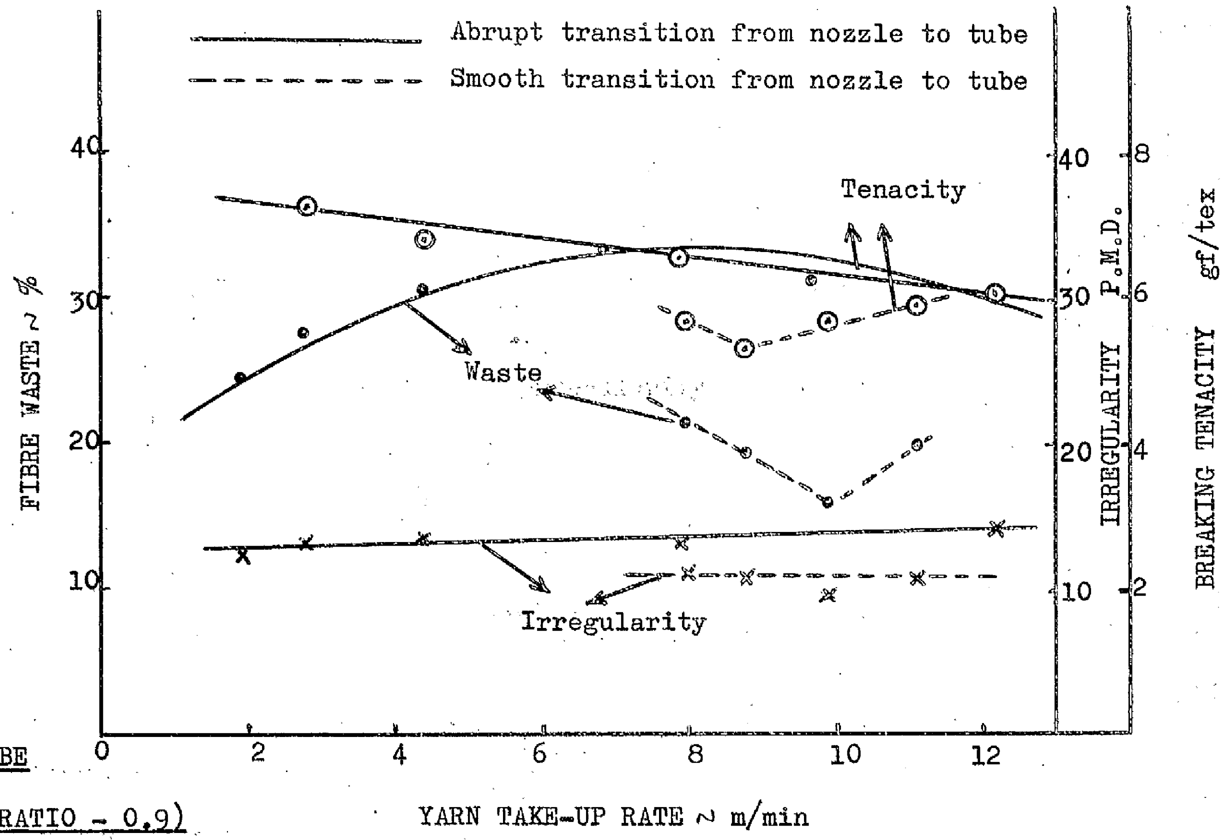



Fig. 5.23.

SMOOTH FLOW TRANSITION FROM THE NOZZLE TO THE VORTEX TUBE

SPINNING DRAFT RATIO = 0.91




g. 5.24

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ING DRAFT RATIO - 0.9)

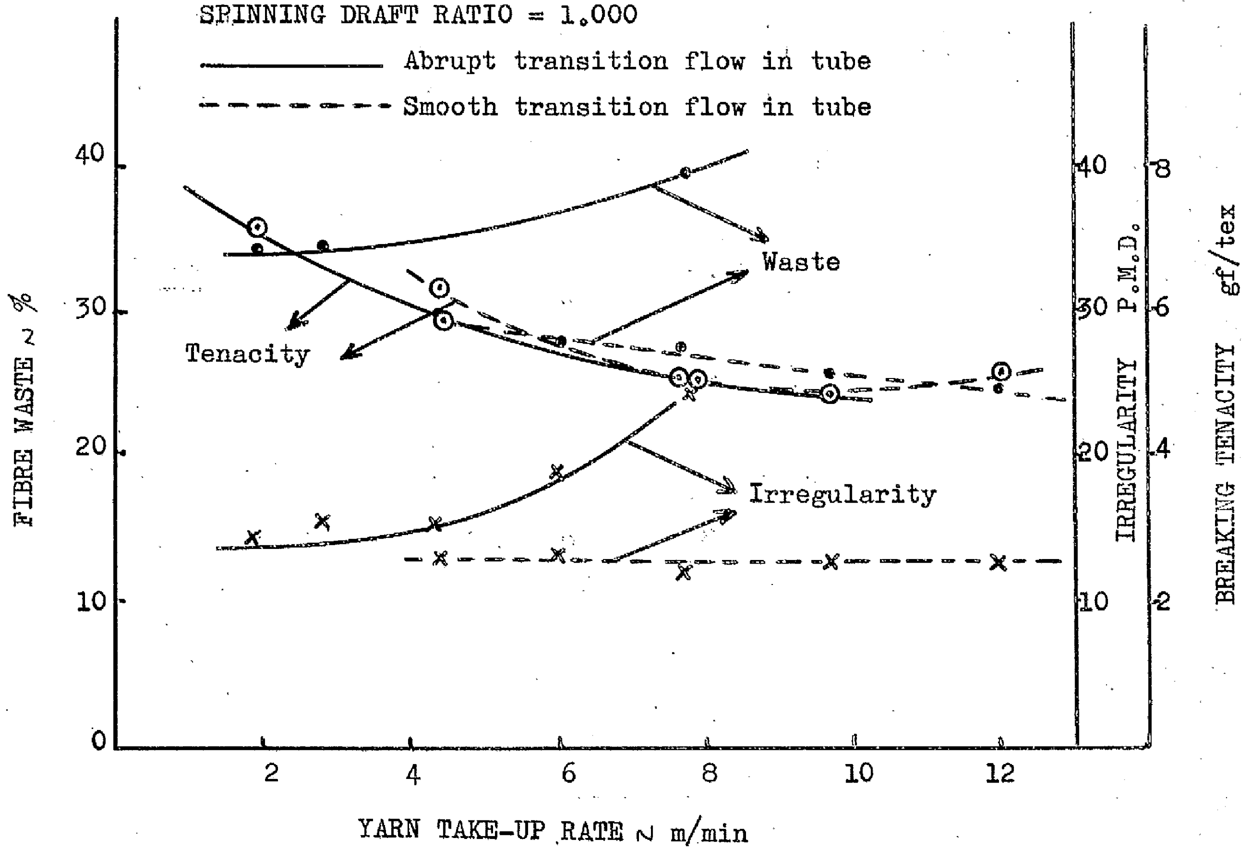



Fig. 5.25

EFFECT OF YARN TAKE-UP RATE ON YARN PROPERTIES WITH SMOOTH AND ABRUPT FLOW TRANSITION IN TUBE (SPINNING DRAFT RATIO - 1.00)

## 5.9. MEASUREMENT OF EQUIVALENT TWISTS IN AIR VORTEX YARNS

As it was not possible to measure the exact number of twists per unit length in the vortex spun yarns, for the reasons outlined in section 5.4.5.4., it was thought that it would be of interest to have an idea of the equivalent twist in the yarns so far made. The equivalent twist was defined as "the twist equivalent to that in a conventionally spun yarn of the same linear density as the vortex yarn and the breaking tenacity of which was equal to that of the vortex yarn.

In order to estimate the equivalent twist, it was considered necessary to spin yarns of nearly the same linear density as those of the vortex yarns but with different known twist multipliers. These yarns were spun on a roving frame because of the difficulty experienced in spinning such low twist multiplier yarns in the ring frame. Yarns with twist multipliers ranging from 1.00 to 2.25 were made and subjected to tensile tests in the Instron tester under the same conditions to those used for vortex yarns. The results were tabulated and graphs were drawn with breaking tenacity of yarn and (a) twists per unit length of yarn and (b) twist multiplier of yarn. These curves are shown in Figs. 5.26. and 5.27.

For low twists, it might be fair to assume that the breaking tenacity is proportional to twists per unit length of yarn. The point at which the tenacity of vortex yarn intersected the curves in the figures was taken as an approximate indication of the equivalent twists per unit lenth and equivalent twist multiplier of the vortex yarn. It appeared that the vortex yarns so far spun in this preliminary study possessed equivalent twists of about 5 turns per inch. The equivalent twist multiplier ranged between 1.50 and 1.75.

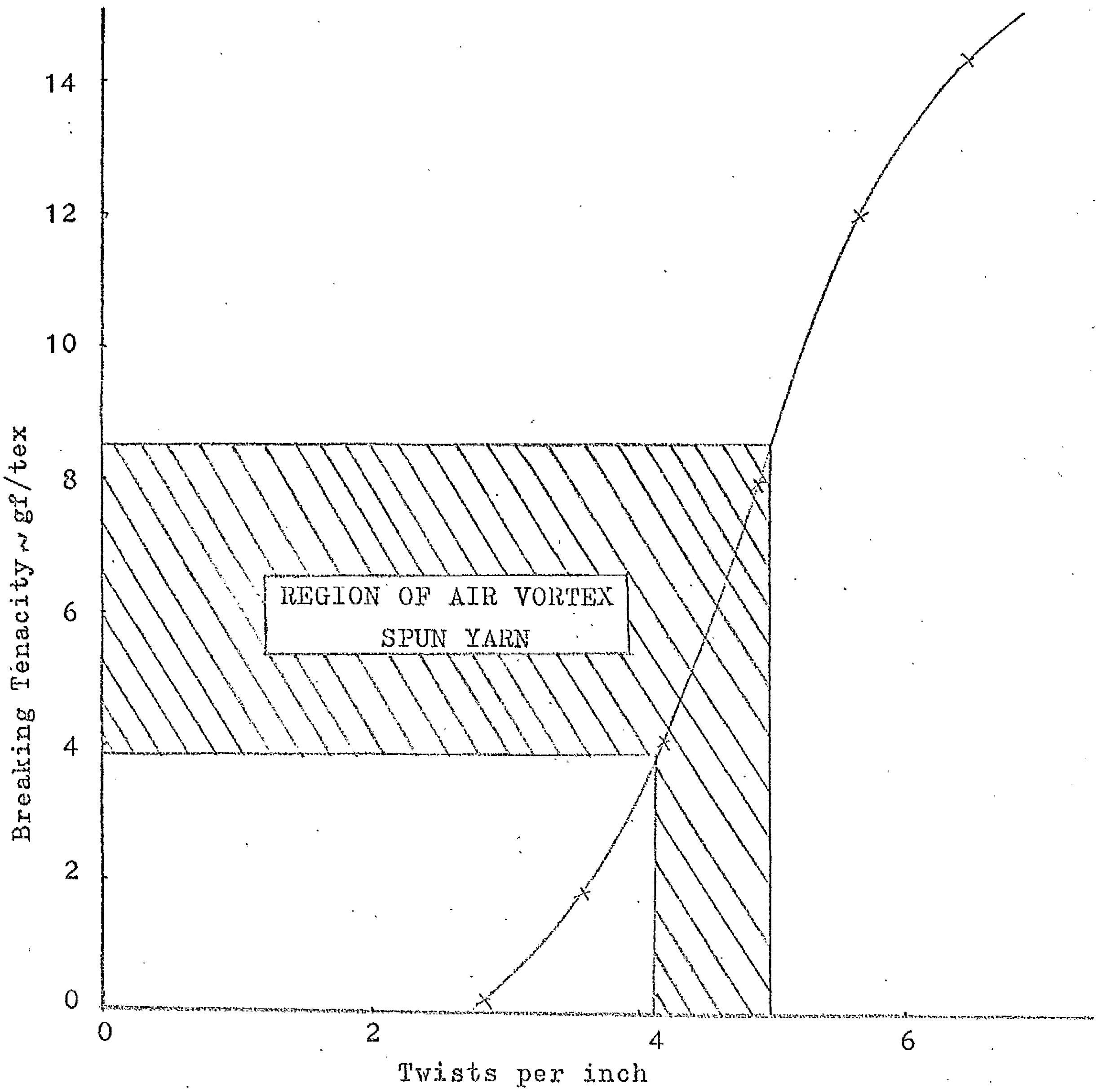



Fig. 5.26.

RELATIONSHIP BETWEEN TWISTS PER INCH AND BREAKING TENACITY IN CONVENTIONAL YARNS

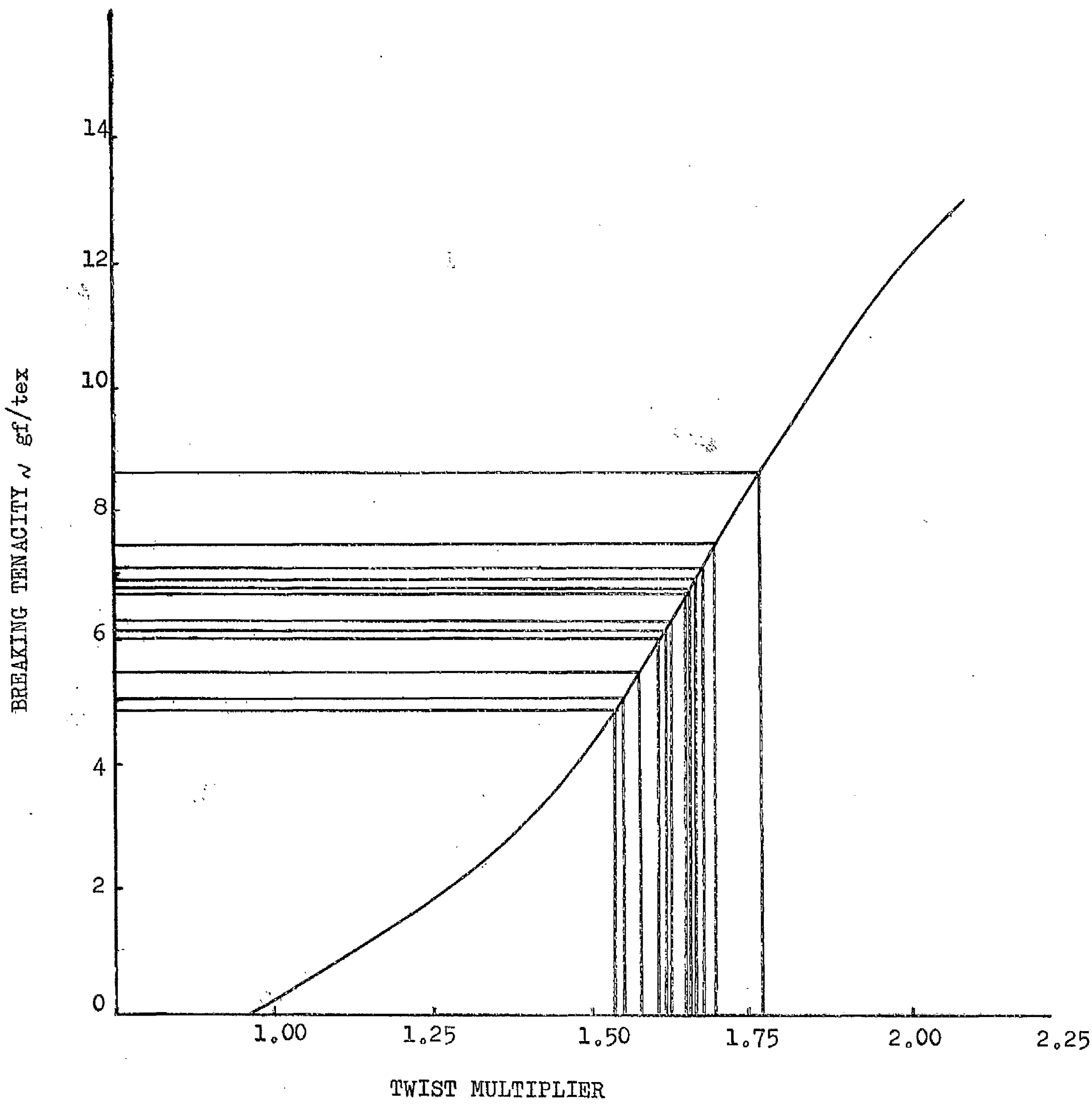



Fig. 5.27

AN EVALUATION OF THE EQUIVALENT TWIST MULTIPLIER OF VORTEX SPUN YARNS

## 5.10. CONCLUSIONS FROM THE PRELIMINARY INVESTIGATIONS

The critical examination of the design parameters of the spinning tube resulted in a modified nozzle design and it showed the need for proper control over the static charges formed in the tube during spinning. The overall spinning performance showed a remarkable improvement with the use of the modified nozzle and the effective application of static eliminator. The yarn take-up speed was increased by about a factor of five, the waste percentage was reduced by about 75% and the breaking tenacity of yarn improved about six fold when compared to the figures obtained before the start of this preliminary study. In spite of the fact that the general improvement was quite dramatic, there was ample scope for still further improvements in order to match the quality of yarn obtained from conventional spinning. The yarn take-up speed needs to be particularly improved upon and the waste to be reduced further.

The preliminary study contributed much to progress but it seemed that many more steps would be needed to make this method of spinning approach the stage of becoming a commercial proposition and posing a challenge to the conventional methods of spinning.

# CHAPTER 6

## A PRELIMINARY STUDY TO OPTIMIZE THE DIMENSIONS OF THE SPINNING TUBE

# CHAPTER 6

## A PRELIMINARY STUDY TO OPTIMIZE THE DIMENSIONS OF THE SPINNING TUBE

### 6.1. INTRODUCTION

The encouraging results obtained with the modified air vortex system gave the necessary impetus to carry out further experimentation with the basic nozzle design. It was desired to arrive, if possible, at an optimum design and thus obtain a still further improvement in the spinning performance.

In this study, the term "standard nozzle" is used to refer to the modified nozzle based on Hirway's design, the dimensions of which are shown in Fig. 6.1. The term "standard tube" means a tube of 1 in. inner diameter. Both the standard nozzle and tube were made of Perspex. It must be emphasized that although the term "standard" was used, it did not mean that the dimensions of the nozzle and tube mentioned above were optimum. The word "standard" was applied merely to distinguish the modified nozzle and tube from those of different designs used elsewhere in this study.

The following working conditions were kept constant in all the tests mentioned in this chapter.

(a) Two interframe bobbins of 1.25 hank each, made from Egyptian combed cotton fibres of 1 7/16 in. staple length were fed to a drafting unit.

(b) A SKF PK 211 drafting unit attached to a SKF Spintester supplied the fibres to the vortex spinner.

(c) The total draft in this unit was kept at 12 and this included a break draft of 1.4.

(d) A "spinning draft ratio" of 0.9 was maintained in the spinning tube.

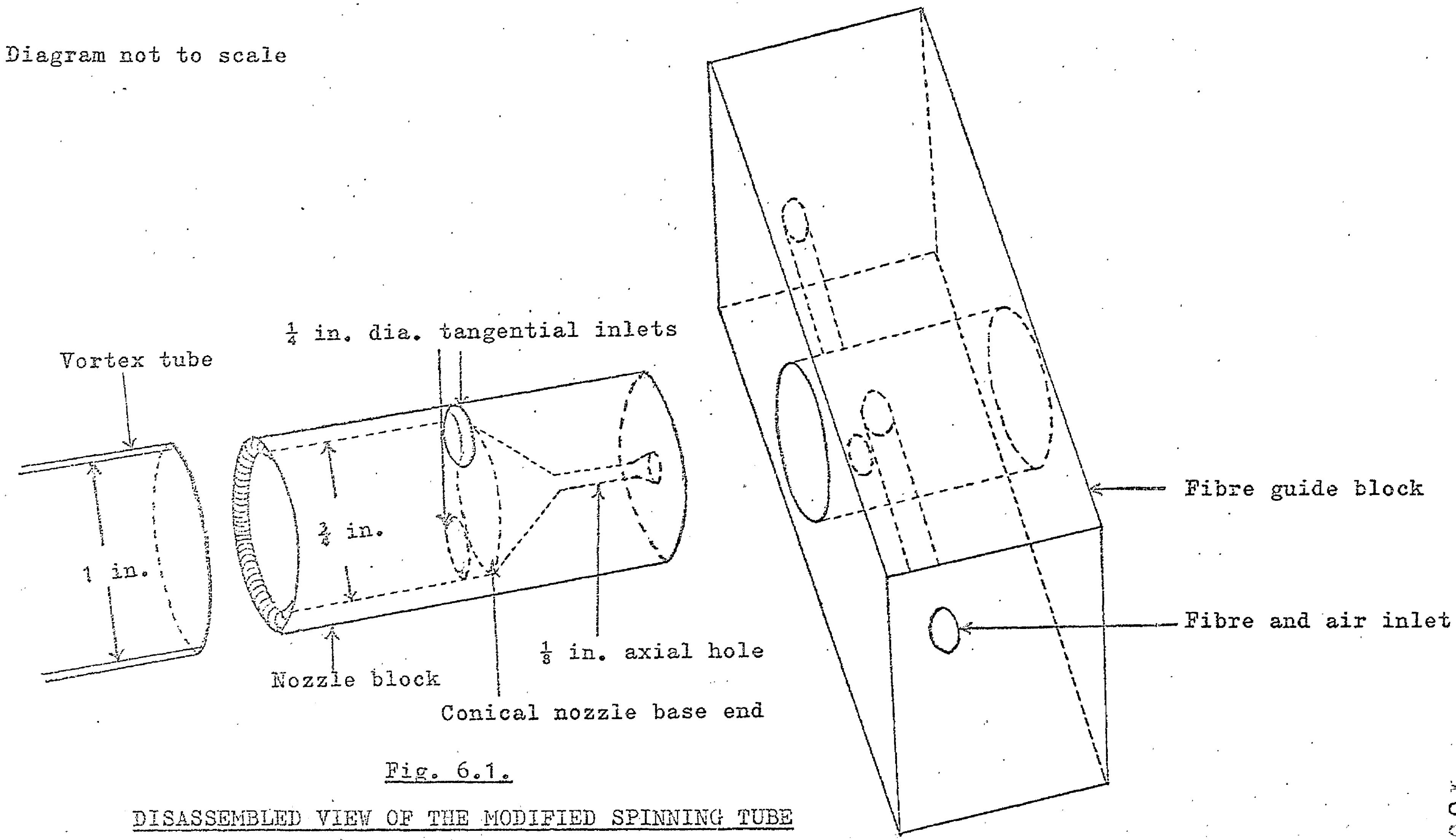



Fig. 6.1.

DISASSEMBLED VIEW OF THE MODIFIED SPINNING TUBE

(e) An overall pressure difference of ~25 in. of water column was maintained in the tube.

(f) The electrodes of a Shirley static eliminator was placed at about 6 in. from the nozzle.

(g) The relative humidity of the atmosphere was kept at 55% ± 1% and the temperature at 70° ± 2° F.

This chapter is broadly divided into two parts. The first part deals with experiments aimed at optimizing the nozzle and tube design. It was noticed during these experiments that the presence of step transitions in any joints in the spinning tube resulted in poor spinning performances of the tube. It was, therefore, felt essential to study the nature and behaviour of different types of flow transition and their effects on fibre and yarn movements during spinning. This study formed the subject matter of the second part.

## PART I

The main aim of this study was to make a general assessment of the effects of various parameters involved in nozzle and tube design on the spinning performance. The alterations made in the design of the nozzle and the tube consisted essentially of varying the size, shape and material used in their construction. In brief, this chapter attempts to draw some inferences concerning the nozzle and tube design based on the results of experiments performed with non-standard nozzles and tubes. It should be pointed out that the conclusions arrived in some of the experiments were based to a large extent on careful and detailed observations made on the yarn quality, fibre assembly efficiency and yarn output rate. In some cases, it was difficult to obtain accurate results of the yarn characteristics due to frequent breakages of yarn during its formation and in certain other cases, spinning was almost impossible. In these cases, only subjective judgement could be made.

6.2. DESIGN ALTERATIONS TO TUBE

Design alterations to the tube were considered first because it was relatively simple and quick to modify the tube.

The tube design was considered to consist of three parts. They were as follows:-

(a) Size, i.e., tube bore,

(b) Shape

and (c) Material of its construction.

The three different aspects of tube design were varied separately whilst the other two were usually kept unchanged. The standard nozzle was used whenever possible, otherwise standard nozzle dimensions relating to the tangential inlets and axial hole were used on the nozzle and the least variation from the standard was maintained.

6.2.1. Tube bore

In this exercise, tubes of different diameters were tried. They were

(a) $\frac{1}{2}$ in. bore,

(b) $\frac{3}{4}$ in. bore,

(c) 1 in. bore,

(d) $1\frac{1}{2}$ in. bore

and (e) 2 in. bore.

All these tubes were made from 'Perspex'* for the reasons mentioned later in section 6.2.7.

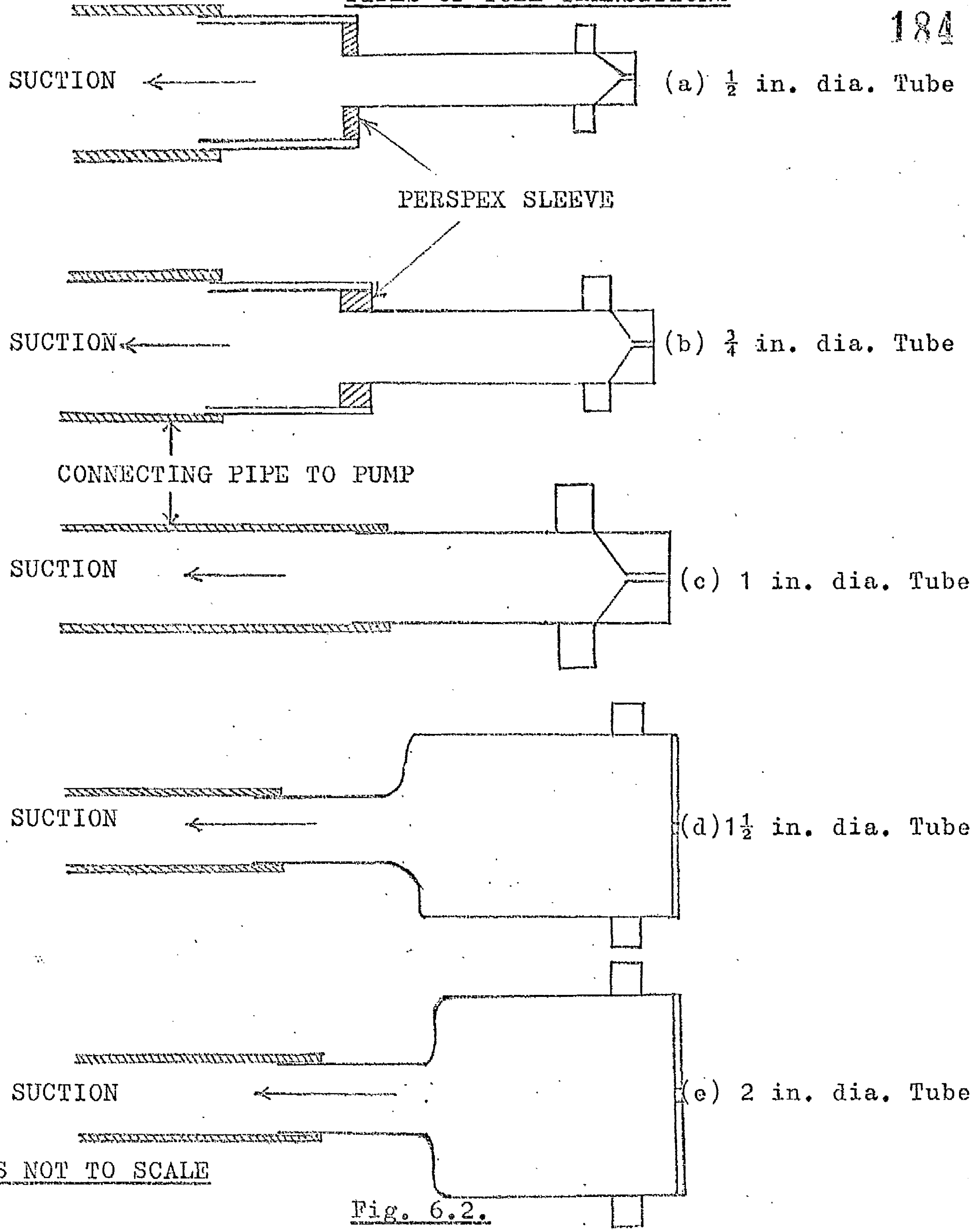
*-Perspex is a regd. trade mark of poly(methyl methacrylate) manufactured by Imperial Chemical Industries Ltd., England.

Each tube was usually about a foot long. The general construction of these tubes might not, at first sight, appear necessary to be included here but this factor seemed to present some interesting problems later on during the experiments. In order that these problems be clearly understood, it was thought relevant to give at least an outline of the general pattern of construction of these tubes and their nozzles.

6.2.2. Tube construction

Since the standard nozzle could not be fitted into any of the above non-standard tubes it was, therefore, essential that nozzles be made specifically for each tube. These nozzles were attached to the tube body itself and these were made to retain as far as possible the dimensions of the standard nozzle. Thus the sizes of the tangential inlets and axial holes were incorporated in them without much difficulty but it was necessary to alter the dimension of the nozzle bore so as to correspond to that of the non-standard tube to which the nozzle was attached. The nozzle with fibre guides on the tangential inlets was affixed on one end of each tube, as shown in Fig. 6.2. The other end of the tube could not be connected directly into the vacuum pump used for air suction because the size of the suction inlet in the pump was fixed (about $1\frac{1}{4}$ in. in diameter). A rubber pipe(later on replaced by a polythene pipe) of a suitable outside diameter to correspond with the suction inlet size and an inner diameter of about 1 in. was used as a connecting link between non-standard tube and the pump. Perspex stepping rings were sleeved on to the open end of $\frac{1}{2}$ in. and $\frac{3}{4}$ in. diameter tubes to facilitate the connections between these tubes and the pipe

TYPES OF TUBE TRANSITIONS




DIAGRAMS NOT TO SCALE

Fig. 6.2.

CONNECTION OF TUBE WITH PUMP

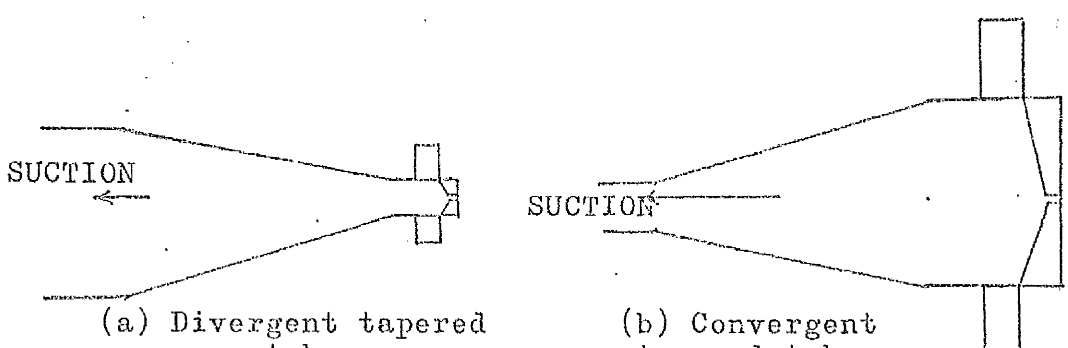



Fig. 6.4.

TYPES OF TAPERED TUBES

giving a sudden enlargement. With tubes of larger bores(such as, $1\frac{1}{2}$ in. and 2 in. bores), it was necessary to introduce a Perspex tube to reduce the bore size. Fig. 6.2. shows these enlargements and reductions in tube bores.

It was thought that the introduction of the intermediate tube was a workable means of reducing the bore size and that it would not unduly upset the flow in the tube. Indeed it was not realised at that time that sudden transitions in the flow path would have adverse influences on spinning. However it was not too long before it was observed that a sudden transition had a pronounced detrimental effect on the fibre and yarn movements in the tube. The spinning too was badly affected. A study of this particular behaviour of flow with respect to vortex spinning was considered important in order to avoid the poor spinning performance of the tube arising mainly from the flow characteristics. This study is dealt with in Part II of this chapter.

6.2.3. Experimental results and discussions

From a study of Table 6.1. which shows the results of the tests on various diameter tubes, it is obvious that tubes larger than 1 in. bore performed poorly.

The centrifugal force acting on a yarn lying inside the tube is directly proportional to the yarn mass, the tube radius and the square of the angular speed of yarn. For a given yarn count and length of yarn in the tube, the mass of yarn remains constant. Therefore, under these conditions, centrifugal force may be said to vary as $\frac{V^2}{R}$, where V = velocity of yarn helix and R = tube radius. If it is assumed that the velocity of the air at the tube surface was maintained constant in all the tubes during the spinning process and the yarn velocity was also constant, then the centrifugal force acting on yarn would have been inversely proportional to the radius. Any increase in centrifugal force would give increased frictional drag which would reduce the yarn speed, which, in turn, would reduce the centrifugal force. A balance would be obtained for each condition and thus the concept of constant yarn speed is seen to be untenable. Thus it would be expected that the driving torque would be proportional to $\frac{V^2}{R}$ but since the driving torque is a function of the yarn count and of the local air velocity, the determination is far from simple.

In practice, it was found that the yarn speed did vary for the different tube sizes experimented with even though the air flow rate of the pump was kept fairly constant throughout.

The abrupt changes in tube diameter gave rise to considerable pressure losses at the transition zone. Since the overall pressure difference was maintained constant in all the expgriments,therefore the air flow rates were at times considerably reduced and this too resulted in substantial reductions in the yarn rotational speed.

Apart from the reduced yarn speeds, the poor spinning performances of large tubes might be attributed to the serious disturbances caused to air and fibre flows and also to the yarn movements. These disturbances might have been caused by the sudden contractions.

Thus the combination of all the above variable factors made it almost impossible to establish a relationship betwe'en the yarn speed and the tube diameter.

The spinning performance of the $\frac{1}{2}$ in. tube was far better than those of the $1\frac{1}{2}$ in. and 2 in. tubes but it was inferior to those of the $\frac{3}{4}$ in. and 1 in. bore tubes. With a $\frac{1}{2}$ in. tube bore, the high rotational speed of the yarn inside the small radial space of the tube tended to cause a vigorous agitation of the air flow passing through. This tended to cause disturbances in both the air vortex and the fibre flows. Due to the flow disturbances, the process of fibre assembly tended to be upset and this led to a disorderly attachment of fibres to the yarn. This situation was further aggravated by the movement of long fibres within the relatively small confines of the tube. The staple length of the fibres used in this experiment was 1 7/16 in. and, therefore, the lap length of a fibre was almost equal to the tube circumference. All the points mentioned above tended to cause yarn irregularities and perhaps this explains the production of a highly uneven yarn with the $\frac{1}{2}$ in. tube.

It may be mentioned in this context that the truth of the fibre length-tube diameter relationship mentioned above was borne out of the fact that the $\frac{1}{2}$ in. tube produced reasonably even yarns with the short-stapled fibres, such as, comber waste, asbestos etc. This seems to indicate that there should exist a relationship between staple length of the fibre and the best tube radius.

It was evident from Table 6.1., included in Appendix , that the general spinning performance of the tube of $\frac{3}{4}$ in. bore was better than that of the 1 in. bore tube, although both their individual performances were really quite good. The reason for this might be sought in the increased rotational speed of yarn in $\frac{3}{4}$ in. tube, the increase in speed being as high as 18% over that of the 1 in. tube. The increased yarn speed might bestow the additional advantage of a proportionate increase in yarn withdrawal rate in order to obtain a yarn quality similar to that produced with the 1 in. tube.

From the above considerations, it seemed that a tube bore of $\frac{3}{4}$ in. was the ideal choice when spinning with staple fibres of about $1\frac{1}{2}$ in. length.

6.2.4. Tube shape

So far, only circular tubes of uniform diameter throughout their length were tried. It was felt that it might be interesting to know the behaviour of fibre flow and yarn formation in tubes of various shapes. There were certain limitations in the choice of tube shapes. Triangular, rectangular or multi-sided shapes were completely ruled out. Since air, fibres and yarn must move smoothly along the wall of the container in order to effect good spinning, it was essential that discontinuities must be fully avoided. Hence this study was confined to circular tubes but with varying diameters along their lengths. The two different tube shapes that were experimented with were as follows:-

(a) tapered tubes

and (b) "drum" type tubes.

The material used for the tapered tube and nozzle was Perspex.

Fig. 6.4,* shows the types of tapered tubes employed in this exercise. Spinning with tapered tubes, both divergent and convergent types, will be dealt with in section 6.9.4. It is considered sufficient to mention that tapered tubes, in general, yielded good yarns but the spinning performance with the convergent type was definitely better than with a divergent type.

* p.184

Fig.6.14(d)* shows the different drum type tubes. These were so called because one of them was a modified "drum" of the early SACM/UMIST break spinner. Also the rest looked more like the "drums" of the rotor spinners rather than vortex tubes. The performances of the drum type tubes are also dealt with in section 6.9.4., in connection with the effect of sudden contraction in tube transition on vortex spinning. It need be only mentioned that spinning was almost impossible with any of these "drum" type tubes and the reasons for this are given in the same section.

6.2.5. Material of tube construction

In this experiment, tubes of the following materials which were readily available were tried.

(a) Perspex (polyacrylic),

(b) Glass,

(c) Polythene,

(d) Polystyrene,

(e) Polyvinyl chloride (PVC)

and (f) copper.

The object of this exercise was to select the best possible tube material purely from the point of view of its spinning performance.

A bore dimension of 1 in. was chosen in all these tubes, the main purpose of which was to adhere to the standard tube dimension mentioned earlier. The length of each tube was usually about 2 feet. The standard Perspex nozzle was used with each of these tubes in turn.

6.2.6. Experimental results and discussions

Table 6.2. shows the results of the various tests made with the different types of tubes. It may be observed from this table that the general spinning performance was not

* p.233

encouraging especially with polythene, polystyrene, pvc and copper tubes. In fact the spinning performance was very poor and the yarns produced were of poor quality both in terms of their evenness and breaking tenacity. The fibre assembly efficiency was also low.

It was felt that the causes of this poor spinning performance should be ascertained. With this object in view, it was thought that an insight might be gained from a systematic study of the frictional characteristics of yarns in contact with these tubes.

A Shirley kinetic friction tester was used to find the values of the kinetic frictional coefficients( $\mu_y$ ) between a standard yarn and the different tube materials. (The standard yarn was a scoured, strong folded cotton yarn of 5/32 s cotton counts run at a speed of 60 yards per minute. The testing method used was the one recommended by the British Standards Institution[82] .

Table 6.3. shows the measured values of the kinetic frictional coefficients for the various tubes. It may be observed from this table that the values of $\mu_y$ between the standard yarn and polythene, polystyrene and pvc tubes were higher than those corresponding to the Perspex and glass tubes. In addition to the nature of the tube material, the roughness of the tube surface(which were perceptible to the eye as well as to the touch with polythene, polystyrene and pvc materials) might have also contributed its share towards an increase in the effective friction. The unevenness in tube surfaces were extrusion marks. Perhaps the deterioration in spinning performance was in some way related to the high frictional coefficient of the tubes.

The effect of the high values of $\mu_y$ was such as to tend to reduce the rotational speed of forming yarn. As will be discussed later in section 6.7. , the friction factor of air flow depends upon the magnitude of the roughness of the tube wall. A high degree of surface roughness of tube will, therefore, tend to retard the air flow rate and any retardation on air flow rate will be immediately reflected in the rotational speed of the yarn. A large, appreciable drop in yarn speed will tend to cause

(a) the fibre capture rate of forming yarn to be reduced; this is because the number of times the yarn intersects the fibre trajectory will tend to decrease with reduced yarn speed, and it is likely to result in a lowering of the fibre assembly efficiency which, in turn, will increase the waste losses,

(b) the effective twist insertion rate to be reduced, with the consequent result of a low insertion of twist per unit length; the yarn produced will, therefore, tend to be weak.

It may be assumed that the kinetic frictional values of the yarn are reflected in the behaviour of the fibre/tube combination (the fibre being of the same material as the yarn was composed of). Then the following emerges.

Any undue increase in frictional values between fibres and tube might adversely affect and retard the rate of fibre flow in the tube. Fibre retardation, even of a small magnitude, is most undesirable because this will tend to lead to an uneven telescoping of the fibres. Also there will be a tendency to crumple the fibres. The assembly of the crumpled fibres in the yarn will produce a weak, full and irregular product.

The following observations made during and after the tests seemed to testify to the validity of the above reasonings.

With the polythene, polystyrene and pvc tubes

(a) the rotational speeds of yarn were much lower than that corresponding to the Perspex tube,

(b) the values of twists/unit length in the yarns produced were relatively low,

(c) the waste losses incurred were high

and (d) the values of yarn irregularity were also high.

On the other hand, with the copper tube the frictional behaviour of yarn (and perhaps fibres too) was similar to that of Perspex and glass tubes. The frictional coefficient values of copper and Perspex tubes showed no appreciable difference. Therefore the reasoning applied to poor spinning performance of the tubes mentioned above did not seem to hold good for the copper tube and obviously, reasons had to be sought elsewhere.

With the copper tube, there was no evidence of the accumulation of electro-static charges and this was because of the electrical conductivity of the tube material. With non-metallic materials, charges do accumulate and it has been emphasized in section 8.5., that the presence of some static charges are essential for a good and efficient fibre assembly. Perhaps this point is best illustrated in the test carried out with the copper tube. The almost complete absence of static charges is, therefore, the most likely reason for the poor spinning performance of the copper tube.

6.2.7. Selection of the tube material

Spinning with Perspex and glass tubes yielded almost similar results. Their overall spinning performances were certainly much better than the rest of the tubes used in this experiment. So, of the different materials of tubes tested, the final selection of the tube material seemed to rest between glass and Perspex.

Perspex and glass share the following properties:-

(a) Transparency. This optical characteristic will not only permit clear viewing of yarn helix in the tube (and sometimes the fibre helix too) but also facilitates the taking of photographs.

(b) Both Perspex and glass are highly prone to develop static electrification. A controlled amount of static present in the tube is conducive to good performance of vortex spinning.

However Perspex scores over glass in the following ways:-

(a) Perspex is not as fragile as glass and it has a high strength to weight ratio.

(b) The ease with which Perspex can be machined to close limits with standard workshop machinery.

(c) The resilient nature of Perspex accomodates small interferences in fit, especially so necessary when fitting nozzles into tubes.

(d) Scratches, if made, can be readily removed by polishing and a high degree of surface finish can be obtained.

On the basis of the above considerations, it was decided that the material for tube (as well as for nozzle) should be Perspex.

## 6.3. STUDY OF THE NOZZLE DESIGN

The dimensions of the "standard" nozzle was given in section 6.1. An exploded view of the nozzle was shown in Fig. 6.1. Modifications were carried out on the different parameters of the nozzle in order to find an optimum nozzle design which could spin a reasonably regular and strong yarn with a high fibre assembly efficiency.

In all the modifications to the "standard" nozzle design, the inside diameter of the nozzle was kept unchanged at $\frac{3}{4}$ in. because it was felt that the nozzle bore dimension would behave almost in a similar manner to that of the tube dimension under spinning conditions. In the previous section dealing with tube design, it was found that a $\frac{3}{4}$ in. tube gave the best spinning performance when fibres of 1 in. to $1\frac{1}{2}$ in. staple length were used.

During the early stages of this research, the nozzles were made separately from tubes for the following reasons:-

(a) ease of manufacture

and (b) to facilitate the connection of a wide range of nozzles and tubes.

The assembly of nozzles and tubes of this design led to the presence of transition at the joint. It was not appreciated at the beginning of these experiments that nozzle-tube transition would greatly affect the spinning performance. Nozzles were always made in Perspex for the reasons mentioned earlier.

### 6.3.1. Nozzle-tube transition

Since the length of the nozzle was usually short, the forming yarn almost always extended beyond the nozzle and into the tube. In the preliminary investigations carried out on Hirway's nozzle, it was observed that a sudden transition from nozzle to tube possessed drawbacks as mentioned elsewhere in this chapter. The deleterious effects associated with sudden nozzle-tube transition were noticed at a fairly early stage of this research. The remedial action involved the machining of a smooth, divergent tapering at the transition between the nozzle and the tube itself. This modification improved the general spinning performance as mentioned in section 5.8.1. It was, therefore, incorporated as an essential design ingredient in the nozzle design. In this context, it may be mentioned that Perspex tubes of 1 in. bore (the "standard" tube) were generally used.

6.3.2. Fibre entries

6.3.2.1. Cylindrical tangential inlets

Having obtained fairly reasonable improvements in both yarn quality and fibre assembly efficiency with the smooth chamfering of the nozzle-tube transition, the next step in nozzle design was directed towards an improvement of the breaking tenacity of yarn. It was felt that increasing the strength of vortex flow might give the desired results. So, with this aim in view, an attempt was made to increase the number of tangential inlets in the nozzle with the condition that the total air consumption remained constant at a given air pressure within the tube. This condition was necessary to standardise the various tests and its was achieved by keeping the total area for air entry in all nozzles nearly the same as that of the standard nozzle. On this basis, the dimension of the different tangential inlets were calculated and then made to the nearest 64th of an inch in nozzles with 3, 4 and 6 entries. The dimensions of these nozzles were as follows:-

Nozzle A - 3 X $\frac{13}{64}$ in. diameter tangential inlets.

Nozzle B - 4 X $\frac{11}{64}$ in. diameter tangential inlets.

Nozzle C - 6 X $\frac{9}{64}$ in. diameter tangential inlets.

In the nozzles A, B and C the tangential inlets were placed respectively at 120°, 90°, and 60° apart from each other in a plane perpendicular to the tube axis. All these nozzles were provided with a $\frac{1}{8}$in. diameter axial holes for yarn withdrawal. It was found during spinning that fibres fed from a drafting system entered the vortex tube through more than one inlet at a time. This behaviour of fibre flow was particularly noticeable in nozzles B and C where the inlets were placed very close to each other. It was highly desirable to feed the fibres through only one inlet at a time because feeding fibres through many inlets produced uneven yarn. Perhaps the fitting of fibre guides might have solved the problem.

Table 6.4. shows the results from the four different nozzles. The spinning performance of the standard nozzle was undoubtedly the best of all. It was noticed that as the tangential inlet size was decreased, the spinning performances became correspondingly poorer. This created a suspicion that the actual intensity of the vortices in nozzles A, B and C were drastically affected and that instead of increasing in strength, as hoped for, they might have even reduced. This suspicion seemed to be true because the rotational speeds of a seed yarn introduced into the different nozzles showed a decrease as the number of tangential inlets was increased. The yarn speeds are shown in Table 6.5.

In an another attempt to increase the vortex intensity, the tangential inlets were arranged to lie in two parallel planes close to each other. These planes were perpendicular to the tube axis. In other words, the nozzle entries were grouped in two's. Thus in one particular form of this nozzle design, as shown in Fig. 6.5., there were two $\frac{1}{4}$ in. tangential inlets, a and b, spaced at $\frac{3}{8}$ in. from each other(measured from the hole centres) and another set of two similarly placed inlets, c and d, at $180^{\circ}$ from the previous set.

During spinning with the above nozzle, the fibre flow divided itself into two streams and entered the two inlets a and b. However, careful manipulation of the nozzle position with respect to feed point made the fibres enter through either one of the inlet holes. When the fibres were introduced through only the inlet b(which was placed farther away from the yarn withdrawal end), it was noticed that periodic slub formations occurred in the resultant yarn. This was possibly due to the presence of a secondary vortex created by air flowing through the inlets a and c - the main vortex was created by air flowing through the inlets b and d. A certain proportion of fibres fed into the inlet b were observed to move from the main vortex into the secondary vortex and attach at fairly frequent intervals to the forming yarn at the nozzle base end. However when fibres were introduced through only the inlet a, such slub formations were absent. This suggested that all fibres moved from the secondary vortex into the main vortex. The yarn evenness, though much improved in comparison with the former, was not really satisfactory. The yarn breaking tenacity did not show any

Tangential inlets ¼ in. dia.

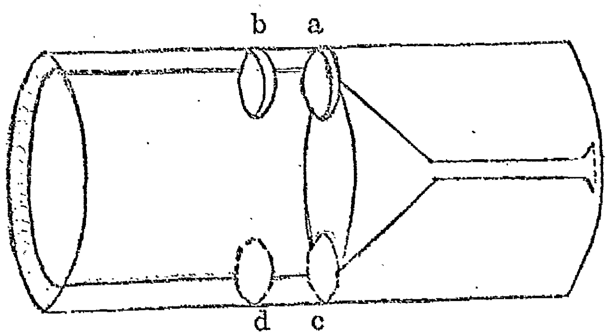



Fig. 6.5.

TWIN INLET NOZZLE

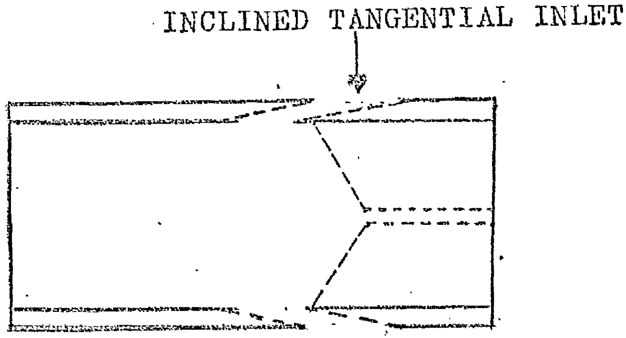



Fig. 6.6.

INCLINED TANGENTIAL INLET NOZZLE

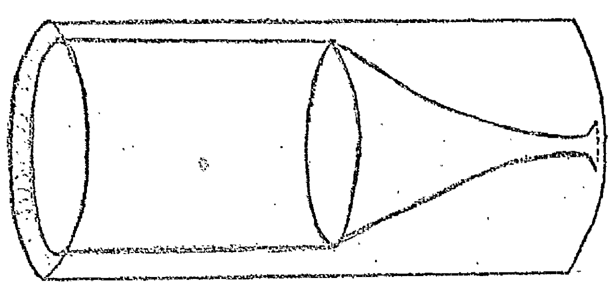


Fig. 6.7.

TRUMPET-SHAPED AXIAL INLET NOZZLE

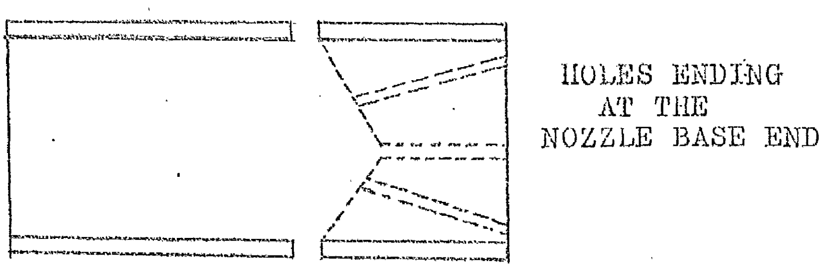



Fig. 6.8.

TANGENTIAL INLETS ON THE NOZZLE BASE END substantial improvement. Contrary to expectations, the general spinning performance with this modified positioning of inlets in no way, improved upon the performances of the standard nozzle. It is quite likely that the interaction of the two vortices in this nozzle might have tended to cause disturbances in the air vortex flow. The disturbed flows tended to produce poor quality yarns. Modifications to the nozzle design on the above lines were, therefore, discarded.

6.3.2.2. Inclined inlets

In all the above experiments, efforts were made to increase the radial component of vortex flow but the impact of such an influence on spinning was found to be generally negligible, and at times it was even detrimental. It was, therefore, thought that as a next step an attempt must be made to find out if an increase in the axial component of vortex flow did, in any way, assist in the formation of a good, strong yarn. With this objective in mind, two nozzles were made. One of them contained two inlets of $\frac{1}{4}$ in. diameter placed at 180° apart from each other and the other with 6 inlets of $\frac{9}{64}$ in. diameter placed at 60° from each other. Unlike any of the previous nozzles, the inlets of these nozzles were arranged to be inclined to the tube axis, as shown in Fig. 6.6.

Experiments performed with both these nozzles were very disappointing. The yarns spun were poor in terms of regularity and breaking tenacity. The fibre assembly efficiency was also quite low. Perhaps the inclination of the inlets was higher than necessary to give the desired effects. This might have tended unduly to increase the axial component of vortex flow at the expense of the radial component, it being remembered that the radial flow component is mainly responsible for imparting the rotary movement to the yarn, which is so essential to good spinning.

All the above modifications seemed to indicate that the solution for obtaining a yarn with improved breaking tenacity lay in an entirely different method of approach to that already discussed. In the meantime, till any such radical approach was discovered, it was felt that efforts should be concentrated on the other aspect of vortex spinning, that is, an improvement in fibre assembly efficiency(or, a reduction in fibre waste loss).

6.3.2.3. Slit inlets

In this exercise, an attempt was made to change the nozzle design with a view to enhance the fibre assembly efficiency. It was observed in the "standard" system that the fibres moved in a narrow helical path. Therefore the fibres tended to group themselves together in this narrow band as they flowed downstream. The forming yarn which swept the entire surface of the tube wall during its movement tended to gather the fibres flowing along the tube wall. Since the fibres tend to be confined to a narrow rope-like path, the forming yarn tended to attach only a certain proportion of the fibres from the surface of the fibre band. This probably explains the poor fibre assembly efficiency with the cylindrical fibre inlet.

It was, therefore, thought that wide helical band of fibres would tend to distribute the fibres more evenly on the tube wall and thus offer greater chances for the forming yarn to collect the fibres. An attempt in this direction was made by designing a nozzle with rectangular(slit) tangential inlets. In the first nozzle of this design, the fibre inlet was 1 in. long and 3/16 in. wide.

It was highly encouraging to find that with the use of this nozzle the fibre assembly efficiency showed a remarkable improvement. The fibre assembly efficiency touched a new record of 95%. With the cylindrical inlet nozzle, this figure was around 70%. Thus the slit inlet nozzle gave a worthwhile increase in the fibre assembly efficiency. The expected improvement in fibre assembly efficiency proved the hypothesis that the fibres were more or less evenly distributed along the tube surface when a slit inlet nozzle was used. This fibre distribution facilitated the attachment of fibres to the forming yarn.

The resultant yarn was very even because of the well organised and efficient fibre assembly during spinning but the yarn completely lacked strength as it was almost twistless. The breaking tenacity of this roving-like yarn was as low as about 2 gf/tex.

Thus the particular design dimension of this nozzle produced a considerable beneficial influence on fibre assembly efficiency but only at the cost of yarn breaking tenacity. Having achieved a tremendous advance in fibre assembly efficiecy, it was thought necessary to return to the problem of the yarn strength. The basic features of the slit inlet nozzle were more or less retained but slight modifications were made in order to study their effect on yarn quality and in particular the yarn breaking tenacity.

It was interesting to note that the design of the axial inlet in this nozzle played an important role as far as yarn strength was concerned. The axial inlet was trumpet-shaped and this is shown in Fig. 6.7. In the "standard" nozzle, this design was made to a taper of about 60°. Incorporation of this particular design of the "standard" nozzle in place of the trumpet-shaped design gave pronounced improvements in the spinning performance of the slit inlet nozzle. Even though the fibre assembly efficiency was reduced to about 85%, there was a marked improvement in yarn breaking tenacity which showed an increase of nearly 300% over the previous figure obtained. This was thought to be a fairly good compromise between fibre assembly efficiency and yarn strength because the fibre waste produced was recoverable for reprocessing. The conical axial hole in the nozzle base end formed, therefore, a basic design feature in all the subsequent nozzles. The design of the axial entry is discussed in some detail in section 6.3.3.

One other important point that emerged from the use of the slit inlet nozzle was that the resultant twist in the yarn was in a direction opposite to that of vortex flow. This nature of twisting is referred to in this work as "reversed" twisting. The presence of reversed twisting in a yarn indicated that the yarn was twisted, to a large extent, by its rolling action on the tube wall. Perhaps the better air distribution with the slit inlet nozzle encouraged the yarn to roll rather than to slide on the tube wall. For a fuller understanding of the mechanics involved in the reversed twisting, please refer to section 9.4.

For the same yarn speed, encouraging the yarn to roll rather than to slide will tend to insert more effective twist per unit length of yarn. Thus reversed twisting seemed to offer a vast potential for achieving a high rate of twist insertion. The slit inlet nozzle, therefore, appeared to present the much needed advance in design.

Alterations were made to the slit length which was reduced in steps of $\frac{1}{4}$ in. from 1 in. length. The other design dimensions were, however, kept the same as those of the "standard" nozzle. The main purpose of these alterations was to find if the yarn quality, especially its breaking tenacity, could be still further improved because there still existed a wide gap between the breaking tenacity values of vortex spun yarns and standard conventional yarns. The gap between the irregularity values was only narrow and hence it was not sought to further improve the evenness of the vortex yarns.

Three slit nozzles were designated as follows:-

Nozzle D - slit dimension: $\frac{3}{4}$ in. long and 3/16 in. wide.

Nozzle E - slit dimension: $\frac{1}{2}$ in. long and 3/16 in. wide.

Nozzle F - slit dimension: $\frac{1}{4}$ in. long and 3/16 in. wide.

Of the three nozzles mentioned above, the spinning performance of nozzle D outclassed those of the others including that of the original slit nozzle, as far as the yarn breaking tenacity values were concerned. The basic difference noticed in yarns spun from these nozzles was that while nozzle D produced reversed twisting, those of the nozzles E and F produced the same direction of twist in yarn as that of vortex flow. Since it was the intention to produce reversed twisting in yarns, work on nozzles E and F was dropped.

Torque measurements were conducted on nozzles with different dimensions of slit openings, both lengthwise and widthwise, to find out an optimum slit design. This is given in Chapter 12.

The width of the slit inlets was varied in steps of 1/16 in., from widths of 1/16 in. to $\frac{3}{8}$ in. The slit length was maintained constant at 1 in. in all the nozzles. The nozzle slit dimensions of the different nozzles are given below:-

<u>slit dimension</u>

Nozzle G - 1 in. long and 1/16 in. wide.

Nozzle H - 1 in. long and 1/8 in. wide.

Nozzle I - 1 in. long and 3/16 in. wide.

Nozzle J - 1 in. long and 1/4 in. wide.

Nozzle K - 1 in. long and 5/16 in. wide.

Nozzle L - 1 in. long and 3/8 in. wide.

Nozzles with slit widths below 3/16 in. tended to produce soft and weak yarns. Those above $\frac{1}{4}$ in. tended to make the yarn helix unstable and because of this, the spinning performances were poor. Nozzles with 3/16 in. and $\frac{1}{4}$ in. slit widths gave almost identical results. Of these two, the final choice of slit width was decided by the air consumption values. The 3/16 in. width inlet nozzle was, therefore, the obvious choice.

### 6.3.2.4. Convergent inlets

All the slit nozzles were constructed with fibre guides, of about a fibre length, and their dimensions were the same as the slit dimensions employed in any particular nozzle. It was felt that a convergent fibre inlet might present the fibres in a more straightened manner than the rectangular inlets. This idea was based on the findings of the experiments conducted with convergent taper tubes and mentioned in the later parts of this chapter.

The stripping efficiency is defined[10] as:-

$$\frac{\text{wt. of fibre fed to card in any given time}}{\text{wt. of yarn plus waste generated in the same time}} \times 100\%$$

Fibres introduced into a convergent slit inlet will tend to be accelerated. The leading end of a fibre will tend to be slightly accelerated with respect to the trailing end. This will tend to impose a straightening action on the fibres. and well-oriented fibres will tend to lead to the production of good quality yarn.

On a comparison of the convergent inlet with a convergent taper tube, it might be noted that with a convergent tube the straightening action on fibres would tend to occur only after the fibres entered the tube region. It is, therefore, quite likely that some fibres may become attached to the yarn even before they are subjected to the straightening action. The convergent inlet seems to score over the convergent taperin this respect.

Experiments performed with convergent entries did show some improvements on yarn quality but these were not radical. Perhaps some other factors, such as, solid friction between fibres and tube wall, static charges etc., might have caused the well-oriented fibres to lose their configurations during their flow in the tube.

When the convergent fibre inlet was applied to a card cylinder, the stripping efficiency (as defined by Chandarana[10], see p.204(a)) was considerably reduced because of the reduced suction.

6.3.2.5. Length of fibre inlet (fibre guide)

As mentioned in section 5.3.1.3., the optimum length of a fibre inlet was found experimentally to be equal to the staple length of the fibres used for spinning. Too short a length allowed the fibres still gripped by the feed roller nip to foul against the rotating yarn inside the tube. This led to false twisting because of the absence of any break in the fibre flow. On the other hand, when long lengths of fibre inlets, say, 3½ in. long, were used (when spinning 1½ in. staple length fibres), there were large irregularities in the final yarn. Perhaps the cause of this irregularity might be explained in the following way:-

In an ideal case of fibre feed, the fibres would be fed one by one with a pre-determined break in their flow, but in practice, however, with the drafting apparatus used for fibre feed some of the fibres were found to move as individuals while others travelled in tufts. The frictional force acting on a fibre due to its sliding on the inlet surface would tend to retard the fibre movement. When fibres are in tuft form, it would be quite likely that not all the fibres would come in contact with the fibre guide surface. Therefore the movement of individual fibres and tufts would tend to vary. This would tend to lead to haphazard movement in the fibre flow. This movement is thought to be somewhat similar to drafting waves experienced in conventional drafting. The attachment of these irregularly moving masses of fibres would tend to result in increased yarn irregularity.

### 6.3.3. Design of axial entry

#### 6.3.3.1. Shape

As already mentioned in section 6.3.2.3., the design of the nozzle base end influenced both the yarn quality and the fibre assembly efficiency. A smooth trumpet-shaped axial hole gave high fibre assembly efficiency and low twist in the yarn. On the other hand, a conical shape with a taper angle of about 60° improved the twists/unit length of yarn but this was at the expense of some reduction in fibre asssembly efficiency.

In all the nozzles, the axial hole was used for the purpose of yarn withdrawal but it should not be forgotten that this hole permitted air to flow into the vortex tube. The trumpet-shaped design will tend to act as a diffuser and so the effect of air flowing through it might be negligible on the main air vortex flow. On the other hand, with a quickly tapering axial inlet, the air flowing through it will tend to impose a considerable impact on the main vortex. The effect of this will be to increase the axial component of vortex flow, and this might account for the increased fibre loss(or, reduced fibre assembly efficiency). Moreover the influence of the axial component will be such as to tend to open out the yarn helix and this will increase the tendency for the yarn to roll on the tube wall. This probably explains the high twist rate.

The effect of different taper angles on spinning was not studied but the taper angle of the drills normally used for cutting nozzle bores produced acceptable tapers conducive to efficient vortex spinning.

<u>6.3.3.2. Diameter</u>

The amount of air flowing through the axial hole will tend to increase with the axial hole size. This air flow, being mainly axial, will tend to add to the axial component of vortex flow. The increased axial component, within certain limits, will tend to produce a yarn with a reasonable amount of twist in it. ~~Since the air flow rate through the vortex tube was assumed to remain constant,~~ Any increase in air flow rate passing through the axial hole is likely to involve a proportionate decrease in the air flow rate through the tangential inlets. This reduction of flow rates through the tangential inlets will tend to decrease the radial component of air vortex flow. This will eventually be reflected in a reduced vortex speed and, therefore, a decreased yarn speed.

The diameter of the axial hole was increased from 1/16 in. in steps of 1/16 in. to a maximum diameter of $\frac{3}{8}$ in. Experiments with nozzles of different axial hole dimensions showed that for medium count yarns, upto 20s cotton counts, the optimum size of axial hole was $\frac{1}{4}$ in. Finer yarns tended to break within the tube under these conditions. Between about 20s and 40s cotton counts, an axial hole dimension of $\frac{1}{8}$ in. was found suitable. Counts finer than 40s c.c. were not spun and hence further limits in this direction are not known.

Axial holes of a size larger than $\frac{1}{4}$ in. tended to create violent disturbances in the vortex flow and this caused the forming yarn helix to become unstable. Yarns of poor strength were produced and the finer counts of yarn tended to break due to the high axial force exerted on them.

6.3.3.3. Tangential inlets on the nozzle base end

A short length of forming yarn lying near the base end of the nozzle is directly acted upon by the incoming air flowing through the tangential inlets. This yarn is referred to as the "drive element" and, as the name implies, is mainly responsible for imparting a rotary movement to the whole of the forming yarn. Any increase to the driving torque imparted to the drive element would tend to add to the total torque already applied to the yarn. This increase in total torque would tend to lead to an increase in the effective twist insertion rate in the final yarn. A stronger yarn would, therefore, be obtained.

It was felt that an increase in driving torque might be brought about by the action of a reasonably strong subsidiary vortex on the drive element. Six tangential holes, placed equi-distant from each other, were made on the conical end of the nozzle, as shown in Fig. 6.8.* The direction of these holes were coincident with the direction of the main tangential inlets in the nozzle. The purpose of this arrangement was to produce an additional subsidiary vortex rotating in the same direction as the main vortex so that an additional torque should be produced.

The breaking tenacity of yarn produced with this nozzle showed only a marginal improvement over the standard. Unfortunately the yarn regularity was very poor and there was a low fibre assembly efficiency. Perhaps the poor spinning performance of the modified nozzle might be ascribed to the deleterious effects of the interaction between the two or more vortices. This interaction might possibly be reduced, or even avoided, by the use of a supplementary nozzle fitted to the yarn exit end of the spinning tube. These supplementary nozzles which are called the "additional twisters" are dealt with in the next section.

### 6.3.3.4. Additional twisters.

Various means to increase the driving torque to the yarn were tried. These were of the external type and consisted essentially of "additional twisters". The main purpose of these twisters was to increase the net twist insertions in the final yarn. The twister rotated the yarn soon after it emerged from the spinning tube. Various types of twisters were experimented upon.

* p.198

Yarns produced with these twisters did not show any remarkable improvement either in their twist gain or in their strength. Most of these additional twisters have been dealt with by Chandarana[10]. So it is considered unnecessary to go further into the experimental set-up of these twisters. Nevertheless it is relevant to consider briefly the mechanism of additional twisting and the possible reasons for the ineffectiveness of the twisters.

In order that the twister should carry out its function effectively, it is considered essential that the following conditions should be fulfilled:-

(a) Initially, the yarn rotational speed in twister should be higher than that in the spinning tube.

(b) If the additional twist inserted in the yarn is to be true rather than false, it is necessary that the twist gained by the yarn should also flow to the open end of yarn lying in the tube.

(c) The direction of twist imparted by the twister to the yarn should be such that the twist is added to that already inserted by the spinning tube. Both the main nozzle and the twister can produce twist either by sliding or by rolling of the yarn on the tube and this affects the direction of twist. This factor must be taken into account when applying this condition.

These twisters were worked by the air suction exerted through the yarn exit hole of the spinning tube. The amount of air flowing through this exit hole is usually only a fraction of the total air flow in the spinning tube. (With a slit nozzle having two tangential inlets of $\frac{3}{4}$ in. X 3/16 in. dimension and yarn exit hole of $\frac{1}{4}$ in. the quantity of air flowing through the exit hole will be approximately one-seventh of that passing through the tangential inlets). The air flow through the twister could only be increased by opening out this exit hole. The maximum opening was limited to $\frac{1}{4}$ in. diameter due to the reasons mentioned in section 6.3.3.2. and because of this, the air flow in the twister was also limited. The air flow rate determined, to a large extent, the speed of yarn rotation and the air flow rate in the additional twister was small because of the limited air flow. It was found with a stroboscope that the yarn speed in the twister was small in comparison with the yarn speed in the spinning tube. Thus condition (a) was not fulfilled in any of the pneumatic additional twisters.

In the process of additional twisting, if there is loss of additional twist at the open end of yarn, then the downstream portion of yarn will be weakened. Thus any frictional drag will reduce the twist loss to the open end and this will tend to weaken the yarn actually in the tube. Beyond a certain point, the forming yarn end would break giving either very poor yarn or a complete breakdown in spinning. It should be also noted that if the angular velocities of the yarn due to the additional twisting and that at the open end are equal, then there can be no twist in the yarn.

It is, however, believed, that if proper means could only be found to rotate the yarn in the twister at speeds much higher than those normally existing in the spinning tube, then the use of "additional twisters" is likely to produce the desired results in yarn. To keep this process simple, it would be preferable to work the twister by pneumatic means alone. In a system employing an efficient "additional twister", it is conceivable that the air vortex spinner will merely act as a fibre assembly device and that the twister will be mainly responsible for introducing the required twist into yarn.

It is considered relevant to include the following for the sake of completion of this particular subject of twisters. It was reported[28] that with a high speed mechanically operated twister(similar to false twisting elements used in bulking machines) placed near the yarn exit, a twist insertion rate of upto 18,000 turns per minute and a yarn withdrawal speed of about 2,000 in./min were attained. This achievement is quite commendable but it is felt that the very purpose of using an air vortex spinner - that of extreme simplicity and freedom from mechanically moving parts - is defeated in this process.

6.3.4. Inclined tangential inlets

Purely as a matter of interest, it was thought to include a few more non-standard nozzle and tube designs.

The first in the list was "inclined tangential inlet". In this nozzle, the inlets were inclined to form an acute angle towards the yarn exit end of the tube. Fig. 6.9. shows the slit inlet design of the nozzle.

A modification made to this nozzle involved the use of a tube of a slighltly smaller outside diameter than the nozzle bore. This tube was mounted on bearings placed at the axial end of the nozzle. The small tube was provided with a number of tangential slots to coincide with the main nozzle inlets. Air flowing through the nozzle inlets caused the small tube to rotate.

The spinning performance of this inclined inlet nozzle with and without modifications mentioned above was not commendable and hence work on these lines was discontinued.

6.3.5. Helically-holed tube

In another design aspect, this time concerned with the tube, a series of slightly inclined holes was drilled in a helical manner on the tube. This whole helix was made almost similar to the forming yarn helix inside the tube.

It was known from the study of the air vortex flow in a tube(section 7.2.11.1.), that the maximum air velocity lies in a radial region slightly away from the tube wall. This was due to the boundary layer effect in turbulent air flow. It was thought that if the yarn were made to lie in this radial region, then perhaps the twist insertion rate might be increased. The main purpose of the series of holes was to take the yarn slightly away from the tube wall and thus make it lie in the high velocity air region.

Experiments made with this arrangement did not produce satisfactory results and, in fact, spinning was much inferior to that with a tube without holes. This was because the fibres and yarn flowed along different radial surfaces inside the tube and so a proper fibre assembly was not achieved. Perhaps the holes also caused disturbances to vortex and fibre flows.

6.3.6. Spinning tube fabrication

A spinning tube was usually made by an assembly of the different component parts, such as, tangential inlet guides,yarn exit end block and the tube. The spinning tube fabricated in this manner seemed to possess certain drawbacks.

Since a large proportion of the fibres move in bodily contact with the fibre guide and tube surface, any minor obstructions in the path of fibre flow would tend to impede the fibre flow and affect the nature of fibre orientation. The fibres might become bent, hooked, buckled etc. and these deformed configurations of the fibres would be detrimental to the formation of a good yarn.

The short length of the yarn near the drive element rubs against the tube wall. The presence of any protrusions at the nozzle inlet and the various junctions would tend to retard the yarn speed. Moreover the abrading action on the yarn due to these protrusions would tend to result in yarn breaks inside the tube.

There were frequent yarn breakages within the tube when a fabricated spinning tube was used. Even the fibre guides fabricated to make long lengths possible seemed to introduce irregularities in fibre flow.

All these detrimental effects could be possibly avoided by the use of a spinning tube made out of one Perspex block. However this method of spinning tube construction is more difficult and expensive than fabrication and so was not attempted.

# CHAPTER 6

## PART II

### 6.4. INTRODUCTION

Firstly, a brief introduction to the different types of air flows normally encountered in tubes is given. This is followed by a study of the behaviour of air flow through various types of tube transitions. Finally the knowledge gained from these flow transitions is applied to fibre and yarn movements in vortex spinning under similar conditions. Experiments performed with different forms of flow transition inaspinning tube are also included.

### 6.5. LAMINAR AND TURBULENT FLOW

There are two different types of fluid flow. viz., (a) laminar and (b) turbulent.

In laminar flow, fluid elements move along smooth paths in laminae or layers with one layer gliding smoothly over an adjacent layer. A laminar flow tends to occur usually under the conditions of low flow velocity, small flow passages and relatively high fluid viscosity (i.e., at low Reynolds numbers). The laminar flow in a horizontal circular pipe has a parabolic velocity distribution.

A laminar flow is not stable under high Reynolds numbers and the flow breaks down into the turbulent regime. High shear stresses exist between layers of fluid particles and these tend to cause an irregular or erratic motion of the fluid particles. The super-imposition of these transverse non-steady motions give rise to turbulence in the flow.

Let $U_m$ be the velocity at the centre of a tube,

$U$ be the velocity at a distance $y$ from the wall and r be the tube radius.

Then the velocity distribution for turbulent flow[83] in smooth tubes upto Reynolds numbers of about 100,000 is given by

$$U = U_m \left( \frac{y}{r} \right)^{1/7} .$$

It will be seen in the next section that turbulent flow is normally encountered in vortex spinning. That is why it is only appropriate to consider turbulent rather than laminar flow.

Having mentioned Reynolds numbers in the previous lines, it is relevant and indeed necessary to define it. Reynolds number, usually denoted Re, is commonly met with in most problems of fluid dynamics.

## 6.6. REYNOLDS NUMBER

Reynolds number can be used as a dimensionless group to describe the magnitude and nature of a flow. It can also be employed as a means of establishing dynamic similarity between flows.

Let l be a characteristic length(such as, the diameter or length of a body or the internal diameter of a tube),

$\rho$ be the density of a fluid passing through a tube,

$\mu$ be its viscosity,

$\nu$ be the dynamic (or kinematic) viscosity of the fluid, where

$$\text{dynamic viscosity} = \frac{\text{coefficient of molecular viscosity}}{\text{density of fluid}}$$

V be the average velocity of flow in the tube

and Re be the Reynolds number.

Reynolds number may be defined as a ratio of inertial to viscous forces acting on a body.

By definition, $Re = \frac{\rho . V . l}{\mu} = \frac{V . l}{\nu}$ in consistent units.

A relatively small value of Re indicates that viscous forces predominate but a larger value of Re indicates that inertial forces predominate.

Experiments[83] have shown that for values of Re less than 2,000, the flow is laminar. In this case, the viscous forces are predominant. Turbulent flow normally exists at values of Re over 3,000 and here the inertial forces predominate. In the transition region with Re values between 2,000 and 3,000, both laminar and turbulent flows may be present.

Under normal conditions of vortex spinning, the measured air velocity flowing through a tube of 1 in. bore, fitted with a nozzle having 2 X $\frac{1}{4}$ in. inlet ports at an air pressure of -25 in. of water column is about 40 ft/sec.

The value [84] of $\rho$ for air at the atmospheric pressure(29.92 in.) and 20° C is $1.61 \times 10^{-4}$ ft$^2$/sec.

$$\text{Therefore, } Re = \frac{40 \times 1/12}{1.61 \times 10^{-4}}$$

$$= 20,683.$$

Hence the air flow in a vortex tube is turbulent.

## 6.7. FRICTION LOSSES IN AIR FLOWS IN TUBES

When air flows in a tube, friction losses occur and this depends upon many factors. In turbulent flow[85], the friction loss is a function of viscosity, density and velocity of the fluid, the length and diameter of the tube, Reynolds number and the degree of roughness of the tube wall.

The influence of surface roughness in the tube is not significant below a certain Reynolds number. This is because the elements producing the roughness are small in comparison with the thickness of the laminar sub-layers.

At higher Reynolds numbers, i.e., for a fully developed turbulent flow, if the height of the roughness elements is large in comparison with the laminar sub-layer, then eddies will be formed behind the peaks of these elements. The eddies generated increase in their intensity as the size of the elements increases and, therefore, the friction factor depends upon the type of roughness. If the surface roughness is very slight, as in the case of glass tubing or Perspex pipes, the friction factor is a function of the Reynolds number only.

The following analytical relation for flow above Re=4,000 for smooth pipes is given[83] by

$$\frac{1}{\sqrt{f}} = 2 \log_{10}(Re\sqrt{f}) - 0.8, \text{ where}$$

f is the friction factor.

## 6.8. EFFECT OF TUBE TRANSITION ON AIR FLOW

The tube transitions may be broadly divided into three categories. They are as follows:-

(a) changes in cross-section of tubes,

(b) bends in tubes

and (c) branches in tubes.

Generally, irreversible pressure losses occur in all tube transitions. In long tubes, these losses may be small in comparison with skin friction losses but in short tubes, especially when the velocity head is considerable, the losses may assume major proportions. These losses involve a wasteful expenditure of energy as far as air flow is concerned. Perhaps these losses may be associated with the poor performance of the vortex spinning apparatus, in which case, efforts should be made to reduce or eliminate them as far as possible. A firm understanding of the causes leading to these losses will perhaps enable the redesign of the vortex spinning system so that these unwanted losses may be reduced. From this point of view, a study of the effect of the nature of tube transitions on air flow is considered important.

6.8.1. Cross-sectional changes in tube transition

The changes made in the cross-sectional area of tubes at the transition region may be classified into three following parts:-

(a) sudden enlargement,

(b) sudden contraction

and (c) gradual taper transition.

6.8.1.1. Sudden enlargement in tube transition

Consider a sudden enlargement in tube transition as shown in Fig. 6.10. (In vortex spinning, this sudden enlargement was obtained when two square-edged tubes of different diameters were sleeved one on top of the other).

In the small tube,

let $V_1$ be the average velocity of air flow,

$p_1$ be the pressure of air

and $A_1$ be the cross-sectional area.

In the large tube,

let $V_2$ be the average velocity of air flow,

$p_2$ be the pressure of air

and $A_2$ be the cross-sectional area.

When air flows through the sudden enlargement, the flow patterns will tend to follow approximately the streamlines represented in Fig. 6.10. The air stream which fills the entire cross-sectional area of the small tube tends to issue as a cylindrical jet into the large tube. This jet is slowed down by the eddying and mixing with the air "pocket" formed at the region AB of the sudden enlargement and then gradually diverges

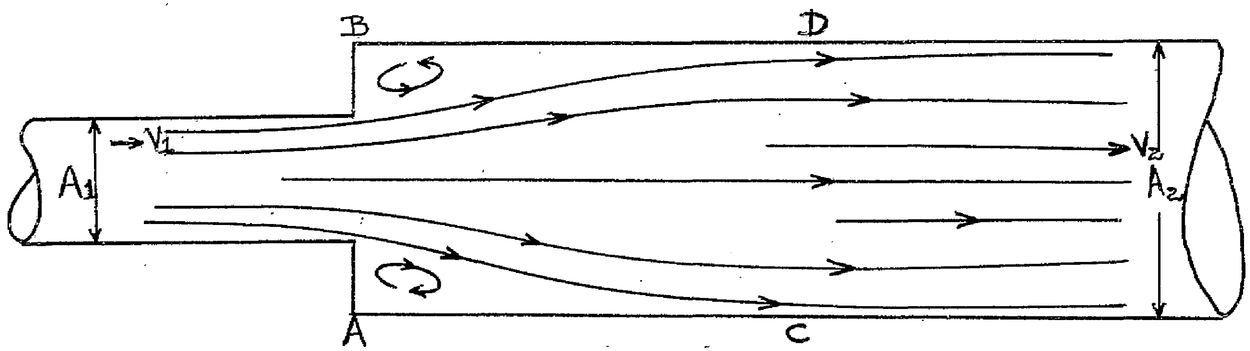



Fig. 6.10

AIR FLOW THROUGH A SUDDEN ENLARGEMENT IN TUBE TRANSITION to fill the whole cross-section of the large tube at some distance downstream, represented in the Fig. 6.10 by the line CD. A certain amount of energy is dissipated as heat in the damping of the turbulent eddies by internal friction and, therefore, the total pressure in the large tube falls. Thus a cumulative loss in the pressure of the system occurs.

The velocity $V_1$ of air flow in the small tube gradually decreases to a value $V_2$ at the section CD of the large tube.

Neglecting change in potential energy, the general energy equation gives the lost head $h_o$ in the form

$$h_o = \left(\frac{p_1}{\gamma} + \frac{V_1^2}{2g}\right) - \left(\frac{p_2}{\gamma} + \frac{V_2^2}{2g}\right), \text{ where}$$

$\gamma$ = the specific weight of air

and $g$ = the acceleration due to gravity.

Now, consider the forces acting on air between sections AB and CD.

Ignore shear forces acting along the wall and assume that $p_1$ acts directly inside the enlarged area, i.e., over the area AB. Then the net force in the direction of flow decelerating the air flow is $(p_2 - p_1)A_2$.

Force = mass X acceleration.

The mass rate of flow is $\frac{A_2 V_2 \gamma}{g}$.

The velocity of the mass $\frac{A_2 V_2 \gamma}{g}$ is reduced from $V_1$ to $V_2$ in each unit of time.

$$\text{Therefore, } (p_2 - p_1)A_2 = \frac{A_2 V_2 \gamma}{g}(V_1 - V_2)$$

$$(p_2 - p_1) = \frac{V_2 \gamma}{g}(V_1 - V_2)$$

Substituting the value of $(p_2 - p_1)$ in the previous equation,

$$h_o = \frac{1}{2g}(V_1 - V_2)^2 .$$

Thus, in the case of sudden enlargement, the head lost is proportional to the square of the difference in air flow velocities in the two tubes.

Since these losses are wasteful, the use of sudden enlargement should be avoided as far as possible.

6.8.1.2. Sudden contraction in tube transition

At the region where air enters a sudden contraction, i.e., from a large tube to a small tube, as shown in Fig. 6.11., the air streamlines tend to contract. After the air flow enters the small tube, the air streamlines reach a minimum cross-section(vena contracta) and then they expand downstream and ultimately assume a uniform flow over the entire cross-section of the small tube.

The losses in a sudden contraction are mainly in the region of vena contracta. Vortices are set up between the main streams and the tube wall near the vena contracta and energy is lost in keeping these in rotation.

A lost head $h_o$ is often expressed in a simple manner as equivalent to $K(\frac{V^2}{2g})$, where K is a dimensionless loss coefficient and V is some characteristic velocity.

In the case of a sudden contraction, as illustrated in Fig. 6.11., where

$V_1$ is the velocity of air in the large tube with cross-sectional area $A_1$

and $V_2$ is the velocity of air in the small tube with cross-sectional area $A_2$,

the lost head is represented by $h_o = K_1 \frac{V_1^2}{2g}$, where $K_1$ is a dimensionless loss coefficient.

The values of $K_1$ for a sudden contraction[86] in tube transition are given in Appendix B.6.1.

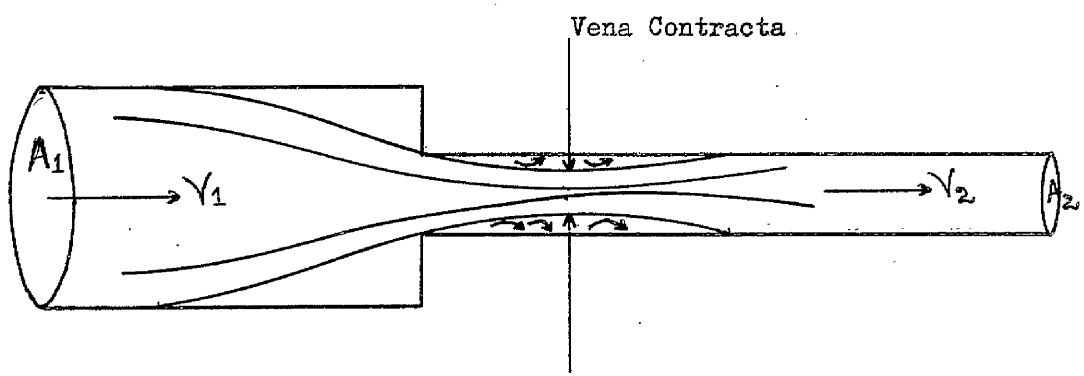



Fig. 6.11

AIR FLOW THROUGH A SUDDEN CONTRACTION IN TUBE TRANSITION

In addition to the above, the type of tube entrance also affects the loss coefficient.

With a sharp tube entrances(87), as shown in Fig. 6.12. (a) and (b),

(a) when the tube ends flush well with each other, the loss coefficient is approximately 0.5

and (b) when the tube protrudes, the loss coefficient is 0.8 to 1.0 .

For a well-rounded tube entrance(87), as shown in Fig. 6.12. (c), the loss coefficient is about 0.05.

During a sudden contraction of the tube cross-section, a flow energy loss exists although it is somewhat smaller than that for a sudden pipe expansion of comparable size.

From the foregoing, it is evident that in practice sudden contractions in tube transition should be also avoided.

6.8.3. Tapered transitions

The flow losses experienced in sudden transitions can be greatly reduced by the introduction of a gradually tapered transition from one diameter to the other. The reduction of losses is largely due to the elimination of the eddies. The loss coefficient K depends upon the taper angle $\theta$ and the area ratio $\frac{A_2}{A_1}$.

Investigations(88) carried out with tapered enlargements show that

(a) the taper angle $\theta$ which gives a maximum efficiency is about $6^\circ$ to $8^\circ$ for a conical(circular) tube

and (b) for a given rate of expansion $(\frac{A_2}{A_1})$, the circular cross-section gives the best efficiency.

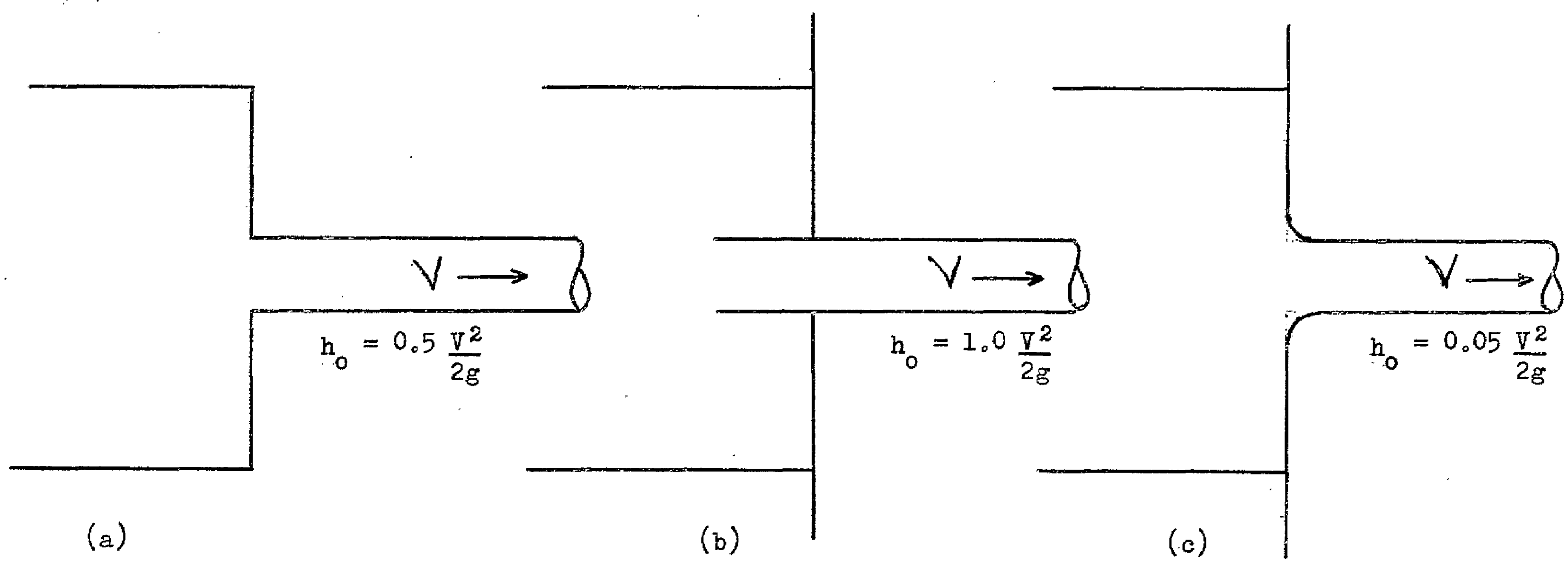



Fig. 6.12

PRESSURE LOSSES DUE TO TUBE ENTRANCES

In a conical tube with gradual expansion (known as a diffuser), the pressure rises in the direction of flow because the increase in diameter reduces the velocity. The slower fluid elements near the tube wall tend to stagnate and to disturb the ideal pressure rise. This results in an energy loss. If the cone angle is too large($> 8^\circ$), "separation" of the flow from the wall also occurs and this causes additional energy losses.

On the other hand, with a convergent section flow losses are small because the pressure gradient is in the same direction as the flow. Fluid elements near the tube wall are continually accelerated by the pressure gradient and, therefore, the flow is maintained even in close proximity of the tube wall.

In general, an acceleration of real fluids tends to be an efficient process and deceleration an inefficient one.

6.8.2. Bends in tubes

The effect of these bends is usually to increase the degradation of energy locally. The loss of head in bends is usually caused by the increased turbulence created from the change in the direction of air flow. The change in flow direction tends to cause an increase in pressure along the outside of the bend and a decrease along the inside.

The tube ends may be either (a) sudden or abrupt or (b) smooth or gentle.

6.8.2.1. Sudden bends in tubes

With an abrupt bend in a tube, as in the case of a sharp elbow( $90^\circ$ bend), the air streamlines adjacent to the tube wall at the inside of the bend will tend to break away from the tube surface and this, in turn, will tend to result in a large eddy formation downstream. These eddies cause a sudden downward step in the energy gradient line, in addition to the gradient caused by the normal tube friction.

6.8.2.2. Smooth bend in tube

If the bend is gentle, no substantial break-away of the streamlines from the tube wall occurs. However, the velocity profile becomes distorted due to the interaction of the boundary layer and radial pressure gradient. A secondary flow is produced at the bend and the effect of this flow persists until the flow reaches a certain distance downstream along the tube.

Losses in bends depend upon the ratio $\frac{R}{D}$, where D is the diameter of the tube and R is the radius of curvature of the bend. They are independent of the Reynolds number. The magnitude of the losses depend, to a large extent, on the sharpness of the curvature of the bend.

## 6.9. APPLICATION OF THE KNOWLEDGE OF AIR FLOW IN TUBE TRANSITION TO VORTEX SPINNING

### 6.9.1. Introduction

In some of Gotzfried's devices and in Hirway's spinner too, there were flow transitions in the spinning tube. In the present research, the early design of the spinner also contained transition in the nozzle-tube assembly. The importance of these flow transitions was not fully appreciated then but it was later realised that a knowledge gained from a study of air flow over tube transitions will be helpful.

It is known that in vortex spinning the air follows roughly in a helical path on the tube surface. For the reasons mentioned in section 7.2.11.1., the pitch of this helix tends to gradually increase in the direction of air flow. The helical flow at any point may be resolved into its circumferential and axial components. The circumferential component tends to predominate near the nozzle region but as the flow moves downstream the circumferential component will tend to decay in a gradual manner and the helix changes. At infinite lengths, it may be fair to assume that the flow will become completely axial.

However, for all the practical purposes, with the spinning tubes of about 2 foot long generally used in the experiments, the helical flow angle did not vary greatly. This was evident from the observations made when fibres were introduced to follow freely the air flow. It was noticed that the fibres moved in a reasonably closed pitch helical path (the fibres tend to move in the same path as that of air but at a relatively low speed).

In the discussions mentioned in section 6.8.1.1., the air was assumed to flow in streamlines parallel to the axis before it reached the tube transition region. In the air vortex spinning tube, the flow path was helical before its entry into any tube transition but in either case subsidiary vortices could be formed or streamlines could be distorted. It is also essential to bear in mind that in a practical system the fibres follow a helical path on the tube wall and any sudden changes in the streamlines can cause fibres to become entangled and deformed.

Spinning was tried with different types of tube transition and the observations made during these tests are included below. An assumption was made in the following discussions that the length of the forming yarn remained almost constant throughout spinning.

## 6.9.2. Effect of sudden enlargement in tube transition on vortex spinning

In the following experiments, a nozzle was mounted at one end of a small tube A. The other end of this tube was sleeved into a large tube B (sometimes, with the help of stepped rings) which was connected to a suction pump. Fig. 6.13.(a) shows this arrangement.

It was observed during spinning that the length of the small tube played an important role in deciding whether the sudden enlargement was conducive to spinning or not.

The general spinning performance with a reasonably long length of tube A which accomodated the forming yarn well inside its length compared reasonably well with that of a spinning tube of the same bore size as tube A but without the sudden enlargement. However it was noticed that there was a substantial pressure loss in the former arrangement. This was quite expected. This pressure loss resulted in a considerable drop in the rotational speed of yarn inside the small tube and because of this, the yarn quality suffered to some extent. The net effect of the pressure loss would be a reduction of the effective utilisation of the air flow. In this connection, it is well to remember that it costs money to make the air flow and it is, therefore, essential that air flow should be well utilised to yield maximum returns. In other words, an ineffective utilisation of air flow would finally result in increased power costs.

Some fibres were observed to rotate in the transition region CD for short intervals of time and then periodically move in the form of small tufts to the suction pump. The nature of this fibre movement indicated the presence of a subsidiary vortex at the transition zone. Perhaps the energy

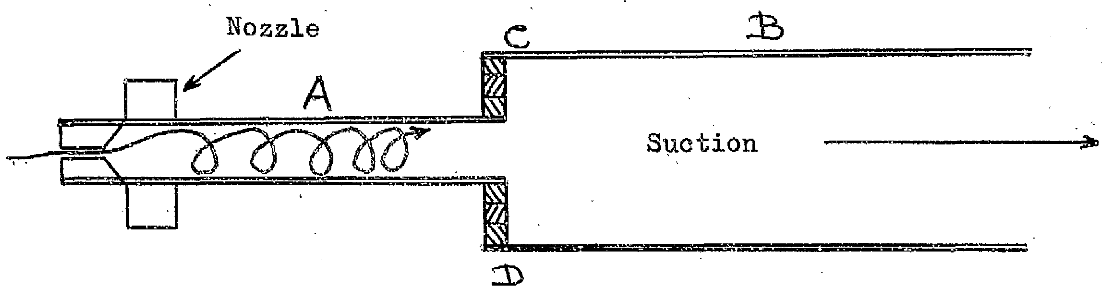



Fig. 6.13(a)

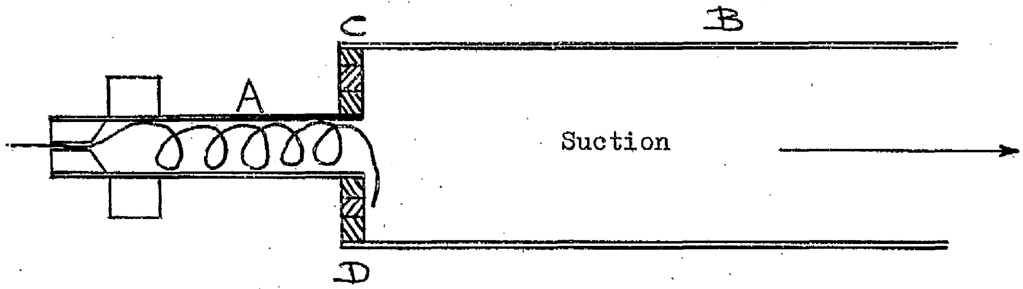



Fig. 6.13(b)

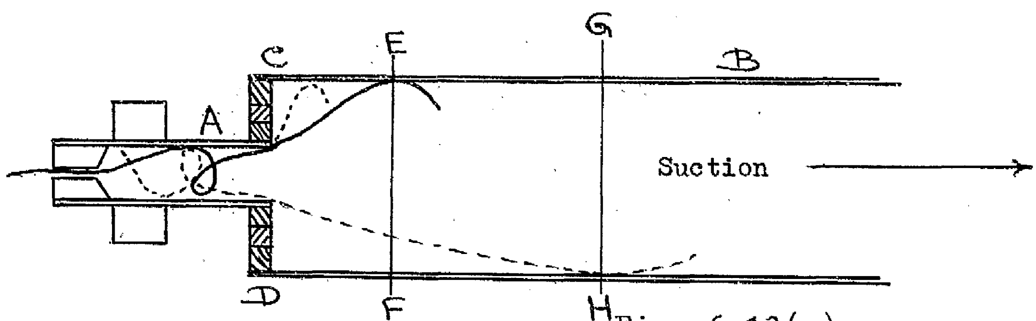



Fig. 6.13(c)

Fig. 6.13.

VORTEX SPINNER WITH SUDDEN ENLARGEMENT IN TUBE TRANSITION lost as pressure losses in the system was utilised for driving the subsidiary vortices.

In the next test, tube A was shortened to an extent such that only a short length of the yarn tail protruded out into the large tube. With this arrangement shown in Fig. 6.13.(b), it was noticed with the help of a stroboscope that the yarn tail during its movement laid itself almost squarely with the tube edge. A whirring noise was produced due to the rubbing action of the yarn tail with the square edge of the tube A. The yarn tail tended to snarl at its end.

When a still shorter length of tube A was used, it was found that the yarn helix became unstable. The reason for this instability might be traced to the fact that a certain length of forming yarn lying nearing the region CD was taken at infrequent time intervals into the subsidiary vortex and this might have affected the smooth helical flow of yarn. With the arrangement mentioned above and shown in Fig. 6.13.(c), the general spinning performance was poor and the yarn regularity was far from good. The cause for the large irregularity might be attributed to the small proportion of fibres which was infrequently caught up in the subsidiary vortex motion and conglomerated into tufts most of which eventually attached themselves to the yarn forming slubs while the rest found their way into the waste collection bag. Moreover the majority of fibres during their flight in the transition zone tended to follow closely the air path and, in so doing, tended to land on the surface of the large tube at a position GH, as shown in Fig. 6.13.(c). On the other hand, the yarn anchored at the tube axis (i.e., the yarn withdrawal hole) tended to follow a different path to that of the fibres and usually tended to land at an earlier position represented by EF. The different positions of the yarn and fibre landings (with respect to the tube length) would tend to result in an uneven fibre spread on the forming yarn and this unevenness would tend to be reflected on yarn regularity. Thus this might be another reason for the poor evenness of yarn.

Furthermore the free flight of fibres from the zone CD to the zone GH would tend to lead to little or no contact with the forming yarn. The reduced chances of the fibres to attach to the forming yarn would tend to decrease the fibre assembly efficiency and so increase the fibre waste. In practice, it was found that in a spinning system with a sudden tube enlargement in the flow path, the waste losses were quite high.

The diameter ratios of the two tubes did not alter much the yarn and fibre behaviours mentioned above although it should be mentioned that the pressure losses in the system seemed to increase with the diameter ratios.

In addition to all the drawbacks mentioned above, the pressure loss which may be, for all practical purposes, treated as a power loss existed in all the different arrangements.

From the foregoing, it was evident that the effect of a sudden enlargement in tube transition, especially near the spinning part of the tube, was unfavourable to vortex spinning.

### 6.9.3. Effect of sudden contraction in tube transition on vortex spinning

With a sudden contraction in tube transition, as shown in Fig. 6.14.(a), both the air and fibre flows will

Air and Fibre trajectories

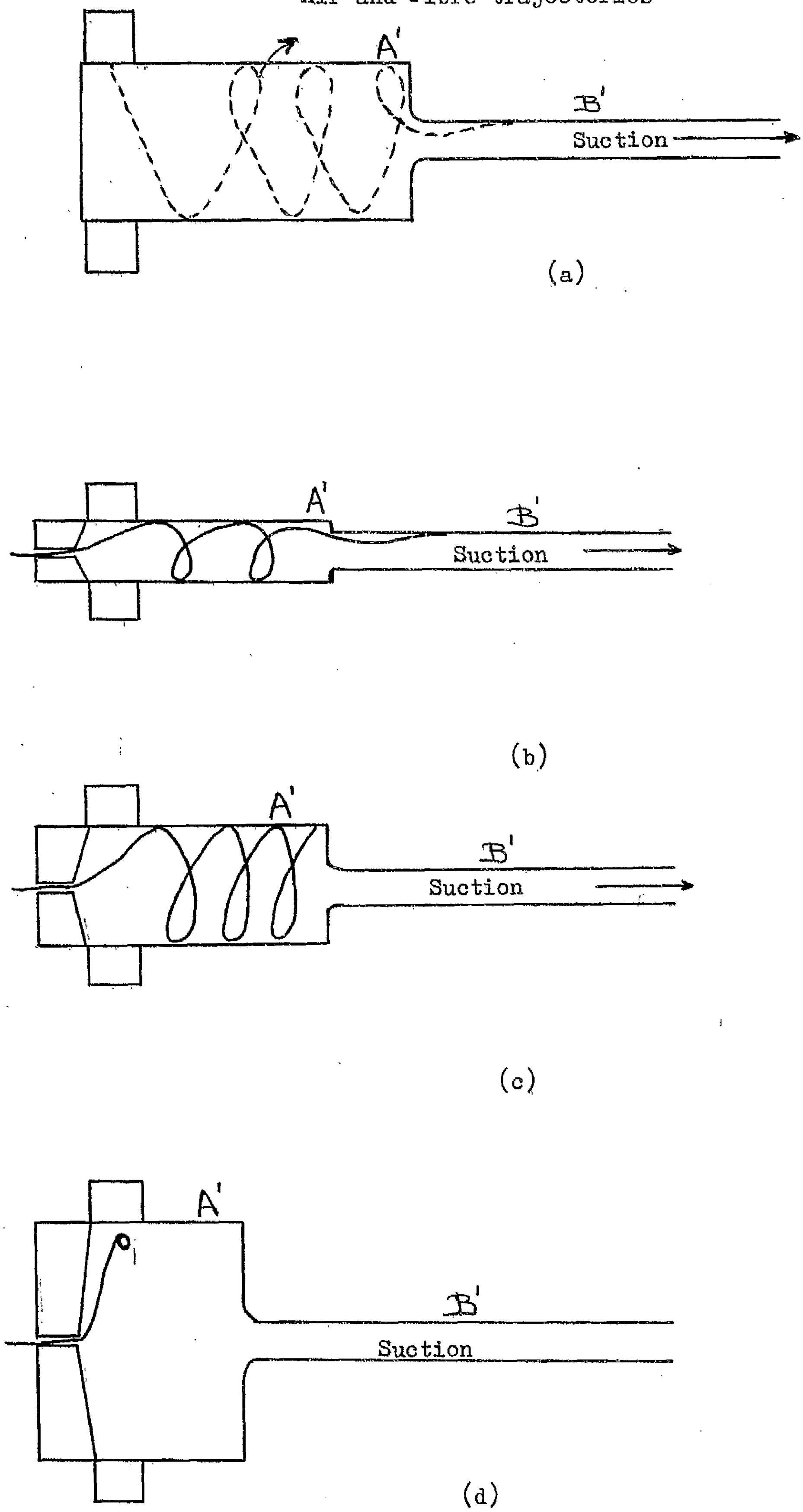



Fig. 6.14

VORTEX SPINNER WITH SUDDEN CONTRACTION IN TUBE TRANSITION tend to proceed along the large tube surface until they impinge against the tube end. Since these helical paths will tend to experience a great difficulty in turning sharply from the end of the large tube into the small tube, it may be expected that, at least for a certain time period, the air and fibre paths will tend to continue their state of motion and, in so doing, will tend to lie on the large tube surface and square with the tube end. Thus the air and fibre paths will tend to become circular at this transition zone. This flow behaviour may tend to act as a buffer for the following vortex (helical) flows and there may, therefore, be a tendency for flow reversal to take place. However one thing seems to be certain, i.e., both the air and fibre flows will be greatly affected at the tube transition zone. It remained to be seen in the following tests if these disturbed flows were to the detriment of vortex spinning. After some time, the air and fibre flows will certainly enter the small tube but it seems highly doubtful if the helical motions will still continue in similar form after the transition stage.

Experiments were conducted with the different combinations of large tube lengths and diameter ratios. Unlike the previous sort of transition, in the present case a smooth bell-mouthed entrance was used at the small tube. This was done to smoothen out the air flow in the transition stage. The various experiments performed in this series are given below:-

A short length of the large tube A' with a bore of upto $1\frac{1}{2}$ times that of the small tube B' did not appear to affect seriously the fibre flow, although a slight disturbance was noticed, However, at large diameter ratios (i.e., greater than 1.5 but lower than 3.0), there were noticeable.

disturbances caused to the fibre flow. It was observed that the fibres tended to rotate at the end of the large tube surface, i.e., in the tube transition region. The fibres gathered themselves into a tuft and it was only after this accumulation of fibres that they moved into the small tube. With still larger diameter ratios(i.e., greater than 3.0) and short tube lengths - this arrangement appeared something like a "drum" spinner - the fibres, at first, rotated on the tube surface until they formed a tuft. This tuft then started rolling inside and gathered more fibres and increased its mass. Finally large tufts so formed found their way into the small tube and frequently choked it up.

The behaviour of the forming yarn seemed to vary with the length of the large tube and also with the diameter ratios of the two tubes. With a tube diameter ratio of upto 1.5 and with a tube length shorter than the forming yarn (Fig. 6.14.(b), the yarn entered the small tube without difficulty. The axial pull acting on the yarn tail lying in the small tube tended to take the yarn out of contact with the large tube surface. The axial pull on the yarn tail and the absence of a helical movement of the yarn lying inside the small tube indicated the absence of helical vortex flow in it. The rotational speed of yarn was also drastically reduced. The general spinning performance was poor indeed.

With a tube diameter ratio greater than 1.5, the forming yarn always tended to rotate on the large tube surface (Fig. 6.14.(c)).This was possibly due to the large magnitude of the centrifugal forces acting on the yarn in comparison with the axial forces exerted on its tail end and perhaps because of this, the yarn more often than not laid itself within the large tube. The high fluctuations in the rotational speed of yarn, when observed with a stroboscope, indicated that the air flow was seriously disturbed and flow reversals might have occurred to a certain extent. The general spinning performance with this arrangement was not encouraging.

It was found that the"drum" shaped spinner(diameter ratio greater than 3.5) introduced a very high degree of twist into a seed yarn(Fig. 6.14.(d)). Perhaps this might be explained by the almost complete absence of the mechanism causing the twist loss existing in a vortex spinner in which the full length of the forming yarn tends to roll on the tube surface and opposes the twist introduced due to the sliding action of the yarn. This is because of the short length of yarn in contact with the tube surface and the large helix angles. However the twist loss mechanism is still present due to the torsional rigidity of the yarn and this perhaps sets a limit to the maximum twist which can be inserted per unit length of yarn. The seed yarn, due to the high rate of effective twist insertion, became shortened considerably in length and this made the tail end of the seed yarn to come away from the tube surface. The yarn contraction caused by high twisting combined with the inability to collect and attach the fibre tufts made spinning impracticable. In short, the drum-shaped vortex spinner did not appear to be a practical proposition.

When the length of the large tube B was greatly increased, spinning was possible even though the diameter ratios were maintained the same as before. At low diameter ratios, less than 1.5, the ~~spinning~~ performance was reasonably good but as the diameter ratio was increased, the spinning performance tended to become gradually poorer.

It should not be forgotten that there was a considerable pressure loss in the air flow.

In general, it must be stressed that any sudden contraction, especially near the spinning section of the tube must be positively avoided in the interests of good performance of vortex spinning.

6.9.4. Effect of tapered tube transition

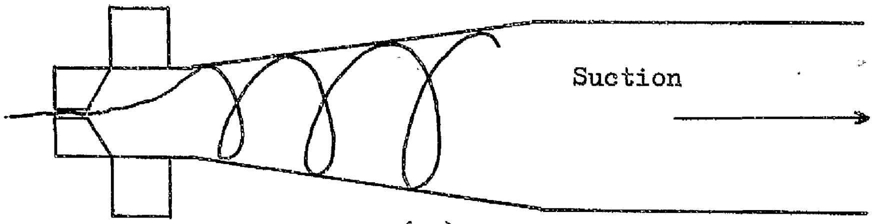
The study of air flow in a tapered transition (mentioned in section 6.8.3.) showed that a taper tube offered a practical means of effecting a smooth flow transition between tubes of different diameters. It also had some other interesting possibilities.

The divergent and convergent forms of taper were examined separately. The arrangement made during spinning with these tapered tubes is shown in Fig. 6.15. The experiments had, however, one basic limitation in that the taper angles of were kept constant.

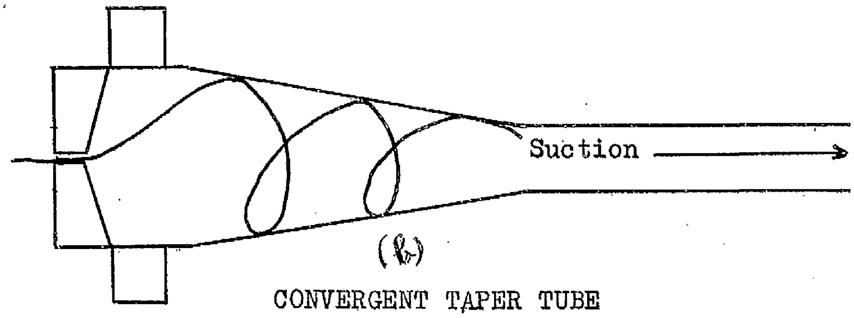
A comparative study of the spinning performance with these two tapers is shown in Table 6.6. . Both systems yielded fairly good yarns and their spinning performances were also reasonably good. Nevertheless it appeared that the general spinning performance with the convergent taper was better than that with the divergent taper. The main reason for this behaviour may be as follows:-

In a convergent taper tube, the velocities of air, fibre and yarn will tend to accelerate towards the suction end of the tube but with a divergent taper they will decelerate.

With a convergent taper, the accelerating fibre velocity will tend to exert a straightening action on the fibres. (Edberg[95] found that a straightening action on fibres was effected by this means). The straightening of the fibres, especially if it happens just before their assembly




(a)
DIVERGENT TAPER TUBE




(b)
CONVERGENT TAPER TUBE

Fig. 6.15

TAPERED SPINNING TUBES

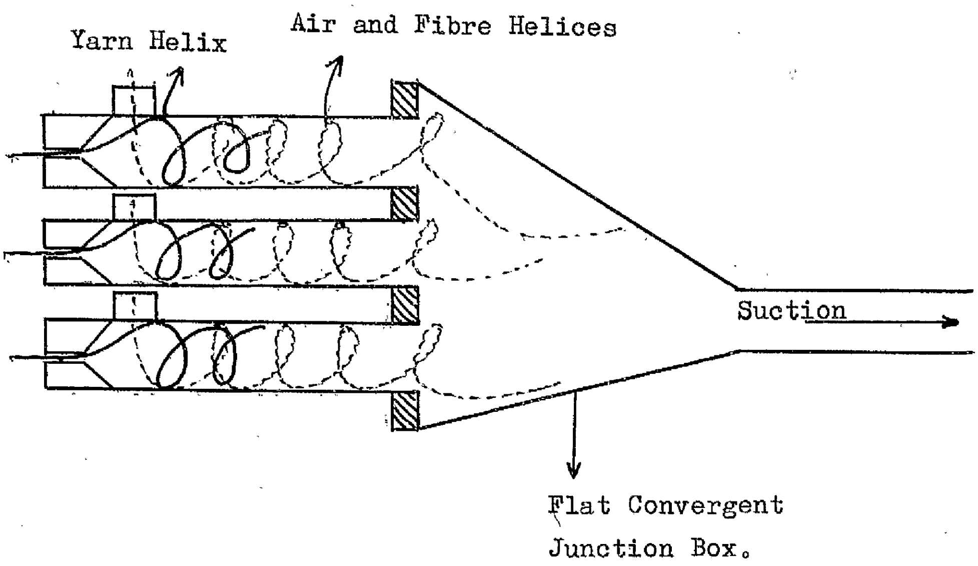



Fig. 6.17

TUBE BRANCHING IN VORTEX SPINNERS

will tend to reduce the number of hooked and bent fibres in the final yarn. An effective increase in the staple length of fibres lying within the yarn will tend to improve the breaking strength of yarn. Furthermore the accelerating velocity acting on the yarn tail will tend to pull the helix more open and this, in turn, will tend to assist the rolling action rather than the sliding action of the yarn. An effective rolling action will tend to result in a great increase in the twist insertion rate although the direction of twist will be opposed to the direction of vortex flow in the tube. Again, because of the rolling of the yarn on the tube wall the fibre assembly will tend to become highly efficient.

On the other hand, with a divergent tube, it is only reasonable to expect that the decelerating velocities will tend to cause the opposite effects. This would seem to suggest that the spinning performance with a divergent tube should be poor. However, in practice, because of the short length of the forming yarn the results obtained with the divergent tube were not vastly inferior to those obtained with the convergent tube.

From the above considerations, it would seem that the preferred choice for a design of the spinning tube with a tube transition would be a convergent tapered tube.

Now the question arises whether a convergent tube should be preferred to a cylindrical tube (i.e., one of uniform diameter throughout its length) for the purpose of spinning. This can only be answered by taking into account the following factors:-

(a) spinning performance

and (b) cost of the spinner.

Spinning performance

Under almost identical working conditions, a convergent taper tube whose largest diameter was equal to the bore of the cylindrical tube ($\frac{3}{4}$ in.) produced a yarn marginally better than that obtained with the cylindrical tube with respect to twist/unit length and breaking tenacity. However the evenness of yarn spun with the cylindrical tube was definitely the better of the two. This is possibly due to the fact that the yarn helix in the tapered tube tends to open out downstream of the tube. It was observed that a short length of yarn tail from the free end assumed an almost straight position parallel to the tube axis. The rest of the yarn, however, retained its helical shape. This is represented in Fig. 6.16. This change in yarn shape tends to alter the fibre capture rate at the different positions along the yarn length. This difference on fibre capture rate will tend to upset the uniform attachment of fibres to the yarn, thereby resulting in an irregularity. Thus the value of a tapered tube is somewhat limited and it is doubtful if a tapered tube is really worthwhile.

Cost of the spinner

A cylindrical tube is readily available but a tapered tube needs to be specially manufactured and this is bound to increase the capital cost of the spinner.

6.9.5. Effect of tube bend on vortex spinning

A sharp tube bend positioned near the spinning part of the tube greatly affected the fibre and yarn movement to the detriment of good spinning. The observed movements of fibres and yarn tended to create an impression of a pulsating flow in the stream. Perhaps this was due to the presence of

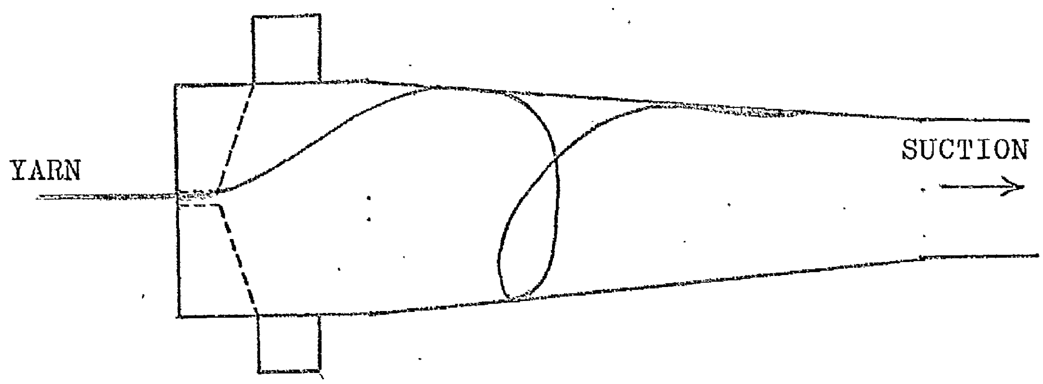



Fig. 6.16.

AN APPROXIMATE YARN SHAPE IN A CONVERGENT TAPERED TUBE secondary flows at the tube bend. A smooth bend did seem to reduce the ill effects caused by the sharp bend. Nevertheless it is best to avoid bends, either sharp or smooth.

It was interesting to note that the tube bends, whether they were sharp or smooth, placed at relatively large distances, about 50 tube diameters, from the nozzle end did not seem noticeably to affect the spinning performance of the tube. Needless to say, the tube bends involved a wasteful expenditure of air flow energy.

### 6.9.6. Effect fo tube branching on vortex spinning

The use of tube branches had its drawbacks too. An arrangement, as shown in Fig. 6.17.*, employed three nozzles with short tubes which were connected to a main tube through a convergent junction box. Air was exhausted from the main tube. It was noticed that the pressure losses were quite appreciable.

A stroboscopic view of the rotation of yarn showed that there were frequent fluctuations in the shapes and also upon the rotational speeds of yarn helices inside the three tubes. This seemed to suggest that the vortex flows were adversely affected. The interaction of the three air vortices inside the flat convergent box(transition zone) might have been responsible for these effects.

It was felt that the use of a smooth,circular tapered transition instead of the flat convergent box might greatly assist in a smooth,undisturbed air flows into the main tube and this might avoid the undesirable effects mentioned before.

* p.238

## 6.9.7. Effect of friction losses on air flow in tubes

In turbulent air flow[85], the friction loss is a function of viscosity, density and velocity of the fluid, the length and diameter of the tube and the degree of roughness of the tube.

Of the various factors that had a direct influence on friction losses, some of them such as the density and viscosity of fluid used, were not controlled as this was beyond the scope of the present research. The velocity of air and the Reynolds numbers were varied to study the effect of different air velocities on the performance of the vortex spinner. A Perspex tube with reasonably smooth tube surface was chosen as the material for the tube and kept as a standard throughout this research. The optimum tube diameter was also decided after a series of experiments. The length of the vortex tube and the connecting pipe was kept as short as possible to keep the friction losses low.

## 6.10. GENERAL CONCLUSIONS

The knowledge gained from all the previous considerations was applied, to the best possible extent, to the air vortex spinning system. Some of the friction losses even though generally regarded as minor losses may, however, assume major proportions in vortex spinning where highly turbulent flows are used in relatively short length and small diameter of tubes. Attention directed towards minimising the various friction losses, referred to in the previous sections, will definitely add to the efficiency of the spinning system.
In addition to these losses, some of the causes leading to these losses are of still great importance from the point of view of spinning since these causes normally have an adverse

effect on vortex spinning. It would be, therefore, necessary for the vortex spinning system to fulfill, as far as possible, the following conditions in order to attain a good spinning performance with the least possible wastage of energy.

(a) Any sudden enlargement or contraction in the working section of the tube must be avoided wherever possible. However if a transition in diameter is found essential it is always advisable to introduce a gradually tapered transition, preferably of the convergent type.

(b) Sharp bends in tubes should be also avoided. However a smooth bend placed at relatively large distances from the spinning section of the tube may be tolerated.

(c) The least branching of tubes should be used or where branching is necessary, it should be such as to preserve as smooth a streamline pattern as possible.

(d) Only a short length of tubing should be used.

From the foregoing, it would appear that the best possible condition would necessarily involve the use of a short, straight, smooth, uniform, circular, rigid tube with an appropriate nozzle on one end.

# SECTION III

# A D V A N C E D   T H E O R Y   O F V O R T E X   S P I N N I N G

## CHAPTER 7

## THEORY OF AIR FLOW IN VORTEX SPINNING

# CHAPTER 7

## THEORY OF AIR FLOW IN VORTEX SPINNING

### 7.1. INTRODUCTION

The method now suggested for spinning yarns by using an air vortex, as already mentioned in Chapter 5, is of recent origin and in fact it is only in the last few years that much interest has been evinced in this form of break spinning. It is reported that yarns have been spun by the air vortex method in research Institutions in Japan, Sweden and England but unfortunately there has been a lack of detailed information on research studies conducted in this particular subject. Presumably in some of these research Institutions either studies have not been carried out in great depth or perhaps not all the research findings have been reported so far.

General surveys of air vortex spinning, usually concerned with the practical aspect of yarn production, have appeared in some technical journals from time to time and the most significant contribution have been made by Lord and his co-workers. While some considerable work of an encouraging nature on the practical side of spinning is covered in these contributions, the theory of vortex spinning has not been fully developed.

It must be emphasized at this stage that valuable initial work on the theoretical aspects of vortex spinning was made by Hirway. The theory of vortex spinning put forward by him seems, in the main, to be correct. In the present study which is an extension of his work, his theory is taken as the basis for further theoretical developments. The theory is reviewed and a critical assessment of it is included in Chapter 4. Much new ground has been covered in the present work since Hirway's theory was published and a good deal of light is thrown on certain behaviours which were not clearly understood then. The mechanics of yarn behaviour has been studied at some length and it appears that some aspects of yarn behaviour inside the tube are more fully understood now. Attempts have also been made to investigate the mechanism of yarn formation. Nevertheless it may well be much work will still remain to be done in order to completely understand the complex nature of fibre assembly and twist insertion which leads to the formation of a yarn.

## 7.2. MECHANICS OF VORTEX SPINNING

### 7.2.1. An approach to the problem

It is now definitely known that a reasonably good yarn can be produced by the air vortex spinning method. With this method the attachment of fibres to each other and the twisting of the attached mass is effected by the air vortex created inside the tube. It seems likely that the fibre attachment as well as the twisting of the fibre mass takes place almost simultaneously.

The nature of this problem which involves an analysis of the behaviour of light bodies in a vortex air flow is rather difficult. As mentioned earlier in the previous section, apart from Hirway's work no substantial contribution towards the theory of vortex spinning is known to have been made. In the light of these considerations, the present first analysis gives a broad and general treatment of the theoretical considerations involved, although in some cases, the subject has been dealt with in detail.

An analytical study of the mechanics of vortex spinning may be broadly divided into four parts. The first part deals with the theoretical analysis of velocity and pressure distributions along the vortex tube when only the air flows. Fortunately much of the theoretical work on air flows in vortex tubes was done by research workers in the field of heat transfer. This subject of heat transfer is almost irrelevant to the present research problem but the analytical study carried out on the air flows involved is quite relevant because of the similarity to the air flow encountered in vortex spinning. It may be mentioned here that the work of Lay(89) in this analytical treatment is quite remarkable and hence it was considered useful to include the relevant material from his work in the present analysis. In fact a summary of his paper is given in the following sections.

In the second part, the fibre flow in a vortex stream is studied and thirdly, the yarn behaviour under the influence of an air vortex is analysed. Finally the mechanics of yarn assembly and twist formation is dealt with by combining the effects of air vortex on the fibres and the forming yarn.

The theory of air flow is dealt with in this chapter while each of the other parts form a chapter on their own.

### 7.2.2. Analytical study of air vortex flow in a tube

It is difficult to arrive at a direct solution of the intrinsic equations of a three dimensional compressible fluid flow, especially if velocity effects are also to be considered. Therefore it is thought best that this complex problem be broken down into simpler models for which solutions may be obtained. These solutions may then be super imposed on each other to give a solution of the final flow equations.

Thus it may be considered that the air flow begins with a potential vortex in a plane. Then by superimposing a sink flow to the vortex solution, an equation for a spiral flow in the plane may be found. As a next step, a general solution in a three dimensional form may be sought by the addition of a uniform axial velocity to the spiral flow. If velocity effects are considered, the free vortex changes into a forced vortex. The final solution is then obtained by superimposing a viscous compressible sink flow on a forced vortex.

Attention may be drawn to the fact that many assumptions made during the course of mathematical developments to simplify the problem may by themselves impose limitations. These are quite likely to cause the final results to deviate from the actual conditions.

Before proceeding to an analytical study of vortex flow, it was thought necessary to discuss vortex motion in general.

### 7.2.2.1. Vortex motion

The term vortex is commonly applied to a fluid motion involving a spin about an axis which may be straight or curved.

In two dimensional flow with a straight vortex axis, two cases may arise in which the vortex streamlines are concentric circles. They are usually called the forced vortex and the free or potential vortex.

### 7.2.2.2. Forced vortex

In a forced vortex, the fluid rotates as a solid body along with the container holding the fluid. There is no relative motion between the fluid and the vessel. A torque is applied to the body of the fluid.

If a vertical cylindrical container holding a liquid be rotated about a central vertical axis, the stream-lines in the liquid will be concentric circles, as shown in Fig. 7.1.

Let r be the radial distance of an element,

v be the linear velocity of that element

and $\omega$ be the constant angular speed (measured in radians per unit time) of the container.

Then, $v = r.\omega$.

The free surface of the liquid is curved and the pressure distribution is parabolic, as shown in Fig. 7.2. in which the co-ordinates x and y are defined.

There are three forces acting on the liquid element at point A. They are:-

(a) the weight of the element W,

(b) the inertial force $= \frac{W}{g}\omega^2.x$ ; this force acts in a radial direction away from the axis of rotation

and (c) the force P; this is the resultant force due to the pressure exerted by the surrounding liquid elements.

Since there is no relative motion between the elements, the force P is normal to the curved surface. These three forces are in equilibrium. Please refer to Fig. 7.2.

Therefore, $P \sin \theta = \frac{W}{g}\omega^2 x$,

$P \cos \theta = W$.

Hence, $\tan \theta = \frac{\omega^2 x}{g} = \frac{dy}{dx}$.

i.e., $\frac{dy}{dx} = \frac{\omega^2 x}{g}$.

On integration, the equation of the curved free surface is given by $y = \frac{\omega^2 x^2}{2g}$. y is a measure of pressure.

Thus in a forced vortex, $\omega$ is independent of radius and there is no shear between adjacent co-axial elements.

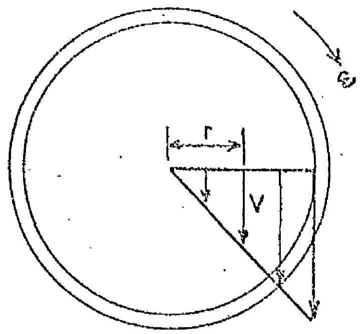



Fig. 7.1.

FORCED VORTEX

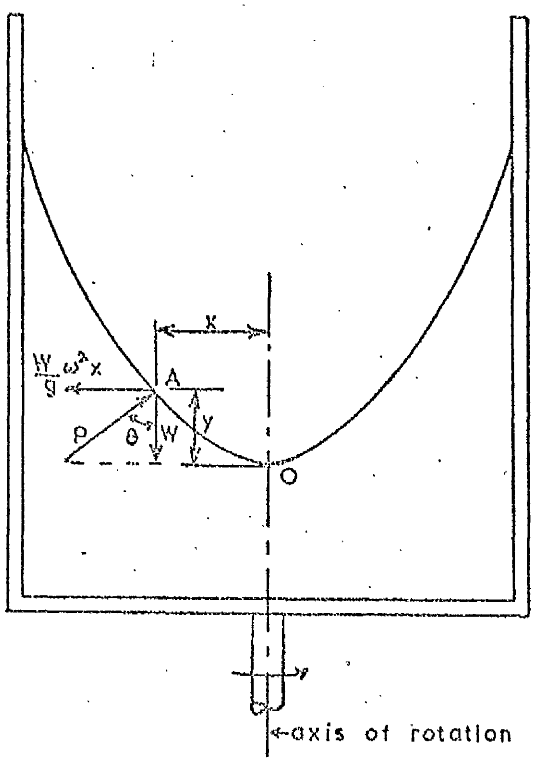



Fig. 7.2.

ROTATING BODY OF LIQUID

The torque needed to rotate the vortex

$T = \frac{d}{dt}(m.r.v.)$ ............................(A)

where T = torque required to rotate the element under consideration and m = mass of the element under consideration.

The product $(m.r.v)$ is the angular momentum.

7.2.2.3. Free vortex

In a free vortex, the motion is irrotational except at the centre, i.e., a vortex which is free to move with the surrounding fluid. Here again, the streamlines are concentric circles but the velocity variation with radius is different from that of a forced vortex.

Imagine a frictionless fluid moving in a horizontal circular path with no torque applied. If torque T is zero, equation (A) becomes

$$\frac{d}{dt}(m.r.v) = 0.$$

On integration,

$$r.v = K$$

or, $v = \frac{K}{r}$ ..........................(B)

where K is a constant.

Fig. 7.3. shows that in a free vortex, the velocity decreases as the radius increases. Since the flow is irrotational, there is torsional shear.

7.2.2.4. Helical vortex

An axial velocity imposed on either a forced or a free vortex would move the vortex in a helical path. This helical path may be termed the "helical vortex". The introduction of this term is necessary because this is the type of vortex that is encountered in vortex spinning.

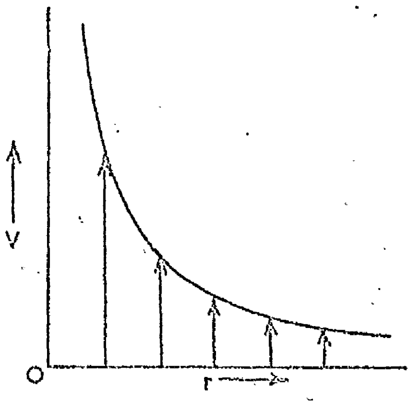



Fig. 7.3.

FREE VORTEX

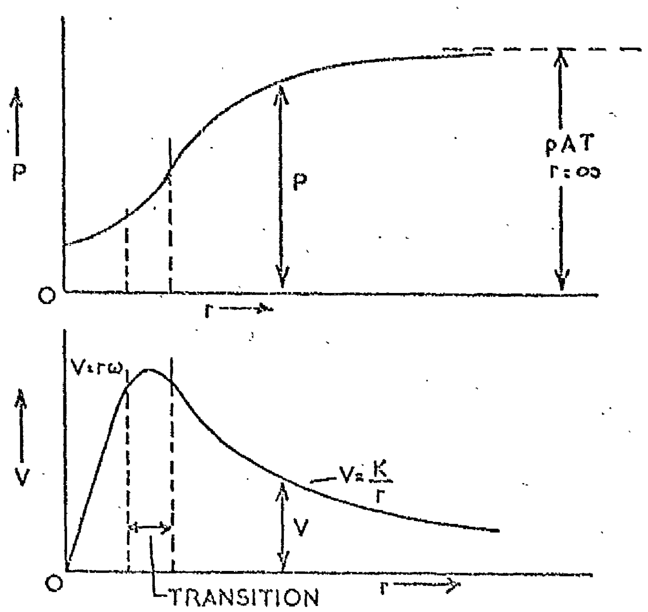



Fig. 7.5.

PRESSURE AND VELOCITY DISTRIBUTION IN A PRACTICAL VORTEX FLOW

## 7.2.3. A theoretical analysis of velocity and pressure along a vortex tube

In order to determine the velocity and pressure distributions in the field of a flowing fluid, assumptions are made that there is no separation or eddying wake formation. At the tube wall, the fluid velocity is zero. There is a boundary layer close to the body surface. In this boundary layer there is a velocity gradient and also viscous shearing between the elements forming the layer. A small distance away from the body, i.e., outside the boundary layer the flow is supposed to be not much influenced by the viscous action in the boundary layer. Hence for analytical purposes it is convenient to consider the entire flow area as two regions. One region is the boundary layer where the friction or the fluid viscosity is taken into account. This is generally known as Prandtl's concept of a boundary layer. Away from the boundary layer is the other region where, for practical purposes, the fluid viscosity is ignored.

### 7.2.3.1. Velocity distribution

Initially it is possible to ignore viscous friction in the flow field outside the boundary layer and then calculate a solution based on potential flow.

Consider a steady flow of a perfectly frictionless fluid moving in a horizontal circular path with no external torque applied.

Let AB and CD be two adjacent streamlines spaced at infinitesimal distance apart. Let their radii of curvature be r and r+dr respectively, as shown in Fig. 7.4.

Let two normals converging at a small angle $d\theta$ be drawn to these streamlines. Then a small wedge shaped elemental area is formed as shown in Fig. 7.4.

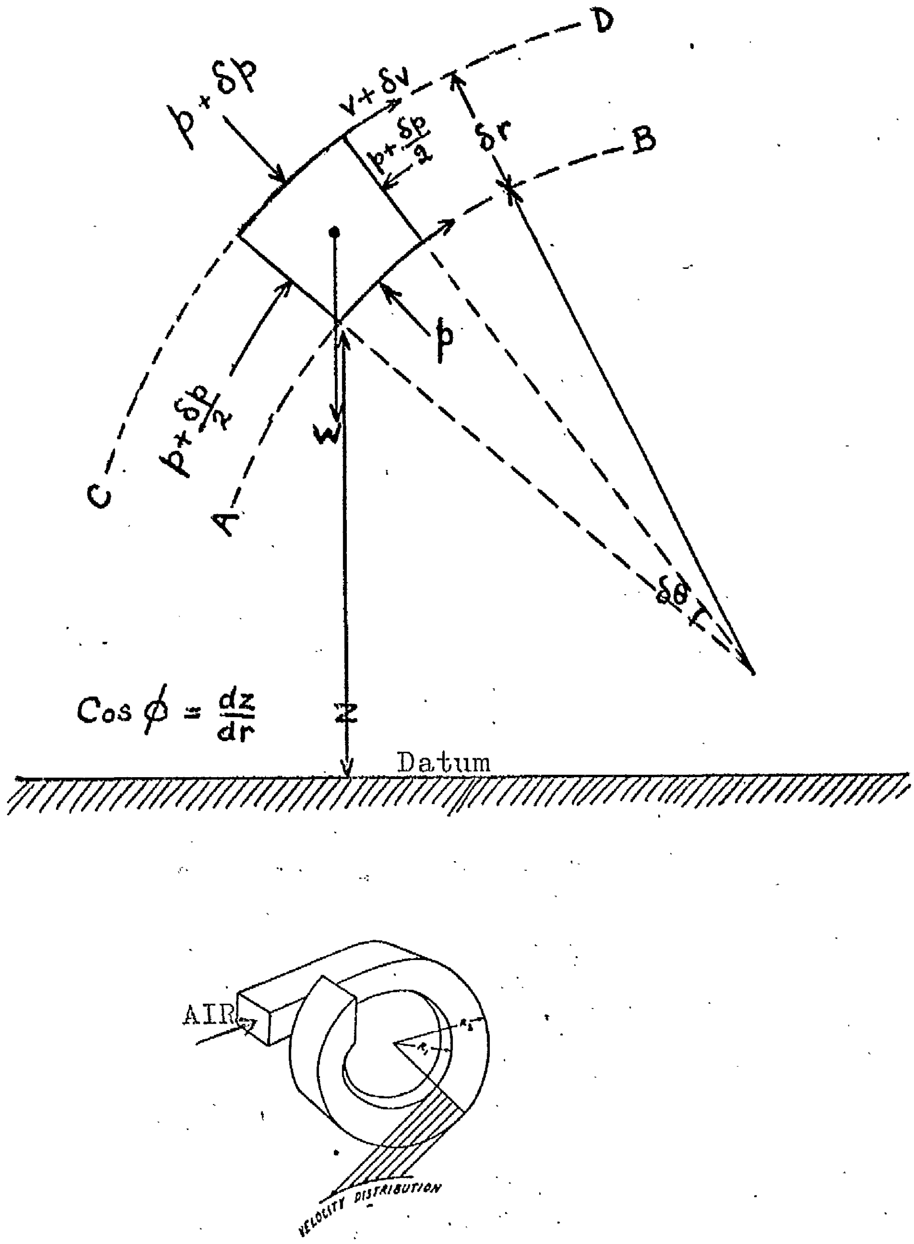



Fig. 7.4.

FLOW IN A CIRCULAR PATH

The velocities and pressures on this elemental area are shown in the figure. The average linear velocity of the streamlines AB and CD are v and v+dv respectively. The pressure varies from p to p+dp as the radius varies from r to r+dr.

Let the depth of the diagram be L where L is measured perpendicular to the plane of the paper, and the inclination of the elemental area to the vertical be $\theta$, where $\cos\theta = \frac{dz}{dr}$.

Then, for equilibrium of the wedge under consideration,

$$p.r.d\theta.L + 2\left(\frac{p+dp}{2}\right).dr.L.\sin\frac{d\theta}{2} - (p+dp)(r+dr).d\theta.L - W\cos\phi + \frac{W.v^2}{g.r} = 0, \text{ where}$$

$W$ = weight of wedge = $r.d\theta.dr.L.w$, and

$w$ = fluid density.

Neglecting multiples of small quantities, the above equation simplifies to

$$-dp.r.L.d\theta - w.r.d\theta.dr.L.\frac{dz}{dr} + w.r.d\theta.dr.L.\frac{v^2}{g.r} = 0$$

$$\text{or, } \frac{dp}{dr} = -w.\frac{dz}{dr} + \frac{w.v^2}{g.r} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

According to Bernoulli's theorem, the sum of the pressure head, the velocity head and the potential head is constant along a streamline. The value of the constant may, however, vary from one streamline to the other, if the streamlines have different origins. If all the streamlines come from a space in which the relationships are static (i.e., in which the fluid is at rest or in uniform motion in a straight line), the constant is the same for all the streamlines. Thus it may be said that no energy is added to the vortex by a torque nor is energy dissipated by friction.

Again by Bernoulli's theorem,

$$\text{Total head (or specific energy) } E = \frac{p}{w} + \frac{v^2}{2g} + Z$$

Differentiating with respect to r,

$$\frac{dE}{dr} = \frac{1}{w}\cdot\frac{dp}{dr} + \frac{v}{g}\cdot\frac{dv}{dr} + \frac{dz}{dr} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Substituting the value of $\frac{dp}{dr}$ from equation (1) into equation (2),

$$\frac{dE}{dr} = \frac{1}{w}\left(-\frac{w.dz}{dr} + \frac{w.v^2}{g.r}\right) + \frac{v}{g}\cdot\frac{dv}{dr} + \frac{dz}{dr}$$

This simplifies to

$$\frac{dE}{dr} = \frac{v}{g}\left(\frac{v}{r} + \frac{dv}{dr}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Equation (3) is independent of the position of(z),i.e., of the position of the instantaneous centre of rotation. Hence it applies to concentric streamlines in any plane. If the total specific energy E is to remain constant not only along the streamlines but also throughout the fluid, then

$\frac{dE}{dr}$ must be equal to zero,

i.e., $\frac{dE}{dr} = 0$.

From equation (3), since $\frac{dE}{dr} = 0$,

$\frac{v}{r} + \frac{dv}{dr} = 0$, or

$\frac{dv}{v} + \frac{dr}{r} = 0$.

On integration,

$\log_e v + \log_e r = C'$,

or, $\log_e vr = C'$,

or, $v.r. = C$, where C and C' are constants.

Therefore, $v \propto \frac{1}{r}$ ..........................................(5)

Equation (5) is characteristic of a free or potential vortex and it suggests that an infinitely large velocity of air can be obtained at the centre of the vortex. This does not, however, occur in practical vortices because viscous effects which were not taken into consideration in the above calculations cause a portion of the fluid in the region near r = 0 to rotate like a solid body. Outside the central core, however, is a transition region and outside this transition region is a free vortex with the velocities in concentric streamlines being diminished in inverse proportion to the increasing radii of the streamlines. The velocity distribution is almost of the hyperbolic type as shown in Fig. 7.5. Thus in practice it may be quite possible to obtain a perfectly forced vortex but it is almost impossible to obtain a perfectly free vortex.

7.2.3.2. Pressure distribution

Once again, consider Fig. 7.4. Let the average area along the curved surface of the wedge be dA. (N.B. dA=L.r.dθ) By dA. Then the mass of this element is $\rho$.dr.dA, where $\rho$ is the density of the element. The normal or radial acceleration is $\frac{v^2}{r}$.

The pressure distribution is determined by considering the force balance. The centrifugal force acting on the fluid element is balanced by the resultant force due to pressures over the surfaces. Ignoring infinitesimals of higher order than the first, the force balance in radial direction is given by

$$dp.dA = \rho \frac{v^2}{r}.dr.dA.$$

$$\text{or} \quad dp = \rho \frac{v^2}{r}.dr \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

This equation (6) shows that the pressure increases with radius in a curved flow. The pressure gradient $\frac{dp}{dr} = \rho \frac{v^2}{r}$ indicates that the pressure per unit area decreases by an amount $\frac{v^2}{r}$ towards the centre of curvature. However the exact variation in pressure depends upon the variation in velocity v with radius r. The general curve for pressure distribution is shown in Fig. 7.5.

## 7.2.4. Free vortex circulation in a two dimensional flow

In order to find an analytical expression for the fluid rotation in a two dimensional flow, consider the infinitesimal and mutually perpendicular fluid lines OA and OB, as shown in Fig. 7.6. The motion of each of these lines may be resolved into a translation plus rotation. During an infinitesimal time interval dt, OA rotates to the position OA' and the relative vertical displacement AA' is

$$AA' = \frac{\delta v}{\delta x}.dx.dt.$$

The angle AOA', taken positive when measured counter-clockwise, is given by

$$AOA' = \frac{\delta v}{\delta x}.dt.$$

the time rate of change of this angle is $\frac{\delta v}{\delta x}$.

Similarly it may be shown that the angular velocity of the fluid line OB is $-\frac{\delta u}{\delta y}$.

Therefore the mean rotation ($\omega$) of a fluid particle is equal to the average.

$$\text{or } \omega = \frac{1}{2}\left(\frac{\delta v}{\delta x} - \frac{\delta u}{\delta y}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Since the circulation for a free vortex is zero,

$$\text{therefore } \frac{\delta v}{\delta x} - \frac{\delta u}{\delta y} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

So the fluid rotation at any arbitrary point upon entrance into the vortex tube is zero and the motion of the fluid particles is as indicated in Fig. 7.7.

## 7.2.5. Solution for vortex tube

The solution for a streamline pattern in a vortex tube can be obtained by combining a vortex flow with a sink flow.

### (a) Vortex flow

Let v be the speed along a streamline of radius r. Then the motion will be irrotational if the circulation $\Gamma$ has

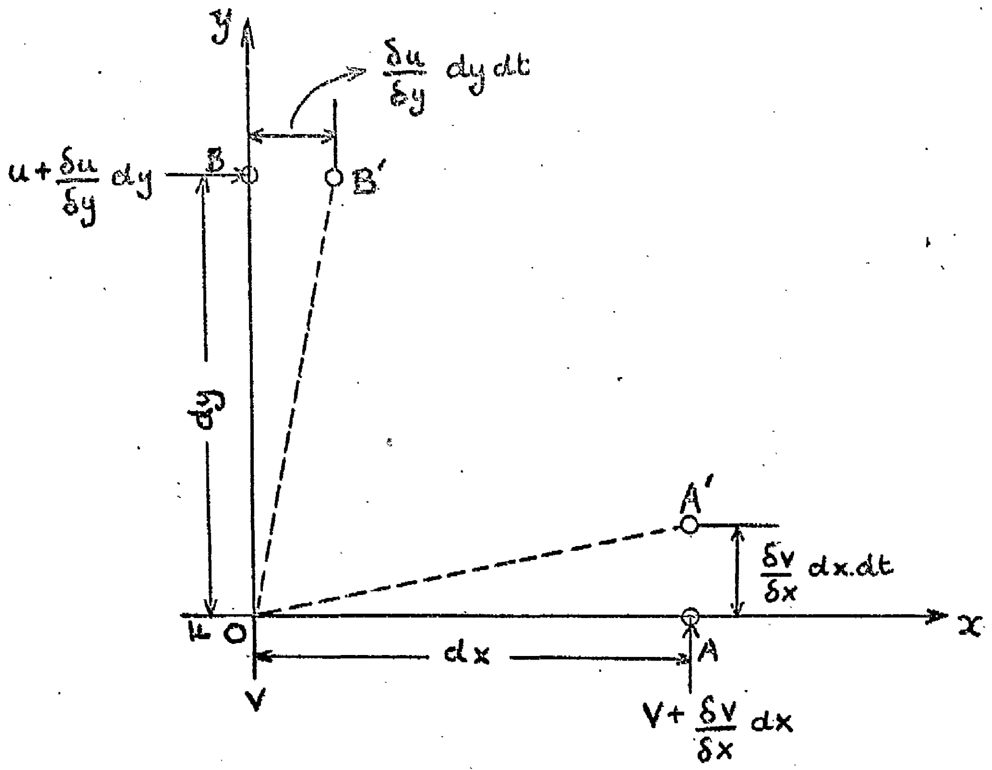



Fig. 7.6.

FLUID ROTATION AT A POINT

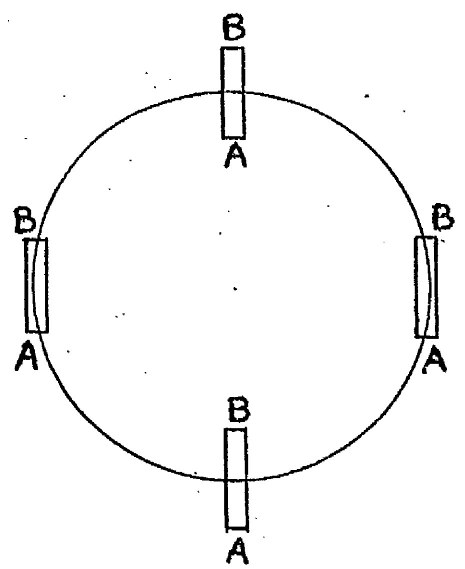



Fig. 7.7.

FREE VORTEX, IRROTATIONAL MOTION

the same value along every streamline.

That is, $\Gamma = 2\pi r v$.

$$\text{or } v = \frac{\Gamma}{2\pi r}.$$

(b) Sink flow

In this case, the streamlines are radial as shown in Fig. 7.8. Let u be the speed at radius r. Then the strength of the sink flow Q is given by

$$Q = 2\pi r . \rho u .$$

$$\text{or } u = \frac{Q}{2\pi r \rho}.$$

The velocity distribution for a sink flow, given by Lay[89], is shown in Fig. 7.9. There are two branches to the curve. Since the vortex tube was worked at subsonic velocities only, the subsonic branch of the curve should be taken into account. It may be also noted from the curve that there is a circle of minimum radius into which the fluid (at sonic speed) cannot penetrate this circle.

7.2.6. Spiral flow

The vortex flow and the sink flow are now combined together to yield a spiral flow. These two flows can be superimposed or combined mathematically by simply adding together the potential function of the two flows. The algebraic addition of two potential functions is similar to a vector addition of the velocities.

It is beyond the scope of this chapter to proceed into the complete details of solving the flow pattern inside a vortex tube. It was felt that it would be sufficient to mention that the flow pattern was obtained by developing a differential equation of flow in terms of velocity potential. This is known as a stream function. The non-linearity and

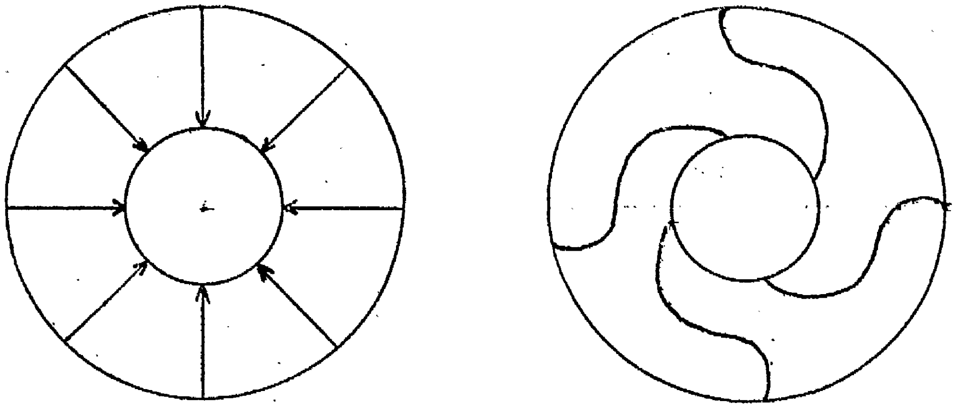


Fig. 7.8.

SINK FLOW

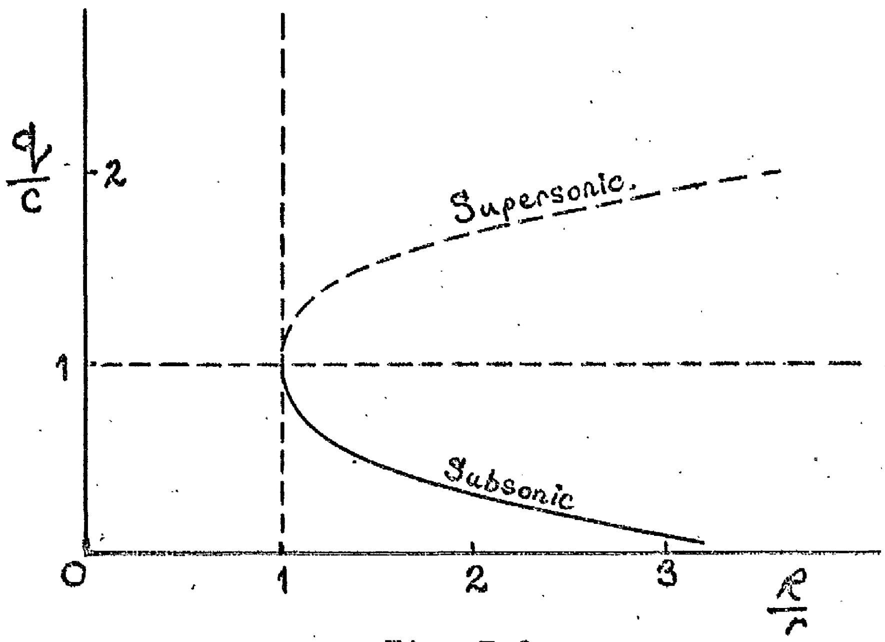



Fig. 7.9.

VELOCITY DISTRIBUTION FOR A SINK FLOW

complexity of the stream function makes it very difficult to obtain solutions for a subsonic flow. Hence the hodograph transformation method is generally made use of in order to reduce the complex solutions to a series of linear equations.

The spiral flow pattern in a plane was obtained by Lay for a vortex tube of 2 in. in diameter and it is shown in Fig. 7.10. This pattern was arrived at by solving the stream functions. This theoretical pattern was claimed by Lay to be almost similar to the flow pattern which was obtained in practice on a plate when an oil spray was injected into the vortex stream(please see section 7.2.10.).

7.2.7. General solution to a three dimensional form

All the theoretical considerations mentioned earlier assumed the flow to be a two dimensional one. For a three dimensional flow, a constant axial velocity is added to the solution derived from the spiral flow. This axial velocity is assumed not to alter the flow equation in the plane and also the pressure, density and temperature of the fluid.

Let $v_1$ (a constant) be the velocity component which is added to the two dimensional flow. The stream function of the two dimensional flow is super imposed on the stream function of the axial flow to give the general solution in space. This addition of a constant velocity in the axial direction does not alter the condition of irrotationality. The diagram of the flow pattern in space is shown in Fig. 7.11., once again as represented by Lay.

7.2.8. Effect of viscosity

The viscosity effects are negligible at that region of the tube relatively near the entrance. As the flow proceeds down the tube, viscosity effects begin to influence the flow

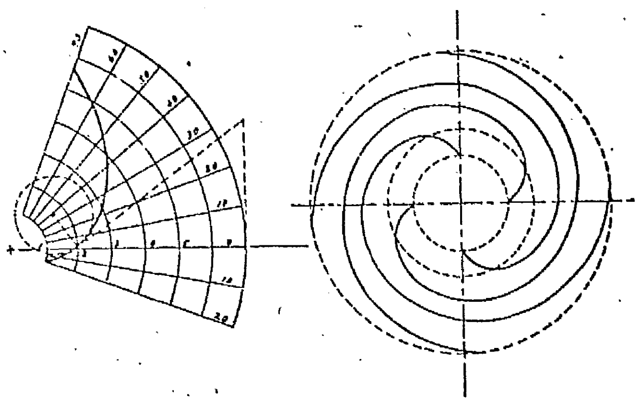


Fig. 7.10.

SPIRAL FLOW PATTERN IN A PLANE

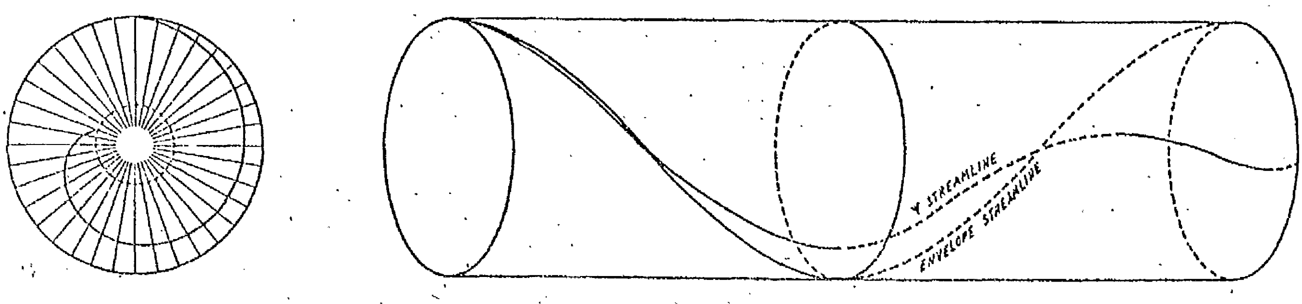



Fig. 7.11.

FLOW PATTERN IN SPACE

and the free vortex changes into a forced vortex.

According to Kassner's[90] concept of shear stress in circular turbulent flow,

the shear stress $\tau = \epsilon \left(\frac{dq}{dr} - \frac{q}{r}\right)$ ................(9)

where $\epsilon$ = turbulent exchange rate,

$q$ = velocity in a hodograph plane

and $r$ = radial distance.

Since the velocity distribution on entrance into the tube is given by

$$q = \frac{K}{r},$$

differentiation yields

$$rdq + qdr = 0,$$

$$\text{or } \frac{dq}{dr} = -\frac{q}{r} = -\frac{K}{r^2} \quad \text{..............(10)}$$

Equation (9) may now be written as

$$\tau = \epsilon\left(-\frac{q}{r} - \frac{q}{r}\right) = -2\epsilon\frac{q}{r} \quad \text{.......(11)}$$

The shearing force and the moment of the shearing force acting on an annular element of fluid at a distance r from the centre are respectively

the shearing force ($F_i$)

$$= 2\pi r \epsilon \left(\frac{dq}{dr} - \frac{q}{r}\right),$$

the moment of shearing force ($M_i$)

$$= r.F_i$$

$$= 2\pi r^2 \epsilon \left(\frac{dq}{dr} - \frac{q}{r}\right) \quad \text{............(12)}$$

On substituting the values of $\frac{dq}{dr}$ and $-\frac{q}{r}$ from equation (10),

$$M_i = 2\pi r^2 \epsilon \left(-\frac{2K}{r^2}\right)$$

$$= -4\pi\epsilon K \quad \text{...................(13)}$$

From equation (13) it appears that an elemental moment of shear stress is constant and independent of r.

The summation of all the internal elemental moments must be zero because there is no external torque applied to the flow on entry to the tube.

Therefore $\int_0^r M_i dr = 0$ ............................(14)

$M_i$ is constant according to equation (13) but equation (14) can only be satisfied if $M_i = 0$. This means that the flow which is irrotational on entering the vortex tube can not continue to remain so but must gradually change into a rotational flow. This can be seen by applying the equation for rotational flow to equation (13).

The characteristic equation for rotational flow is

$$q = \omega r.$$

Therefore, $\frac{dq}{dr} = \omega = \frac{q}{r}$ ........................(15)

Substitution of equation (15) into equation (12) yields $M_i = 0$. Thus there is a change from free vortex to a forced vortex due to viscosity effects.

7.2.9. Lay's experimental study

Having considered briefly the theoretical aspects of air flow, it was thought that it would be appropriate to reproduce some of the experimental results obtained by Lay. It must be re-emphasized that Lay's experiments were mainly concerned with the temperature separation of gases in a vortex tube. The subject of heat transfer is not directly connected with air vortex spinning but it is felt that some of Lay's experimental work and results pertaining to velocity and pressure distributions inside the vortex tube are quite relevant to the present research. Hence the results are reproduced in graphical forms and considered here for application to vortex spinning. The temperature considerations inside the tube cannot altogether be ignored even in the present problem and, as will be evident during discussion of Lay's results, importance is given to the velocity and pressure distributions only.

Lay used a 2 in. diameter uniflow vortex tube. Compressed air was fed tangentially into the nozzle. Measurements in a vortex flow are more difficult than under flow conditions usually encountered. One of the factors which contributes to this difficulty is the presence of strong radial pressure gradients. In addition, the danger of a flow disturbance due to the presence of the measuring devices is large especially at the central core of the vortex where the flow has almost no axial velocity component. In this central region, probes were essentially arranged in their own wakes. Pressure traverses were taken by means of small hypodermic probes and velocity distributions were checked by a miniature hot wire anemometer. Data were collected at 6 or 7 different stations* for different inlet pressures (10, 20 and 30 p.s.i.g.). The results of this work are shown in Fig. 7.12. to 7.17. inclusive. Since the readings near the centre and also near the wall of the tube were found to be very erratic, traverse data were not taken for radial distances less than 0.3 in. or more than 0.9 in. for a 2 in. tube. The erratic nature of the readings near the centre is attributed to flow disturbances and the inconsistent readings near the tube wall may be explained by the wall friction concept of boundary layer conditions.

* N.B. These so called "stations" were at unknown distances along the axis.

$P_{INLET}$ = 10 psig.

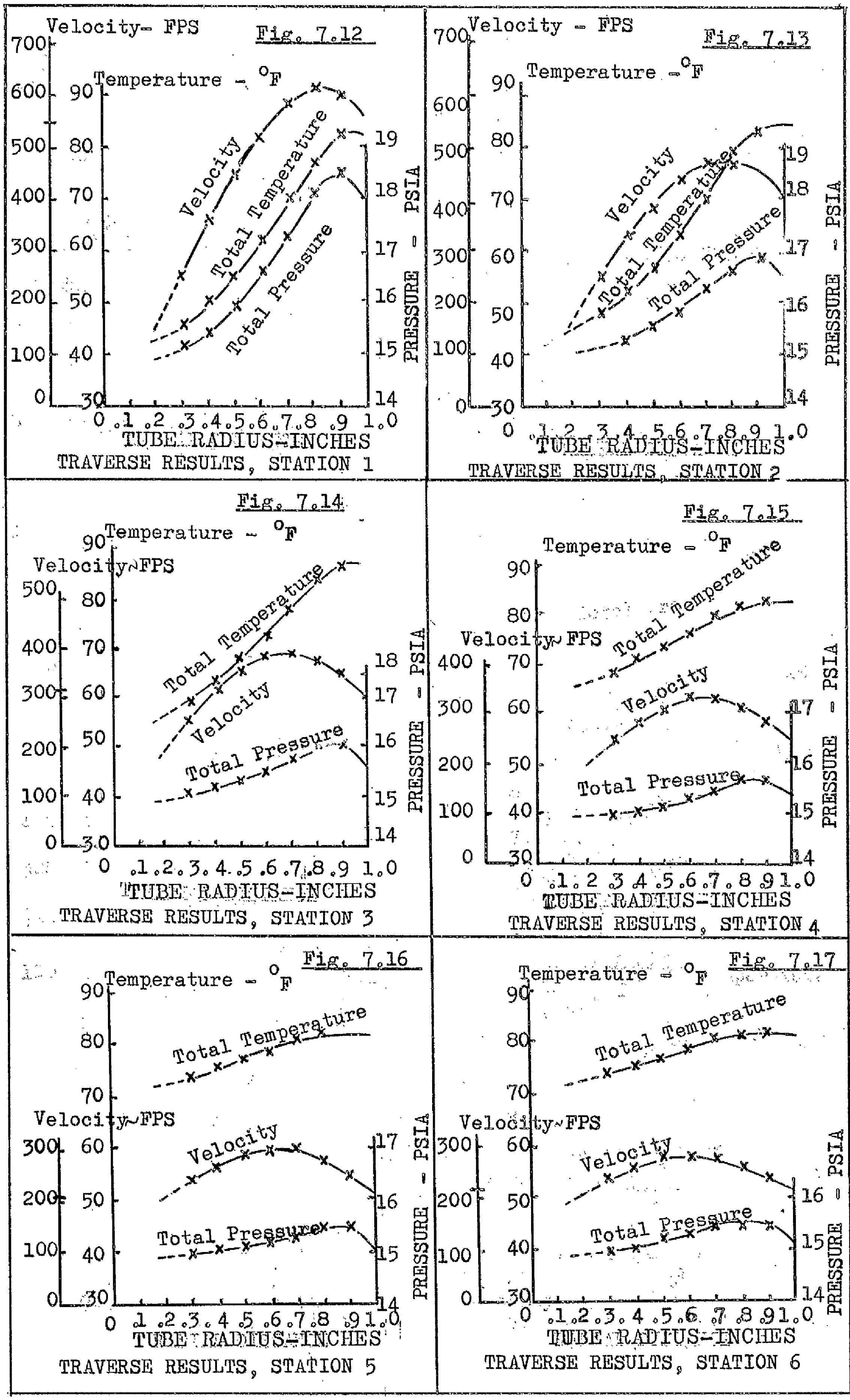



Fig. 7.12 through to 7.17

LAY'S GRAPHS OBTAINED FROM A VORTEX TUBE

### 7.2.10. Flow visualization

Lay, in his experimental study, employed visual methods to obtain flow patterns in the tube. He tried various media such as balsa saw-dust, fine confetti etc. but all these had some drawbacks. Finally he succeeded in taking photographs of flow patterns by injecting coloured liquid and milk through the inlet nozzle. Fig. 7.18., reproduced here, shows the photograph of the flow pattern of the liquid mixture immediately after entry into the vortex tube. This photograph indicates the formation of a vortex sink flow at the entry. Another photograph showing the envelope streamline of the three dimensional flow is reproduced in Fig. 7.19. This may be compared with the theoretical flow pattern shown in Fig. 7.11.

### 7.2.11. Application of Lay's experimental curves to vortex spinning

#### 7.2.11.1. Velocity and pressure flow curves applied to vortex spinning

In order that the results obtained by Lay might be applied to the present problem of vortex spinning, it was necessary to know the likely distribution of velocity and pressure existing on the inner walls of the vortex tube. This region of the tube wall was considered because it was here that most of the fibres and a greater part of the yarn were observed to move. Lay's graphs were not drawn up to the tube wall because the measured readings at this region were erratic. Therefore the values of velocity and pressure at each of the different stations were extrapolated to meet the tube wall. This extrapolation was based on the assumption that the velocity and pressure distribution near the tube wall were in linear relationship with the tube radius. It might be

Fig. 7.18.

PHOTOGRAPH OF FLOW PATTERN WHEN VIEWED FROM THE NOZZLE END OF THE TUBE

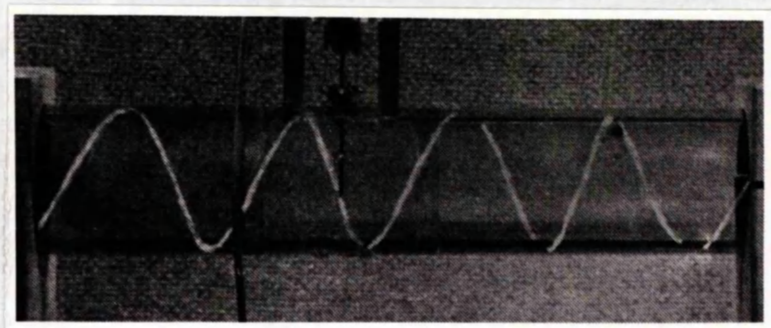


Fig. 7.19.

PHOTOGRAPH OF THE ENVELOPE STREAMLINE IN THE VORTEX TUBE mentioned in this context that it was rather unfortunate that the axial distances of the different stations at which readings were taken were not mentioned in Lay's paper. The absence of this vital information made it difficult to draw many valuable inferences. All that was known was that they were placed at increasing axial distances from the air entry nozzle.

The values of air velocity for different stations extrapolated were plotted against the positions of stations and this is shown in Fig. 7.20. It was noticed that the velocity was maximum at the station nearest to the air entry position in the tube and then the velocity decreased slowly down the length of the tube towards a constant value. Consideration Figs. 7.12. to 7.21. shows that it is desirable that the drive element of the yarn in the tube should be as near to the air entry as possible and should exist at a radius of about 80% of that of tube bore.

Referring to the values of pressure extrapolated from Lay's graphs, it was observed that the pressure was maximum at the position where the air entered the tube and gradually decreased from the nozzle.

It is also to be noted from Lay's graphs that the maximum values of velocity and pressure vary along the length of the tube. At the air entry position, (i.e., near the nozzle), the maximum values were found to be at positions a little further away from the tube wall. The greater the distance from the air entry position, the further away are the peak values of velocity and pressure from the vortex tube wall. This behaviour may give rise to two possibilities.

Pinlet = 10 psig.
Diameter of vortex tube = 2 in.

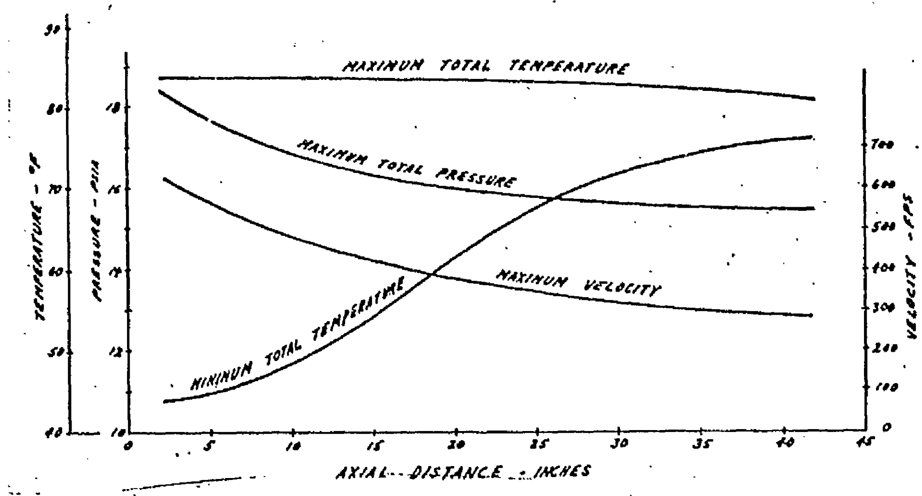



Fig. 7.20.

AXIAL VARIATION OF PRESSURE, TEMPERATURE AND VELOCITY

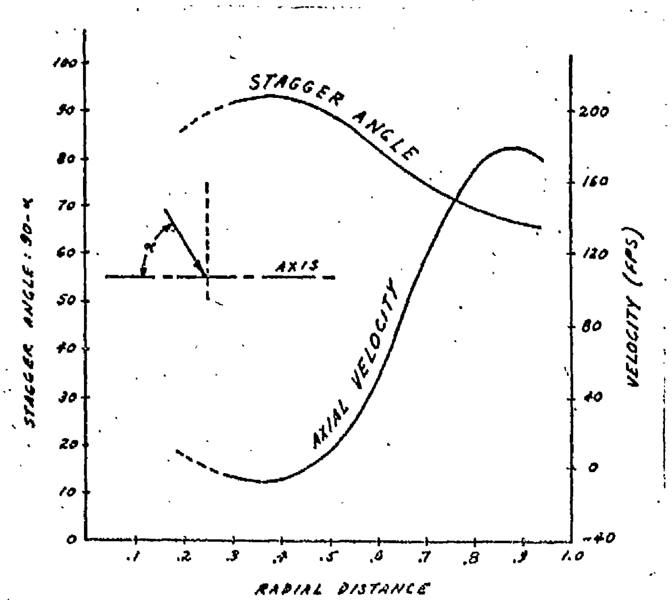



Fig. 7.21.

FLOW ANGLE ; AXIAL VELOCITY

Firstly, at all stations the maximum air velocity is found to be at a little distance away from the tube wall. It is quite likely then that the fibres and the forming yarn moving in the tube near the air entry zone will tend to move along the peak velocity line of the air flow. This is because of the tendency for bodies to move from a region of low velocity to a region of high velocity. Consequently the fibres and yarn in following the peak velocity line may completely leave the tube surface. This might seriously affect the fibre assembly efficiency and, therefore, a large proportion of fibres might go to waste and a bad yarn would be the result.

In a similar manner, the maximum values of pressure at positions away from the tube wall also seem to suggest that the fibres and the forming yarn will move over to the region of maximum pressure, thus once again tending to make the fibres and the forming yarn to come out of contact with the tube surface. As mentioned earlier, these peak values of air velocities and pressure move progressively further away from the tube surface as the air flows down to the suction end. In consequence this would result in the fibres as well as the forming yarn tending to follow a similar path to that of the air flow.

The above inference would be true in the case of air flow in parallel pipes but since the fibres and the yarn follow an arcuate path inside the vortex tube, the centrifugal acceleration acting on them would tend to moderate the expected behaviour of fibres and the yarn coming away from the tube wall. In fact at the region of air entry the fibres and the yarn will be very much under the influence of centrifugal forces acting on them and this would, therefore, tend to move them radially outwards on to the tube surface. The centrifugal forces may gradually become reduced as the fibre flow proceeds along the tube because the velocity of fibres would change direction gradually. At the air entry, the motion is almost entirely that of a true vortex whereas at the end of a very long tube it is almost completely axial. Hence it may be expected that with increasing distance from the air entry position, the fibre flow and the yarn path may also tend to progressively move away from the tube wall and these paths will then tend to lie in a region midway between the tube surface and the tube centre. With long lengths of forming yarn inside the tube, the fibre assembly efficiency may not be as high as expected because portions of the yarn tail may well be away from the tube surface. It is quite likely that the fibre flow inside the tube may also move in a path away from the tube wall but different from that of the yarn. When the motions of fibres and yarn take place along different surfaces, the chances of assembly are much reduced. It was found that high fibre assembly efficiencies of the order of 90% to 95% were obtained with short lengths of forming yarn, the yarn length varying between 15 to 25 cm.

Two contrary twisting effects on yarn may exist in a vortex tube. These are:-

(a) the twisting effect due to the rotation of the vortex as a whole in which case the vortex would operate on the yarn as if it were approximately concentric with the vortex itself and

(b) the twisting effect due to torsional shear between two adjacent circular streamlines.

The second possibility is concerned with the twisting effect mentioned in (b). In this case, the twist insertion in the forming yarn will be in the opposite direction to that of the vortex flow. A differential in air velocity existing between the inner and outer surfaces of the yarn would tend to impart a torsional shear on the yarn. It might be also mentioned that solid friction effects between the yarn and the tube surface and also the electro-static charging of the fibres and tube would tend to create reversed twisting.

A small displacement of yarn away from the tube wall will tend to reduce rolling action and make sliding of the yarn easier. However a large displacement will bring yarn to a point where the shear gradient will tend to roll the yarn and insert twist in the same sense as the vortex [illegible]

The velocity probe used by Lay measured not only the magnitude of the velocity vector but also detected the direction of the air flow. So it is, therefore, possible to resolve the velocities into axial and tangential components.

7.2.11.2. Magnitude of the velocity vector

Fig. 7.21. shows the axial velocities traverses at different radii at No.2 station. Some results of [illegible] [illegible] work done by Eckert[91] et al (also in the subject of heat transfer) should be included. These results are similar to those obtained by Lay. However, in this case, a vortex tube of 3 in. diameter was used. Measurements of velocities were taken at 1 in., 6 in., and 18 in. away from the nozzle. The calculated axial velocity component at the three different stations are given in Fig. 7.22. From a study of [illegible]

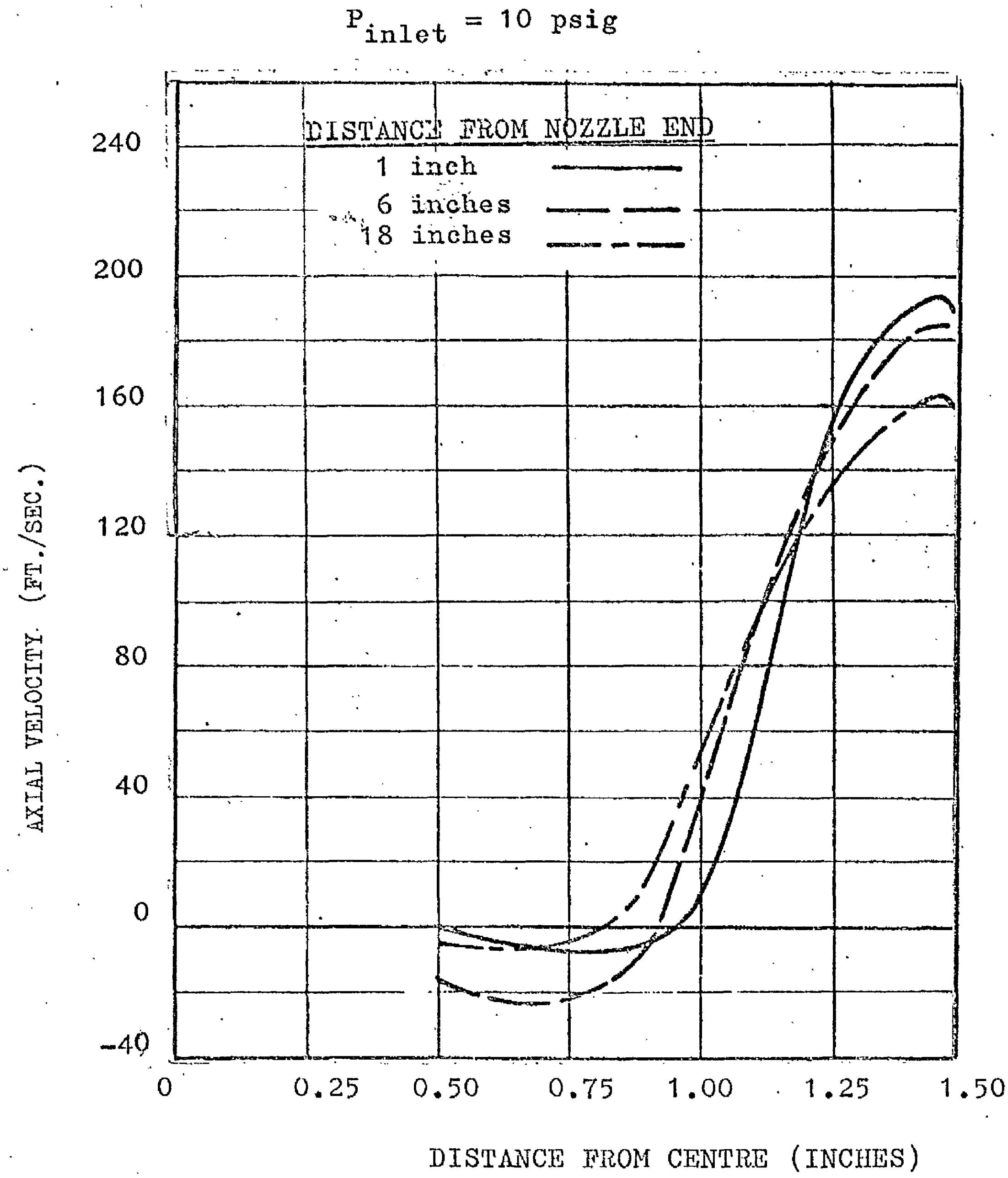



Fig. 7.22.

CALCULATED AXIAL VELOCITY

IN A 3 INCH DIAMETER VORTEX TUBE

this and Fig. 7.21 (page 272), it was observed that the high values of axial velocity were concentrated in a small annular region near the tube wall. (However it must be added that the relative axial velocities were always small when compared to the total velocities shown in Fig. 7.20.). One possible explanation of this phenomenon is that wall friction causes a decrease in both the axial and tangential velocities near the wall as the air moves down the tube towards the suction end. From considerations of continuity of flow, this would result in an increase in axial and tangential velocities at regions away from the tube wall. Such a change would indicate that some of the air near the tube wall must move in towards the centre as the flow proceeds down the tube. In so doing, the air would tend to conserve its angular momentum and there would be an increase in angular velocity as the fluid mass moves towards the centre.

7.2.11.3. Direction of air flow

The flow angle may be defined as the orientation of the velocity vector with respect to the tube axis. Referring back to Fig. 7.21., the flow angle at a typical station (viz., No.2) was plotted against the radial distance across of the tube. Eckert et al also plotted the flow angle at the three different stations (1 in., 6 in., and 18 in. away from the nozzle) against the radial distance and used three different inlet pressures (10, 15 and 20 p.s.i.g.). It was observed from Fig. 7.23. that the flow angle was usually independent of changes in the inlet pressures. It may be, therefore, said that, for a given nozzle design parameter, the flow angle of the air is quite insensitive to changes in air flow velocity.

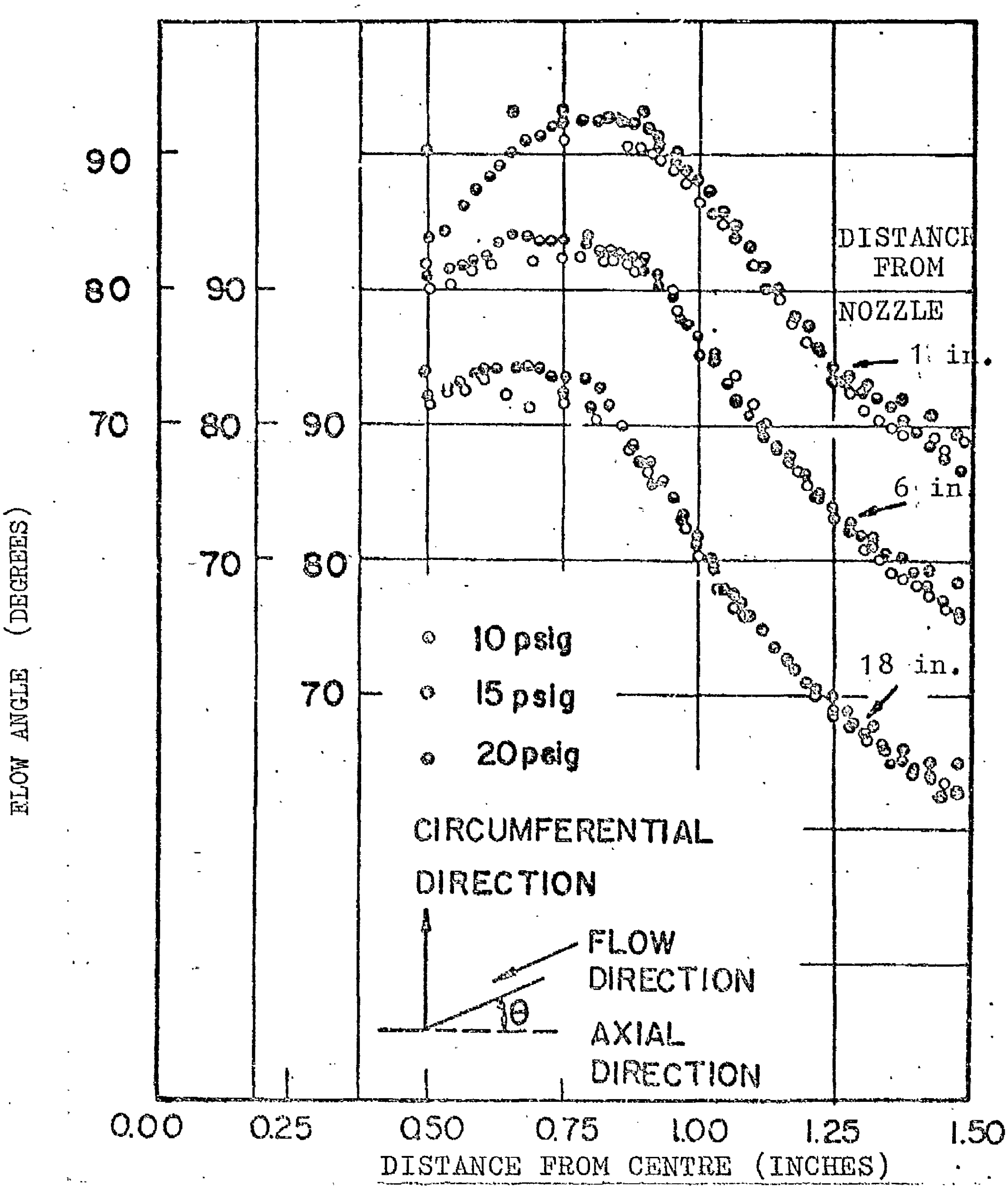



Fig. 7.23.

FLOW ANGLE MEASURED FROM AXIAL DIRECTION

Furthermore it was found by Eckert et al that the air flow usually moved in a helical path towards the suction end in an outer annulus only and that the radial width of this annulus increased with axial distance along the tube measured from the nozzle end. From this it may be inferred that fibres while tending to follow the air flow path will, in all probability, flow through this annular region adjacent to the tube wall for the reasons outlined in section 7.2.11.1. Moreover this fibre flow would be helically disposed and will tend to conform with the air stream path. Since the axial velocity component of a moving fibre would increase in relation to its tangential component as the flow proceeds along the tube, the pitch of the fibre helix and also that of the air helix is bound to increase. In an infinitely long vortex tube, the air (or fibre) flow beginning with a high tangential velocity component would tend to finish with a predominantly high axial velocity at the suction end. The above discussion probably explains the observed helical paths of fibre flow inside the tube with the pitch of the helix increasing down the tube length(please see section 13.4.).

The air and fibre helices will be identical to each other. However it should be borne in mind that although the air and fibre helical paths are same, the velocities of air and fibre are very different for the obvious reason that the fibre is subjected to retardation forces exercised by solid frictional and static forces developed during movement of fibres in the tube.

<u>7.2.11.4. Lay's temperature curves applied to vortex spinning</u>

From the temperature curves obtained by Lay and shown in Figs. 7.12. to 7.17. inclusive, it is evident that the region where the temperature reaches the maximum value is concentrated in a narrow annulus adjacent to the tube wall.

From Fig. 7.24., it is observed that the increase in temperature is sensitive to changes in air pressure, that is, the temperature increases with the speed of the air flow.

The narrow annular region where the temperature rise is maximum is a region in which most of the fibres and the forming yarn should move. The temperature inside the tube is considerably higher than the room temperature. When spinning is carried for a considerably long time, the conditions inside the tube can be quite different from the outside atmosphere and this may affect the spinning operation. Whether this higher temperature is conducive to vortex spinning or not is not yet fully known. However the various possibilities that may arise due to the effects of temperature are given below:-

(a) The high temperature produced near the tube wall region may cause dry conditions inside, that is, it will reduce the relative humidity of the air. A condition of low humidity and high temperature will increase the rate of static charge formation. The effects of large static charges on fibres and yarn are discussed separately in Chapters 8 and 9 respectively.

(b) The fibres become dry. Loss of moisture regain in fibres may give rise to harsh and hairy yarn.

(c) The solid lubricant present within the fibres ( for example, wax in cotton ) is likely to change its physical state and it may soften. The softening of the lubricant may eventually produce deposits of sticky lubricant on the tube surface. These deposits are not of noticeable quantity when the fibres flow for a short duration only but on prolonged running, it is observed that a fine uniform coating

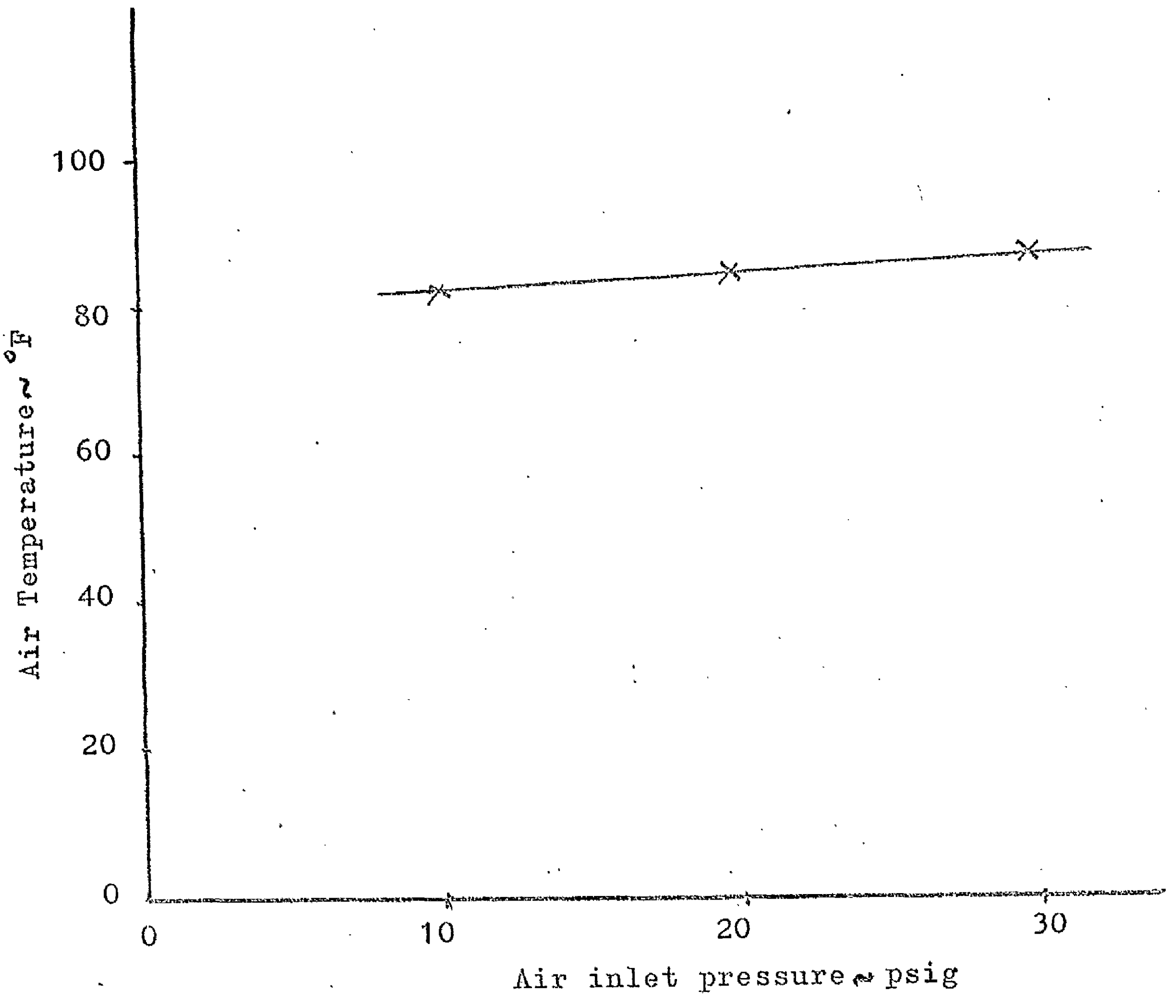



Fig. 7.24.

EFFECT OF AIR INLET PRESSURE ON THE AIR TEMPERATURE INSIDE THE VORTEX TUBE consisting mainly of waxy substances is found usually near the nozzle section of the tube. This coating might cause the following to occur:-

(1) The sticky nature of the coating might tend to cause the fibres to slow down abruptly on entering the vortex tube. The sharp deceleration imposed on the leading end of fibres would tend to cause the fibres to become crumpled. This would tend to lead to bad fibre assembly which, in turn, would tend to produce a poor, irregular yarn. Moreover the crumpled nature of the fibre configuration will mean an effective shortening of staple length of fibres. This will be reflected in the low breaking tenacity of the yarn.

(2) The coating might affect the coefficient of friction($\mu$) between the tube wall and the forming yarn. The increased coefficient of friction might encourage the yarn to roll inside the tube.

(3) The coating might affect the build up of static charges.

The above effects mentioned in (1), (2) and (3) may be mitigated because

(i) the high speed of fibre movement gives a very short time of contact between them and the tube wall

and (ii) it takes a reasonably long time for a significant build up of the deposit; this is because the lubricant is present in very small quantities in fibres like cotton.

However the tackiness on the surface of the fibres may have its advantages too. These advantages are as follows:-

(i) It may help to bind the fibres firmly together in the final yarn and thus contribute towards increased yarn strength.

(ii) The waste collected might be small because the high fibre condensation on the tube wall as a result of the coating on the wall and the sticky surface of fibres might tend to increase the fibre assembly efficiency.

(d) The mechanical properties of fibres, especially their modulus and torsional rigidity, are affected by heat. Generally most of the fibres and in particular those of the thermo-plastic type would tend to undergo a decrease in modulus with a rise in temperature. Those fibres which are thermo-plastic at low temperatues may be partially heat-set during spinning operations. For cotton fibres, heat setting probably will not take place. Cotton yarn in which twist is usually set by hygroscopic means will tend to react in a different way. The torsional rigidity of cotton fibres, unlike those of thermo-plastic man-made fibres, will tend to increase with temperature. This might be possibly due to the loss of moisture regain. Fibres passing through the hot region in the tube will tend to be deprived of their normal moisture content and, therefore, the yarn formed will tend to be fairly twist lively due to a reduction of twist in. Moreover because of twist liveliness, a large proportion of twist introduced into the yarn will tend to leak out through the free end.

Having discussed the question of heat setting, it is necessary to add that it is highly doubtful if heat setting will occur under the conditions normally used today with most of the fibres because the temperatures reached inside the tube will not be sufficient to produce marked changes in fibre characteristics. However it is conceivable that these effects might be utilised in the future, for example, by the use of high pressure air or perhaps by using heated air in conjunction with fibres having low temperature characteristics.

# CHAPTER 8

## THEORY OF FIBRE FLOW IN VORTEX SPINNING

# CHAPTER 8

## THEORY OF FIBRE FLOW IN VORTEX SPINNING

### 8.1. INTRODUCTION

A study of the fibre flow in a vortex tube is considered necessary for an analysis of the general problem of vortex spinning. The possible effects of air flow on fibres were discussed at some length in the previous chapter because it was thought quite relevant to the discussions then. However these discussions may also be considered along with the following.

Fibres flowing along an air stream in a vortex tube are subjected to

(a) the aerodynamic forces,

(b) the acceleration forces; these includes
(i) the centrifugal forces
and (ii) the deceleration forces,

(c) the frictional forces between the fibres and the tube wall and

(d) the electro-static forces generated by the movement of fibres along the tube wall.

All the forces mentioned above seemed to be interlinked with each other in some way. This may be explained as follows:-

The air flowing into the vortex tube creates aerodynamic forces which will influence the fibres introduced into the tube. The fibres will tend to be carried along the same helical path as that of the air flow. These fibres will tend to be accelerated during their movement and they will be forced to follow a curvilinear path in the tube surface. As the fibres are thrown onto the inner surface of the tube, they are subject to the action of centrifugal forces. The acceleration forces are likely to predominate at the air entry region but as the particles advance along the tube wall the deceleration will come into play. Fibre deceleration is caused by the solid frictional forces and also by the electro-static forces generated by the movement of fibres in contact with the tube surface. The frictional effects of the fibres may tend to cause the formation of static charges. The greater the energy absorbed by friction due to fibre movement, the greater will be the tendency to generate the static. On the other hand, any increase in static force will cause a rise in frictional force. Thus these two forces seem to be inter-related. With the type of materials normally used for spinning, static electricity is always present in the tube and it increases not only with the time of fibre flow but also with the flow rate and with the dryness of the surrounding air.

The relationship existing between the various forces acting on fibres may be summed up briefly in the following way:-

For any given nozzle design parameter, the aerodynamic force acting on fibres in the tube will increase with the air flow rate. Any increase in the aerodynamic force will tend to cause the centrifugal force on a fibre to increase in proportion to the square of the fibre velocity. As a result of this, the normal force exerted on fibres will tend to become large. This will tend to increase the frictional force which, in its turn, will tend to generate large electro-static forces. The creation of large static forces will, in its turn, tend to increase the frictional force on fibres. It is difficult to say what the ultimate net effect will be but it has been observed that in the case of fibre flow in a Perspex tube, the presence of large electro-static forces made a great proportion of fibres to adhere firmly to the wall surface.

A study of fibre flow will, therefore, necessarily involve a discussion on the effects of aerodynamic, acceleration, solid frictional and electro-static forces acting on fibres.

## 8.2. AERODYNAMIC FORCES ACTING ON FIBRES

The term "aerodynamics" is commonly applied to problems involving the relative movement of air and solid bodies. An analysis of the aerodynamic forces acting on particles released into an air stream is given in Appendix C 8.1.

The most important aerodynamic characteristic of a fibre is its light weight with respect to its size. The aerodynamic force acting on a fibre is proportional to its linear dimensions. It is also proportional to the square of the relative velocity between the fibre and the air stream. It was found by Mayer[92] et al that the acceleration of a fibre increases inversely as the square of its diameter and it is a weak function of its length-to-diameter (slenderness) ratio. Fibres, and in particular well opened tufts, have a high aerodynamic drag coefficient in relation to their mass. It is to be noted that aerodynamic drag forces will arise only when the velocity of the fibre is different from that of the air stream. If, in any given component direction, the air stream moves faster than the fibres it will impose an accelerating force on the fibres in that direction.

On the other hand, a retarding force will act when the fibre is moving faster than the air stream component.

A fibre introduced into an air stream will not follow the air path immediately because of the inertial effects of the fibre due to its mass and its initial velocity. Thus in steady conditions of free flight the only force tending to cause the fibre to move differently from the air is its inertial resistance to movement. Since the mass of the fibre and, therefore, the inertia is relatively small. Such fibres are carried along by even small currents of air and they respond quickly to changes in air movements. Nevertheless, however quick the response may be, there will be a lag and so the fibre path may be different from that of the air. The amount of lag will depend on the mass of fibre and on the abruptness of the air flow change. Initially the fibre will tend to move with a slower velocity than the air. However if the speed and path of air flow does not change sharply, then the inertial effects will be small. In fact, according to Feldman[93], the time required for fibres to reach a speed within 1% of the air velocity is about 6 milliseconds in a parallel uniform flow of air. In this time interval a fibre would have moved only a distance of about 7 inches before attaining the full speed of the surrounding air stream, of say, 100 feet per second. Thus, in a steady uniform flow, the fibres rapidly reach an equilibrium with the air stream velocity.

In the case of fibre flow in a vortex spinning tube, the fibres move in a helical path in contact with the tube surface. A short time after their introduction the fibres will follow an identical path to that of air flow. However since the fibre moves in contact with the tube wall the solid frictional and electro-static forces generated by the fibre movement will tend to retard the fibre flow. Thus even though the air and fibre helical paths remain identical, their respective velocities are very different from each other.

The relationship between fibre linear density and its angular velocity in the vortex tube can be obtained in the following way.

Let $l_f$ be the length of a fibre,
$r_f$ be its radius,
$m_f$ be its mass,
$\rho_f$ be its density,
$tex_f$ be its linear density in tex,
$V$ be the air velocity in the tube,
$\rho$ be the density of air,
$F_f$ be the drag force due to aerodynamic force acting on the fibre,
$\omega_f$ be the angular velocity of the fibre,
$F_{cf}$ be the centrifugal force of the fibre,
$N_f$ be the normal force on the fibre,
$\mu_f$ be the coefficient of soild(sliding) friction between the fibre and the tube wall,
${}_aV_f$ be the relative velocity of the fibre with respect to air,
$C_{Df}$ be the body drag coefficient,
$\theta$ be the angle between the fibre and the tube axis,
$S_f$ be the projected area of the fibre,
$r$ be the inner radius of the tube bore
and $g$ be the acceleration due to gravity.

$$tex_f = \frac{\text{weight of the fibre}}{\text{length of the fibre}}$$

$$= \frac{m_f}{g} \cdot \frac{1}{l_f}$$

$$= \frac{\pi r_f^2 \cdot l_f \cdot \rho_f}{g} \cdot \frac{1}{l_f}$$

$$= \frac{\pi r_f^2 \cdot \rho_f}{g}$$

$$r_f = \sqrt{\frac{tex_f \cdot g}{\pi \cdot \rho_f}} = \sqrt{\frac{g}{\pi \cdot \rho_f}} \cdot \sqrt{tex_f}$$

$$\text{or, } r_f = \text{constant} \cdot \sqrt{tex_f} \quad \ldots\ldots\ldots\ldots (1)$$

The forces acting on the fibre in the tube are

(a) the air drag force $F_f$ ,

(b) the centrifugal force $F_{cf}$

and (c) the frictional force which is equal to $\mu_f N_f$ .
The force due to static charge friction is ignored in this discussion.

$F_f$ may be resolved into vertical and horizontal components, viz., $F_f \sin\theta$ and $F_f \cos\theta$, as shown in Fig. 8.1.

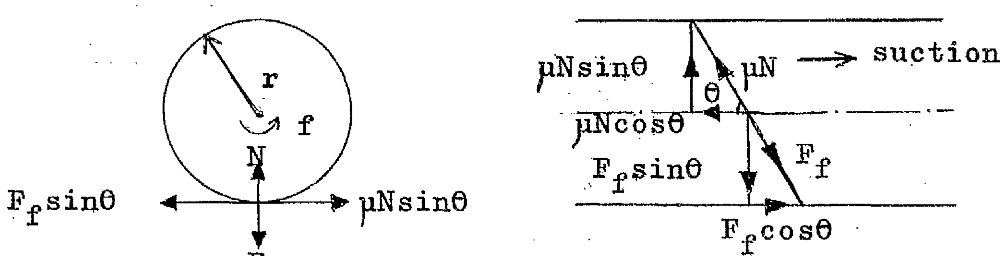



Fig. 8.1.

In a similar manner, $\mu_f N_f$ may also be resolved into the two components, viz., $\mu_f N_f \sin\theta$ and $\mu_f N_f \cos\theta$ .

In a state of equilibrium,

$F_f \sin\theta$ must be equal to $\mu_f N_f \sin\theta$

$F_f \cos\theta$ must be equal to $\mu_f N_f \cos\theta$

and $F_{cf}$ must be equal to $N_f$ .

$$\text{Now} \quad F_f = \tfrac{1}{2}.\rho.({}_aV_f)^2.C_{Df}.S_f.$$

$$= \tfrac{1}{2}.\rho.({}_aV_f)^2.C_{Df}.2r_f.l_f.$$

$$\text{or } F_f = \rho.({}_aV_f)^2.C_{Df}.l_f.r_f \quad \ldots\ldots\ldots\ldots (2)$$

$$F_{cf} = m_f.\omega_f^2.r$$

$$\text{or, } F_{cf} = \pi.r_f^2.l_f.\rho_f.\omega_f^2.r \quad \ldots\ldots\ldots\ldots (3)$$

$${}_aV_f = V - \omega_f.r.\frac{1}{\cos\theta} \quad \ldots\ldots\ldots\ldots (4)$$

$$F_f \sin\theta = \mu_f N_f \sin\theta = \mu_f F_{cf} \sin\theta$$

$$\text{or, } F_f = \mu_f F_{cf} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Substituting the values of $F_f$ and $F_{cf}$ from equations (2) and (3) respectively, the equation (5) becomes

$$\rho({}_aV_f)^2 C_{Df} l_f r_f = \mu_f \pi r_f^2 l_f \rho_f \omega_f^2 r$$

$$\text{or, } \rho C_{Df}({}_aV_f)^2 = \mu_f \pi \rho_f r r_f \omega_f^2$$

$$\text{or, } \frac{\rho C_{Df}({}_aV_f)^2}{\mu_f \pi \rho_f r} = r_f.\omega_f^2, \quad \text{or } k_1({}_aV_f)^2 = \omega_f^2.r_f \quad \ldots(6)$$

$$\text{where } k_1 = \frac{\rho C_{Df}}{\mu_f \pi \rho_f r} = \text{constant.}$$

Substituting the values of ${}_aV_f$ and $r_f$ from equations (4) and (1) respectively, the expression (6) can be rewritten as

$$k_1\left(V - \frac{\omega_f.r}{\cos\theta}\right)^2 = \omega_f^2.\text{constant}\sqrt{tex_f}$$

$$\text{or } \frac{k_1}{\text{constant}}\left(V - \frac{\omega_f.r}{\cos\theta}\right)^2 = \omega_f^2\sqrt{tex_f}. \quad \text{Let} \sqrt{\frac{k_1}{\text{constant}}} = k_2.$$

$$\text{Then } k_2\left(V - \frac{\omega_f.r}{\cos\theta}\right) = \omega_f.\sqrt[4]{tex_f}$$

$$\text{or, } k_3 = \omega_f\left(\sqrt{tex_f} + k_4\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where $k_3 = k_2V$ and $k_4 = \frac{k_2.r}{\cos\theta}$ ; $k_3$ and $k_4$ are constants.

$$\text{Now } \frac{k_3}{k_4} = \frac{k_2V}{\frac{k_2r}{\cos\theta}}, \quad \text{or } \frac{k_3}{k_4} = \frac{V\cos\theta}{r} \quad \ldots\ldots\ldots\ldots (8)$$

To establish an order of magnitude,

let $V = 5000$ cm/sec

$r = 1.25$ cm

and $\theta = 60^\circ$

$$\text{Then} \quad \frac{k_3}{k_4} = \frac{5000 \times 0.5}{1.25} = 2000$$

If $k_4$ is arbitrarily kept as 1, then the expression (7) becomes

$$\omega_f(\text{tex}_f + 1) = 2000$$

| $\text{tex}_f$ | $\omega_f$ |
|---|---|
| 0 | 2000 |
| 1 | 1000 |
| 4 | 829 |
| 9 | 732 |
| 16 | 667 |
| 36 | 580 |
| 64 | 522 |
| 100 | 481 |
| 256 | 400 |

Fig. 8.1.(a) shows the angular velocity($\omega_f$) of the fibre plotted against the fibre linear density($\text{tex}_f$).

Case 1. If $\text{tex}_f = 0$, then $\omega_f = \frac{k_3}{k_4} = \frac{V \cos \theta}{r}$

$$\text{Now} \quad {}_aV_f = V - \frac{\omega_f \cdot r}{\cos \theta} = V - r \cdot \frac{1}{\cos \theta} \cdot \frac{V \cos \theta}{r} = V - V = 0$$

In this case, $\omega_f$ is equal to the angular velocity of air.

Case 2. In all other cases,

$$\omega_f < \text{the angular velocity of air.}$$

That is, the fibre velocity in a vortex tube is always less than the air velocity.

It should be mentioned that Stalder(94) had also treated this problem in a similar manner.

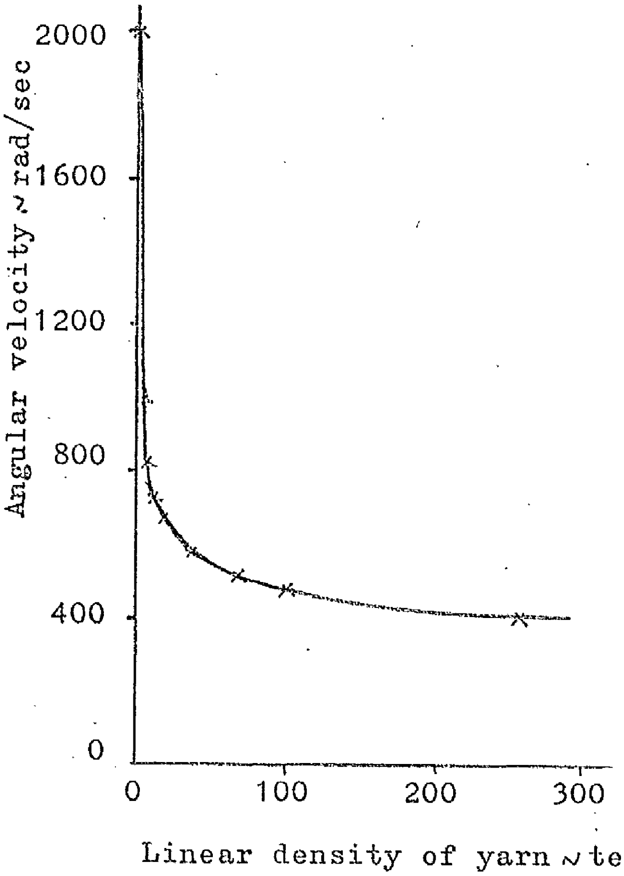



Fig. 8.1.(a)
RELATIONSHIP BETWEEN LINEAR DENSITY AND ANGULAR SPEED OF YARN

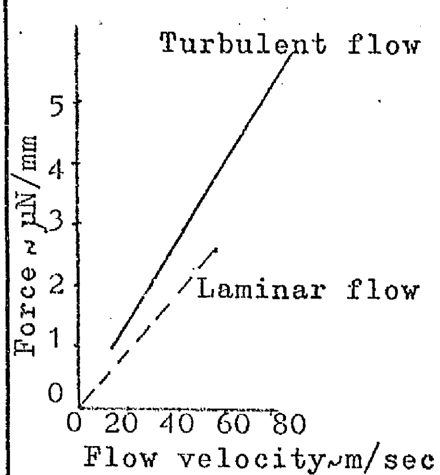



Fig. 8.2.
RELATIONSHIP BETWEEN FORCE PER UNIT LENGTH OF FIBRE AND AIR FLOW VELOCITY

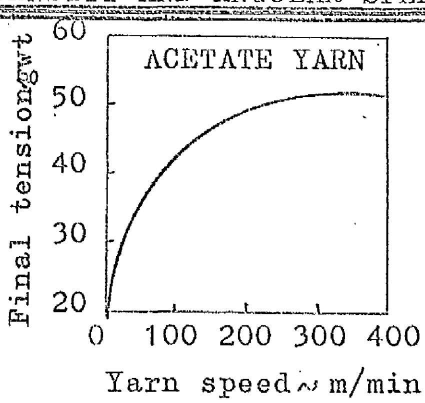



Fig. 8.3.
VARIATION OF TENSION WITH YARN SPEED

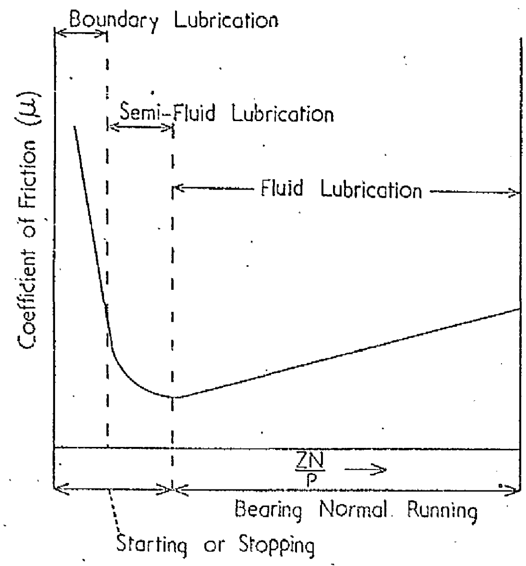



Fig. 8.4.
FRICTIONAL BEHAVIOUR OF A JOURNAL AND BEARING

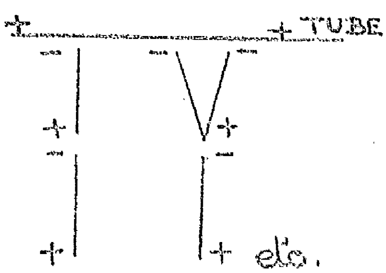



Fig. 8.5.
BEHAVIOUR OF FIBRES IN A CHARGED TUBE

8.2.1. Edberg's study on fibre flow

It may be said that generally most of the break spinning methods, and in particular the air vortex method, make use of air currents to transport the fibres from the feed to the assembly point. In general, most of the fibres, including the cotton fibres, are usually not straight and they assume a crimped shape with bends and hooks.

Edberg[95] studied the behaviour of fibres in air streams. The experiments were designed to investigate the possibility of separating the entangled tufts into individual fibres and parallelising the fibres by means of air currents alone. The experiments consisted essentially of three parts. They employed

(a) the use of laminar air flows in a straight, circular pipe of uniform diameter,

(b) the use of turbulent air flows in a straight, circular pipe of uniform diameter

and (c) the use of conical tube construction with the diameter decreasing towards the direction of air flow; in this case, the mean velocity of air increased towards the narrower part of the tube.

The first series of experiments were made with the fibres held stationary in a reasonably stable laminar air flow at low velocities (less than 5 m/sec.). It was found that the stretching forces on the fibres were too small to straighten out the hooks in them.

In the second series, experiments were conducted at high air velocities (10 to 100 m/sec.). It was found that an air speed of 80 m/sec gave a force of about 6 microNewtons per millimetre and the force required to straighten a single hooked fibre varied between 4 and 7 μN/mm, depending on the type of hook.

Fig. 8.2. shows the experimental values of the force per unit length acting on the fibre suspended in the air stream plotted against the air velocity. It may be noted that the slope of the curve for the turbulent flow is steeper than that for laminar flow. Experiments at turbulent flows showed evidence that parallelisation of staple fibres could be effected to a remarkably high degree by means of air flow alone.

In the final series, the tube was capable of being adjusted to produce different convergent-divergent flow paths towards the flow direction. The modifications were made for the specific purpose of giving accelerating air flows. The effect of this acceleration of air speed on the fibre configuration was studied with the help of short-duration, flash photographs covering the convergent path of the tube. It was found that a convergent angle of 30° gave the best results because a significant straightening of fibres was noticed and the number of parallel fibres increased considerably. In fact it was observed that the greater the acceleration of air flow, the greater was the parallelising effect provided that the turbulence created inside the tube did not disturb the effect of parallelisation.

Edberg concluded that it was not possible to disentangle the tufts and separate them into individual fibres by means of pneumatic means alone. However when fibres were presented as singles (from a previous process), then the use of high speed air on its own could orient the fibres and make them lie parallel to each other during their flight. This effect could be more pronounced with a tapered tube than with a circular tube of uniform diameter.

8.2.2. Application of Edberg's observations to fibre flow in vortex spinning

Low velocities of air flow are of no practical importance as far as vortex spinning is concerned because the relatively small aerodynamic forces created might produce only low rotational speeds of yarn in the tube. These low speeds would be reflected in slow take-off rates of yarn which would be unlikely to be economical. Moreover the suction at the nozzle with such low velocities may not be adequate to transport fibres properly from the feed to the assembly part of the spinning system.

High air velocities are normally used in vortex spinning. Air velocities of 100 m/sec and above are quite common. Very high air speeds will tend to increase the proportion of fibres going to waste. Fibre loss can probably be reduced by decreasing air speed but this will be achieved at the expense of twisting rate. An optimum air speed can possibly be worked out by taking into consideration such factors as the rate of twist insertion, fibre loss, cost of air consumption etc.

The following observations from Edberg's study may be usefully applied to the problem of vortex spinning:-

(a) Since high-speed air cannot separate the entangled tufts and clumps into individual fibres, it is essential that the feed to the vortex tube must be already processed so that the fibres can be supplied individually into the system.

(b) Fibres introduced one by one into the tube stand a great chance of being oriented with their length towards the flow direction due to the action of high speed air. Such a fibre orientation is likely to be conducive to good yarn formation.

(c) A fibre flowing in a tapered tube tends to be accelerated during its onward movement. This acceleration tends to make the fibres straight and well oriented with respect to the flow direction. From the point of view of fibre presentation which would be almost ideal in this case, it would be reasonable to expect that the use of a tapered tube would be conducive to the formation of a regular and strong yarn. The effective shortening of the staple length, as noticed in the structure of vortex spun yarns, is one of the factors responsible for the low strength of these yarns. This drawback might be remedied by maintaining the fibres in a straight and taut condition during their assembly. The straight and parallel alignment of fibres might improve the yarn regularity. Thus it remains to be seen if the use of a tapered tube would bring about the desired improvements in vortex yarns.

It might be pertinent to add the remarks made by Krause[96] with regard to fibre flow in an air stream. According to Krause, "... transferring fibres from a mechanical drafting system through an air stream will result in a near-ideal fibre distribution per cross-section as long as the average number of fibres in the cross-section is less than three. With more fibres in the cross-section, a tendency for tuft formation becomes apparent".

## 8.2.3. Tuft flow in a vortex tube

When a fibre attaches to the forming yarn, the fibre is subjected to sudden retardation forces. The mass of a tuft is relatively much larger than that of a fibre. Therefore if a tuft attaches to the yarn, the tuft will be subjected to comparatively large retardation forces. The attachment of a tuft to the forming yarn can only be effected if the cohesion between the tuft and the yarn is sufficiently strong so as to overcome the forces acting on the tuft tending to snatch it away from the main body of the yarn. Moreover the strength of the forming yarn at the point of tuft attachment should exceed the tension created by the tuft.

The various possibilities that may occur when a tuft flows inside a vortex tube are as follows:-

(a) The acceleration forces of the tuft are usually high. The forming yarn may not provide sufficient resistance to the movement of the tuft flowing past it, in which case, the tuft may not become attached to the yarn. It will eventually be carried into the suction pump.

(b) If, however, the tuft gets caught by the forming yarn, say, near the tail end of yarn, then there is every possibility that the forces exerted on the tuft may exceed the cohesive force of the forming yarn at the point of tuft attachment. If the former exceeds the latter, this will result in a break. The tuft with the remnants of the forming yarn will find its way into the waste collection.

(c) Since the forming yarn is tapered, its strength varies from place to place. The strength diminishes towards the tapered end. A tuft attached to the forming yarn at a place of maximum thickness in the yarn stands a better chance of remaining attached to it than one attached at the tail end. However this attachment will form a slub in the resultant yarn.

## 8.3. ACCELERATION FORCES ON FIBRES

Fibres subject to the influence of aerodynamic forces tend to follow the curvilinear path of the air stream inside the tube. They are accelerated from their initial velocity and they tend to attain the air stream velocity. In so doing, the fibres are thrown on to the tube wall and they are, therefore, subject to the action of acceleration forces. These forces tend to keep the fibres well pressed against the tube surface during their onward movement. This acceleration force is a vector sum of two components, viz., tangential acceleration and normal or centripetal acceleration.

Let the mass of fibre be $m_f$,
its linear velocity be $V_f$,
its angular velocity be $\omega_f$
and the radius of the tube be r.

Then tangential acceleration force $(f_t) = m_f \frac{dv_f}{dt}$.

and centripetal acceleration force $(f_c) = m_f \cdot \omega_f^2 \cdot r$.

The gravitational acceleration force may be ignored because the weight of a fibre is small; the gravitational acceleration force acting on a fibre is negligible especially in comparison with the centrifugal force acting on it.

The deceleration forces acting on fibres are those mainly due to solid friction caused by fibre movement. The static charges also tend to retard the fibre movement. These are dealt with in the next sections.

## 8.4. EFFECT OF SOLID FRICTION ON FIBRE FLOW

The two classical laws of solid friction state that

(a) the frictional force F is proportional to the normal load N so that the coefficient of friction $\mu = \frac{F}{N}$ is constant for a given pair of bodies

and (b) the frictional force is independent of the geometric area of contact between the two surfaces.

Generally fibres do not have a truly constant coefficient of friction. Usually values of $\mu = \frac{F}{N}$ are quoted to express the magnitude of friction under particular conditions. The value of $\mu$ varies with many factors, such as, load, speed, temperature, humidity, the exact state of surface etc.

There are two kinds of solid friction, viz., static friction and kinetic friction. Static friction is that force which opposes the tendency to move due to the forces acting on a body at rest and its limiting value occurs when the body is at the point of transition from rest to motion. Kinetic friction is that force which resists continued sliding. The value of kinetic friction is usually less than that of static friction for a given pair of bodies.

When dealing with the flow of fibres inside a tube it may be assumed that the type of friction that is generally encountered is kinetic rather than static friction. Very little work seems to have been done on the effect of speed on the friction of clean fibres on the materials that have been found useful for vortex spinning tubes. On the other hand, there has been a large amount of work carried out on the friction of lubricated fibres and it is generally agreed that friction increases with speed. Roder[97] experimented with lubricated yarns at speeds ranging from 2 cm/min to 2000 cm/min and he found that although there was a drop in the value of friction between the low speeds of 2 cm/min to 90 cm/min, the value at higher speeds increased with a rise in speeds. This is shown in Fig. 8.3.

The possible effects of solid friction on fibre flow may be given as follows:-

(a) Since the leading end of a fibre comes in contact with a tube surface, the solid friction will tend to decelerate this end more rapidly than the trailing end. This behaviour might induce the fibre to "buckle" or "crumple up". The buckling or crumpling of the fibre will reduce the effective staple length of fibre. Fibres assembling together with such configurations will tend to lead to poor quality yarns, both as regards regularity and strength. The poor regularity may be due to the reason explained in (b). The low strength of yarn is probably due to a reduction in the effective cohesion between fibres because of their short lengths.

(b) When fibres are supplied continuously, the sudden deceleration imposed on the leading end of fibres might tend to make the fibres pack together and form agglomerates. These agglomerates will tend to spoil the fibre orderliness which is reckoned to be so essential for good fibre assembly.

(c) If the leading fibre end has a greater deceleration than the trailing end, the fibre will tend to assume a crimped shape. Yarns made from such crimped fibres will tend to be very extensible.

(d) A uniform deceleration imposed throughout the fibre length might tend to maintain the configuration of fibre shape existing during fibre supply. Due to the variations in the mass of one fibre to another, the velocities of the fibres will differ from one to another. When fibres of differing velocities come into contact with each other, the inter-fibre friction between the fibres will tend to vary. Random contacts of the fibres moving with differing velocities will introduce fibre disorderliness due to variations in the inter-fibre friction. This disorderliness of fibres will tend to produce an irregular yarn.

8.4.1. Hydrodynamic lubrication and fibres

As discussed earlier (Chapter 7, section 7.2.11.4.), the temperature of the narrow annular region adjacent to the tube wall is higher than the inlet air temperature. The fibres which move on the tube wall may be influenced by this temperature rise. Depending upon the surface temperature reached, it is some extent likely that a solid lubricant(such as wax in cotton fibres) may be transformed by heat into a semi-liquid condition . Lubricated flow conditions would then be the appropriate lubrication to consider. The movement of fibres may be impeded because light bodies, such as fibres, may experience a stick-slip movement due to change in conditions. If the fibre flow is seriously affected, this will result in a badfibre assembly. Moreover, the sticky nature of the lubricant may increase the frictional force acting on the fibres. In practice, it was observed when spinning with wool fibres containing grease that the fibres tended to stick to the tube wall and the speed of fibre movement was seen to be quickly reduced to low values.

There is a possibility that the type of lubrication encountered in fibre flow inside the tube could be hydrodynamic in nature. This is because it is quite likely that a continuous film of air may completely separate the moving fibres from the tube wall. Thus if there should be such air lubrication, the frictional force acting on the fibre may be much smaller than might otherwise be expected.

In an ideal case of hydrodynamic lubrication, the friction is extremely low and there is no wear of moving parts. The resistance to motion is caused solely by the viscosity of the lubricant. For the purpose of illustration, the frictional behaviour of a journal bearing is shown in Fig. 8.4.

Let the viscosity of the lubricant be Z,
the rotational speed of journal expressed as the number of revolutions per minute be N,
and the nominal pressure on the bearing, i.e., the load divided by the projected area of the bearing be P.

It is observed under condition of fluid lubrication, the coefficient of friction $\mu$ is low and it is proportional to $\frac{ZN}{P}$.

<u>8.4.2. Air lubrication in fibre flow</u>

Assuming that there is air lubrication only, the frictional force on fibres will be quite low. The effective coefficient of friction $\mu$ is simply a linear function of $\frac{ZN}{P}$. This behaviour might give rise to two effects, viz.,

(a) the frictional force will increase, though only gradually, with the speed of the fibres

and (b) as discussed in section 7.2.11.4., the temperature near the tube surface, i.e., in a narrow annulus adjacent to the tube wall rises with air velocity and so with fibre velocity also. This increase in temperature will lower the air velocity which, in its turn, will tend to reduce the effective coefficient of friction $\mu_f$. The frictional force will thus tend to reduce with fibre speed due to this cause.

These two effects are contradictory to each other. So it may be reasonable to assume that the increase in frictional forces due to increased fibre speeds are negligible in practice.

Air lubrication with its associated low values of coefficient of friction will tend to induce the fibres to move along the air streamlines and will also tend to make the fibres attain the velocity of the air. It may not be entirely possible to achieve the latter condition due to the mass of the fibre involved. There will certainly be a time lag in the fibre speed, the amount of lag depending upon the fibre mass and the value of the coefficient of friction between the fibre and the tube wall but the fibre flow will follow smooth streamlines and will only diverge therefrom when there is a fairly abrupt change in flow direction.

In air lubrication, since the fibres do not touch the tube surface but float about very near it, the fibre assembly into yarn may be impaired. If the forming yarn and fibres happen to travel at different distances from the tube wall, then the collection of fibres by the forming yarn will be seriously reduced.

## 8.5. EFFECT OF STATIC ELECTRIFICATION ON FIBRES

The movement of fibres against the inner wall of the Perspex vortex tube will tend to generate static electricity. The conditions favourable for static generation depends upon many factors. Amongst these factors, the two that are of great importance are

(a) the characteristics of the fibres used in spinning and (b) the nature of the surface with which fibres come in contact.

Cotton fibres (contrary to their general behaviour in conventional processing where a negligible quantity of static charge is formed) will tend to produce static charges which, if left uncontrolled, might finally lead to the production of a bad yarn. Considerable electro-static charges will tend to be created when regenerated cellulose or man-made fibres are used. In the present research, Perspex (acrylic) tubes were generally used for vortex spinning. These tubes are highly prone to static electrification. Metallic tubes, on the other hand, did not produce any noticeable charging effects on fibres, nor for that matter did they produce good yarns.

The other factors which tend to contribute to static generation are equally important. The rate and time of fibre flow and the atmospheric conditions during spinning might play a significant role in charge formation. Under steady conditions, the amount of static forces will tend to increase with the rate of fibre flow. Also they will tend to increase exponentially with flow time. Again conditions of low humidity and high room temperature tend to be favourable for rapid static charge formation.

The presence of static charges in small quantities may not normally impair the fibre assembly and in fact it mayht form an essential requirement for proper spinning, as explained later. If, however, the static formation inside the tube is left uncontrolled then a stage will be reached when the fibres will tend to adhere to the tube wall. This attached fibre mass will tend to gather additional fibres which are fed into the system and this will tend to build up the fibre mass resulting in tuft formation. The flow of fibres freshly introduced will tend to become unsteady due to obstructions caused by the clinging tuft of fibres on the tube wall. This behaviour will tend to result in irregular attachment of fibres along the forming yarn and a bad uneven yarn will be the result. Thus the presence of large electro-static charges will tend to be detrimental to good spinning. In summing up, it may be seen that a small amount of charge tends to be beneficial whereas the presence of large charges tends to be detrimental to vortex spinning. A control over charge formation ought to be exercised so that a constant level of requisite amount of charges may be always maintained in the tube.

The electro-static attraction between the opposite charges at the place of charge separation will effectively tend to increase the normal force between the two surfaces. This will lead to an increase in the frictional force on the fibre. It is indeed difficult to ascertain the exact proportion of the observed friction due to this effect. However the frictional effects caused by the static will tend to decelerate the fibres. This retardation may lead to telescopic condensation of fibres and hence a bad fibre assembly. The effect of fibre retardation on the formation of a yarn is discussed in section 8.4.

When electrically charged a fibre becomes a di-pole, that is, one end of the fibre carries a net negative charge and the other end a net positive sharge. One end of the fibre will tend to be attracted to the tube surface and the other end to be repelled. The tube wall will tend to attract towards itself the fibre end of opposite polarity to its own, thus tending to make the other end of fibre to project into the inside of the tube. Several possible effects may arise due to the charging of fibres, viz.,

(a) The fibres travel along the air streamlines but because of frictional effects due to static charge, they will tend to travel at an ever diminishing velocity. This, in turn, might tend to improve the fibre capture by the forming yarn.

(b) Because of the charges, the fibres may travel with their axes inclined to the streamlines and this may increase the aerodynamic forces acting on them. Also this mode of travel may assist the fibres to assemble on to the yarn because the fibres stand out from the tube surface.

(c) Because like charges repel each other, the fibre ends of the same polarity will tend to repel each other. Since all the like charges face the same way, the tendency to repel one another might make the fibres to become uniformly spaced. Orderliness of fibres is a pre-requisite for good spinning and, therefore, it may be expected that this uniform spreading of fibres may be conducive to good fibre assembly. The final result may be a strong, regular yarn.

(d) Because of the attraction of unlike charges, the fibres might tend to agglomerate, possibly in a rope-like manner as indicated in Fig. 8.5.* This might give rise to the formation of tufts. Attachment of tufts will tend to cause slubs in the forming yarn and the resultant yarn will tend to be of poor uniformity. Alternately, these tufts may be drawn into the suction pump and collected as waste because the fibre agglomerates may be exposed to the higher air velocity region away from the tube wall and this may tend to break away large agglomerates.

(e) Highly charged fibres may attract dust and dirt particles from the atmosphere and so form "fog marks" in the yarn.

Since the purpose of the tube surface is to cause the fibres to meet and assemble on the forming yarn, the deceleration of the free fibres due to friction might or might not be very important although the friction acting on the fibres once assembled on the yarn might well be. It might be more important for the fibres to be evenly distributed and held in attitudes conducive to good assembly.

The effects mentioned in (a), (b) and (c) tend to produce good fibre assembly and, therefore, good even yarns but the effects (d) and (e) tend to cause bad yarns.

From the foregoing, it appears that it may not necessarily be a good thing to eliminate the static charges and indeed attempts to use a metal spinning tube, as mentioned earlier, proved unsuccessful. On the other hand, excessive charging may seriously retard the fibre flow and also the rotational speed of yarn tail. The latter effect will tend to limit the torque available for twist insertion into the fibre assembly. Hence it would appear that a compromise is needed in the amount of charge present in the tube.

* p.294

# CHAPTER 9

## THEORY OF YARN MOVEMENT

# CHAPTER 9

## THEORY OF YARN MOVEMENT

### 9.1. INTRODUCTION

In this chapter, the discussions are mainly confined to the movement of a seed yarn in the spinning tube. In air vortex spinning, the seed yarn is inhaled into the tube through an axial entry which is coincidental with the tube axis. This seed yarn is caused to rotate due to the aerodynamic force acting on it. Unlike the fibres, all the elements forming the yarn are interlinked. Hence rotation given to any part of the yarn in the tube causes the whole of the yarn to rotate. Again since the yarn passes through the axial hole, the yarn rotates about the tube axis. Due to this rotation, the yarn is centrifuged out. The containment of this moving yarn by the tube wall introduces retarding forces due to solid friction and static charges. The various forces acting on yarn - aerodynamic, centrifugal and frictional forces (due to solid friction and static charges) - have been already discussed in detail in the previous chapter and most of the comment is applicable to yarn but also there will be forces transmitted from one fibre to the next.

### 9.2. MAGNITUDE OF THE FORCES ACTING ON YARN

The different forces acting on an element of yarn are given by

aerodynamic force $= \frac{1}{2} \rho ({}_aV_y)^2 . C_{Dy} . S_y$

(the symbols are explained in section 8.2.; subscript y is used for yarn)

centripetal force $= m.\omega^2.r$, where

$m$ = mass of yarn,

$r$ = tube radius

and $\omega$ = angular velocity of yarn.

frictional force = $\mu . F$ where,

$\mu$ = the coefficient of friction between the yarn and the tube surface

and F = the normal force.

A change in the linear density of yarn will cause a change in the centrifugal force and this will ultimately affect the tension. It may be safely predicted from the relationship between centrifugal force, tension and yarn mass that

yarn tension $\propto$ linear density of yarn.

Again a change in the rotational speed of yarn will affect the centrifugal force and tension.

Since $\omega = \frac{2\pi N}{60}$, where N is the rotational speed of the yarn, centrifugal force $\propto \omega^2$.

Therefore,

yarn tension $\propto$ (yarn speed)$^2$.

## 9.3. YARN SHAPE IN THE VORTEX TUBE

Throughout the present work, the term "forming yarn" is applied to that length of yarn extending from the exit hole in the tube to the free end of the yarn lying inside the vortex tube. The forming yarn may be considered to consist of three portions, viz.,

(a) the portion which lies between the yarn exit hole and the tangential ports of the nozzle; this portion may be called the "drive element" of the yarn (this is shown in Fig. 9.1.),

(b) the short yarn length in the nozzle region lying directly in the path of air entering the tube; this may be called the "intermediate element"

and (c) the remaining length of forming yarn up to the free end.

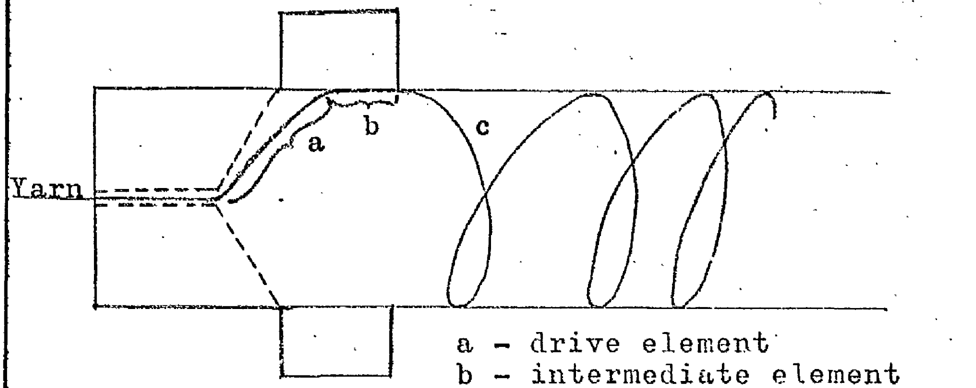



Fig. 9.1.

YARN HELIX IN A VORTEX TUBE

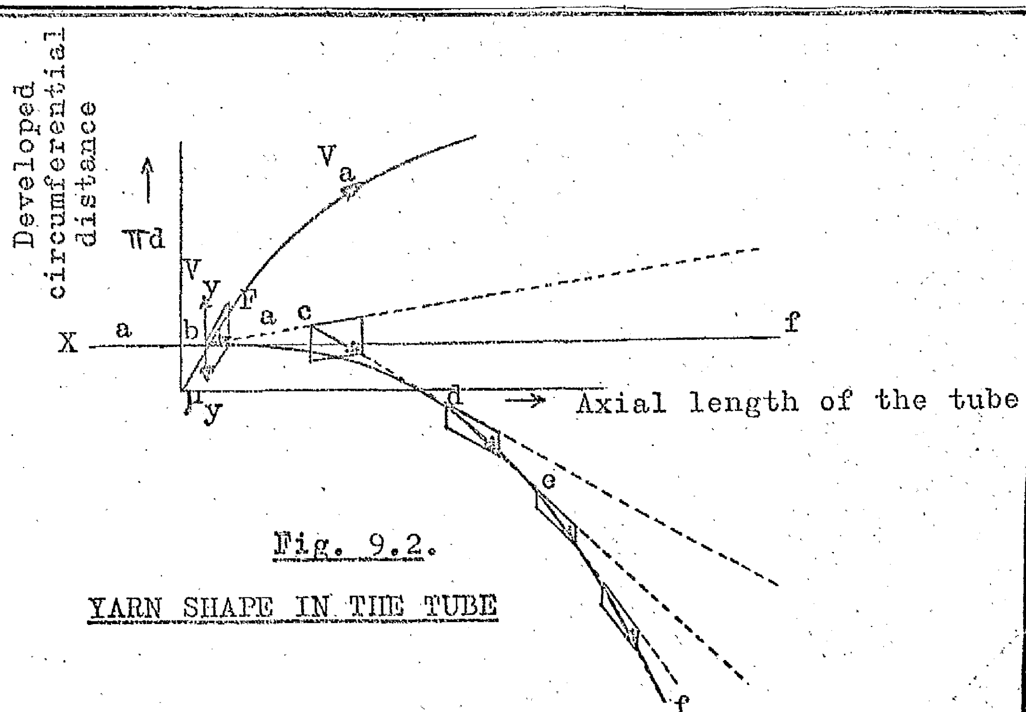



Fig. 9.2.

YARN SHAPE IN THE TUBE

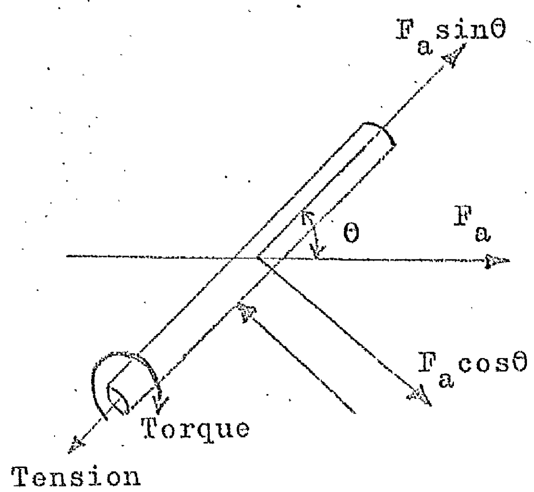



Fig. 9.3.(e)

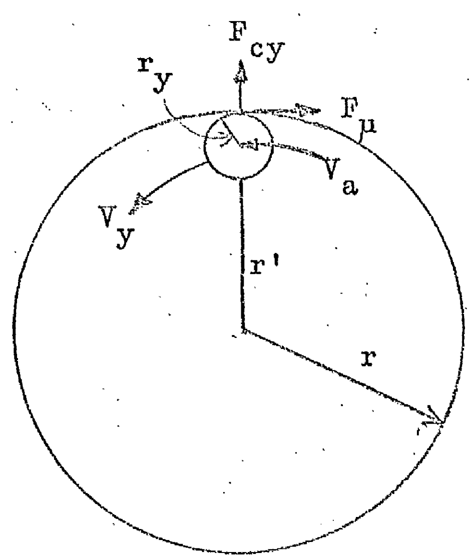



Fig. 9.5.

It had been noticed that the shape of the forming yarn was approximately helical and that the pitch of the yarn helix gradually reduced towards the free end when suction was applied to the vortex tube. This behaviour of yarn needs explanation.

The air flowing through the tangential ports of the nozzle first acts on the short length of the yarn which constitutes the drive element. Rotation of the drive element causes the remaining length of yarn to follow its movement. In so doing, the remaining length of yarn tends to lag behind in its movement and this causes the yarn to assume an attitude (or position) in a direction opposed to that of the air flow. The air flow tends to induce the yarn to follow the vortex streamlines and, in so doing, the yarn suffers a radial acceleration which tends to keep it in contact with the tube wall. The radial acceleration of the yarn combined with the inertial lag due to its movement tend to make the yarn assume an approximately helical shape.

An attempt is made to give a theoretical explanation to this form of yarn behaviour.

Consider the circumferential surface of the vortex tube to be developed into a single plane. The trajectory of the air stream is represented by the curved line $V_a$, as shown in Fig. 9.2. Assume that one end of a yarn is anchored near the axial end of the tube so that the yarn withdrawal rate is zero and the other end is free to rotate inside the vortex tube. If the yarn withdrawal rate is zero, an element of yarn can only move circumferentially on the inner tube surface and under steady conditions there will be, therefore, no axial component to the movement. A length of yarn af anchored at X is free to be acted upon by the air stream flowing through the nozzle. The aerodynamic force $F_a$ acting on the yarn will tend to move the yarn element at b perpendicular to the tube axis but this element is restrained by frictional forces, inertial lag, stiffness of yarn (because the yarn is made up of a number of elements linked together and is continuous). Therefore the force acting on b will tend to create an equal and opposite reaction force. The resultant of this reaction force and the force $F_a$ will determine the path taken by the remaining yarn. If resultants of yarn reaction forces and the force $F_a$ are drawn at each of the yarn elements at c, d and e, then it can be seen that the forming yarn will take a shape approximately helical, as shown in Fig. 9.2. It may be also noticed from this figure that the direction of yarn helix (the slope) is of opposite hand to that of the air helix.

The velocity diagram of a yarn element is shown in Fig. 9.3.

Let $V_a$ be the velocity of the air stream,

$V_y$ be the velocity of an element of the forming yarn at a point A on the tube wall,

$_aV_y$ be the velocity of yarn with respect to the air,

$F_a$ be the force acting on the yarn element,

$F_\mu$ be the frictional force exerted between the yarn and the tube wall; (this frictional force includes both solid frictional and static frictional forces and it is assumed to remain constant in this treatment),

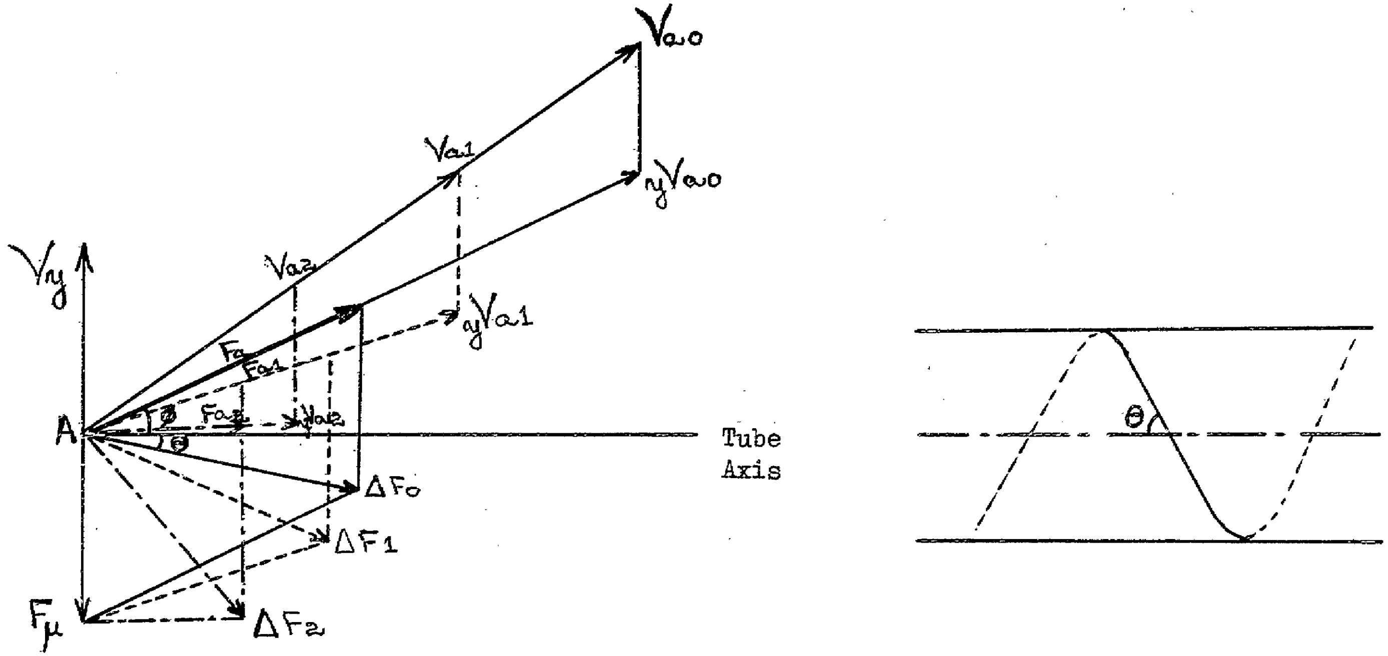



Fig. 9.3

VELOCITY DIAGRAM OF A YARN ELEMENT

$\phi$ be the angle ${}_yV_a$ makes with the tube axis and $\theta$ be the angle the resultant velocity of yarn element($\Delta F$) makes with the tube axis.

The vector difference between $V_a$ and $V_y$ is represented by ${}_yV_a$. $F_a$ represents the pneumatic force acting on the yarn at point A and has a magnitude which is a function of ${}_yV_a$. The frictional force $F_\mu$ acts opposite to $V_y$ round the tube wall and the resultant of $F_a$ and $F_\mu$ gives $\Delta F$ which acts at an angle $\theta$ to the tube axis. $\Delta F$ represents the increment of force acting on the element of yarn and the summation of these increments along the yarn determines the tension in it. Each element of yarn will try to align itself in the direction $\Delta F$ for that element but it might be restrained from doing so by the stiffness of the yarn. Where the deviations from a pure helix are not very great nor sudden, the stiffness effect may be ignored in order to arrive at a reasonable approximation.

From the diagram, it may be observed that the direction of $\Delta F$ is no longer parallel to that of air flow and indeed it is opposed to the air stream(and fibre) path. This proves theoretically that the yarn and air(and fibre) helices will be of opposite hands.

Note:- It must be added here that the direction of yarn helix depends to a large extent on the position of the air entry and also on the length of yarn lying inside the tube. All the above treatment has been made with the assumptions that (a) the nozzle is positioned near the axial hole end of the tube

and (b) a considerably long length of yarn is lying inside the vortex tube.

If the nozzle were to be positioned at a distance away from the axial hole end(somewhere in the middle of the tube length) so that the tail end of the yarn is acted upon directly by the air stream, then it may be seen that the yarn tail end will tend to orient itself towards the direction of air flow. The remaining length of yarn will tend to align itself in the same direction. Therefore, in this case, the yarn and air helices will be in the same direction.

However, it was a normal practice in this research to position the nozzle quite close to the closed tube end. The forming yarn was also reasonably long. Hence, under these conditions, it is pertinent to consider the case where the yarn shape and the air(or fibre) helical path are opposed to each other.

Consider various elements of yarn along the helix.

<u>Condition 1</u> :- $V_y$ is constant.

Since all the elements in a forming yarn are interlinked and form a continuous yarn, $V_y$ is constant for all elements of yarn along its length.

In Fig. 9.3a, the subscripts 0, 1 and 2 denote the conditions of yarn elements at progressively increasing distances from the nozzle end. $\Delta F_0$, $\Delta F_1$ and $\Delta F_2$ represent the resultant forces acting on these yarn elements.

Now as the air flow progresses down the tube, its velocity in the vicinity of the tube surface decreases as described in section 7.2.11.1.

As $V_a$ decreases, ${}_yV_a$ decreases, $F_a$ decreases and therefore $\phi$ decreases. Since $V_y$ is constant for all elements, the normal force will be constant if the yarn tail is of uniform thickness along its length. Under these conditions, it is reasonable to assume that $F_\mu$ remains constant and, therefore, $\Delta F$ will reduce in magnitude and there will be large changes in $\theta$ which is such that the yarn helix tightens towards the free end.

In actual spinning conditions, the forming yarn is tapered towards the free end. The effect of variation in cross-section of yarn will affect $F_a$ as well as $F_\mu$. The progressive decreases in values of $F_a$ and $F_\mu$ towards the free end of yarn will tend to result in corresponding reductions of the magnitude of $\Delta F$. These progressive reductions in the magnitude of $\Delta F$ will tend to increase correspondingly the values of $\theta$ towards the open end of yarn. This will, in turn, lead to a much quicker tightening of the yarn helix towards the free end as compared to the previous case where the forming yarn was considered to be uniform in thickness along its length.

<u>Condition 2</u> :— $V_a$ is varied at the nozzle.

For the sake of simplicity, assume that the forming yarn is uniform in thickness along its length. Consider a typical section of yarn, i.e., one which will describe a whole helix.

As $V_a$ decreases, $V_y$ decreases. In the previous case, it was reasonable to assume that $F_\mu$ was constant but this would not be true when $V_y$ is decreased. This is because

(a) the coefficient of friction $\mu_y$ is a function of the yarn velocity $V_y$,

that is, $\mu_y = f(V_y)$

and (b) the normal force acting on yarn due to centripetal force is equal to $\frac{V_y^2}{r}$, where r is the radius of the tube;

$$\text{therefore } F_{\mu} = f'\left(\frac{V_y^2}{r}\right),$$

that is, the frictional force increases directly with the yarn velocity.

If $F_{\mu}$ decreases, the yarn velocity $V_y$ will increase and ${}_aV_y$ will decrease in consequence. A decrease in $V_a$ results in some reduction in ${}_aV_y$(but not as much as might be expected) and both $F_a$ and $F_{\mu}$ will reduce. It seems likely that θ will also decrease and, therefore, the helix will become elongated or if $V_a$ is increased the yarn helix tends to tighten up.

9.3.1. Effect of changes in helix angle of yarn tail

The force $F_a$ acting on the yarn element may be resolved into its components, viz., $F_a \sin\theta$ and $F_a \cos\theta$, as shown in Fig. 9.3.(a).

sliding force on the yarn element:

$$F_a \sin\theta = \Delta \text{ tension},$$

rolling force on the yarn element:

$$F_a \cos\theta \times 2r_y = \Delta \text{ torque}.$$

The condition for the yarn to slide or to roll is determined by the angle θ(say, $\theta_{critical}$).

Consider the case where $\theta < \theta_{critical}$, where

$$\tan\theta_{critical} = \frac{\mu_{rolling}}{\mu_{sliding}}.$$

In this case, $F_{\mu}$ will tend to decrease for a given value of $V_y$ and so θ will decrease, that is, when rolling is established it tends to elongate the helix. $V_y$ will also tend increase and thereby tend to cause θ to increase further. A new equilibrium will then be established.

In general, it may be said that a tight yarn helix will tend to make the yarn slide and an open helix will tend to encourage the yarn to roll.

## 9.4. TWIST INSERTION IN YARN

As already explained in section 9.3., the forming yarn is driven by the drive element which, in turn, is caused to rotate by the aerodynamic force acting on it. The drive element is thus subjected to pneumatic forces. These forces tend to accelerate the drive element and hence the forming yarn. However solid friction and frictional force due to static charges acting on the remaining length of the forming yarn tend to decelerate the yarn. Thus if the yarn tail is allowed to become long, the total torque available to insert twist will be reduced because of the cumulative effects of total frictional forces acting along the length of the forming yarn. (This behaviour was studied by varying the length of the yarn inside the tube and measuring the rotational speed of yarn helix; this is dealt with wink section 12.7.1.).

When working under sliding conditions, it might appear that each revolution of the forming yarn would insert one turn of twist but in reality this is not so because the twist can leak away through the open end of the yarn and be lost. The rotational speed of the vortex must be greater than the net twist insertion rate. Solid friction between the yarn and the inner surface of the tube can give rise to unwinding effects due to the rolling action of the yarn. Moreover shear between co-axial elements of air will also tend to untwist the yarn. The only factor that prevents a complete loss of twist is the fluid friction on the yarn rotating about its own axis within the tube. Thus the system of twist insertion is a constant torque one rather than a constant twist one.

The torque acting on the forming yarn will depend upon the twist loss rate, the yarn diameter, the length and hairiness, the air density and viscosity. Thus for a given vortex speed, the twist loss will tend to adjust itself until the twist retaining torque just balances the torque applied by the air vortex to the helix as a whole.

Solid friction will tend to reduce the amount of torque available to retain the twist. Thus, in the case of a high friction system, the net twist insertion rate will tend to be low and because of this the forming yarn will tend to be weak. This will tend to cause the yarn tail to break and thus cause an increase in fibre wastage. Furthermore the short tails will tend to reduce the torque available and thus the system is likely to be quite sensitive to frictional effects.

It has been suggested in section 10.3., that the more efficient the assembly at each intersection, the less will be the tail length. This will reduce the twist insertion rate. However this is true only to some extent because the frictional forces acting on a long tail due to the rubbing on the tube wall will tend to be greater than with the short tail. Due to the cumulative friction effects the twist gain with a long tail will not be proportionate to the length and indeed for very long tails a twist loss is possible. Consequently, there seems to be little point in aiming for a very long yarn tail within the tube but there might be an optimum length to give the best twist insertion rate.

In the vortex spinning mechanism, the rotation of the yarn about its own axis and, therefore, the final twisting of the yarn is brought about by two opposed effects. They are as follows:-

(a) Twist is introduced into the yarn in the same direction as that of vortex flow. In this case, the yarn slides bodily around the tube during its rotation. Theoretically, for every single turn of yarn helix rotation one twist can be inserted into the yarn, although in practice, the twist above a certain limit(which depends upon the torque characteristics of the yarn) can leak out through the open end. This method of twist insertion, wherein the final twist in yarn is achieved mainly due to the orbital rotation of yarn helix, may be termed twisting due to yarn sliding.

(b) In the second case, the frictional contact between the yarn and the tube wall tends to roll the yarn about its own axis. This rolling action causes the yarn to be rotated in the opposite direction to the orbital direction of the yarn as a whole in the vortex tube. Therefore it follows that the twist in the yarn is necessarily in the opposite direction to that of vortex flow. This method of twist insertion may be termed twist due to yarn rolling. It is also referred to as reversed twisting. It would be expected that the amount of twist inserted into the yarn would be proportional to the ratio of tube diameter to yarn diameter. However, in practice, the amount of twist inserted was very much less than that expected by the above relationship. Perhaps this was due to twist leakage and also due to twist loss caused by the sliding yarn.

The direction of twist in the yarn depends upon many factors. One of the factors which seems to have a considerable influence on twist direction is the coefficient of friction between the yarn and the inner surface of the tube wall. For example, "crazing" of the tube surface increases the twist insertion rate(this is mentioned in section 11.8. The electrification properties of the materials (fibre and vortex tube) also appear to affect this behaviour. However the most important single factor seems to be the design of the nozzle(please see section 12.10.). A nozzle with a large width of inlet tends to produce a rolling action of the yarn whereas a nozzle with a narrow width inlet tends to result in yarn sliding over the tube wall.

Thus, under certain conditions, it is possible to produce yarns of the required twist direction. A reasonably adequate amount of twist in either direction can be obtained and this depends upon factors such as the design of the nozzle, the frictional behaviour of yarn and the material of the vortex tube etc.

9.4.1. Direction of torque on yarn

When a forming yarn rotates inside a vortex tube, the drive element of the yarn balloons away from contact with the tube wall but the remaining length of yarn usually rubs against the inner surface of the tube.

An idea of the torque direction in the forming yarn may be obtained by determining the rotational direction of yarn about its axis in

(a) the drive element

and (b) the remaining length of the yarn.

Consider the torque acting on the drive element of yarn. Please see Fig. 9.4.(a).

Let $\omega_y$ be the angular velocity of yarn and

$R$ be the radius of yarn movement measured to the centre,

$r_y$ be the radius of yarn,

$\omega_1$ be the angular velocity of air acting on the yarn surface nearer the tube centre, i.e., at a radial distance of $(R-r_y)$

and $\omega_2$ be the angular velocity of air acting on the yarn surface farther away from the tube centre, i.e., at a radial distance of $(R+r_y)$.

(a) Drive element

Case 1:

Let $\omega_2 > \omega_1 > \omega_y$

In this case, the torsional shear between co-axial elements of air stream lines will tend to twist the yarn in the same direction as that of vortex flow.

$$\text{Torque on drive element} = K(\omega_1-\omega_y)(R-r_y) + K(\omega_2-\omega_y)(R+r_y)$$

$$= K\left\{(\omega_1+\omega_2)R - 2\omega_y R - (\omega_1-\omega_2)r_y\right\}$$

$$= 2K\left\{\left(\frac{\omega_1+\omega_2}{2}\right)R - \omega_y R - (\omega_1-\omega_2)\frac{r_y}{2}\right\}$$

$\frac{\omega_1+\omega_2}{2}$ may be written as $\omega_m$ where suffix m refers to the mean value.

$$\text{Therefore torque} = 2K\left\{(\omega_m-\omega_y)R + (\omega_2-\omega_1)\frac{r_y}{2}\right\}$$

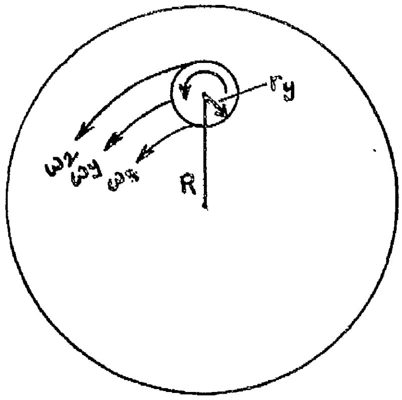



Fig. 9.4 (a)

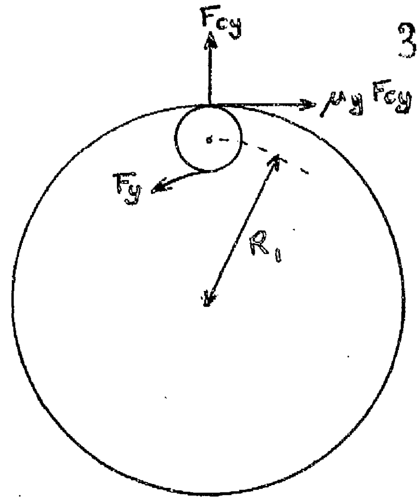



Fig. 9.4 (b)

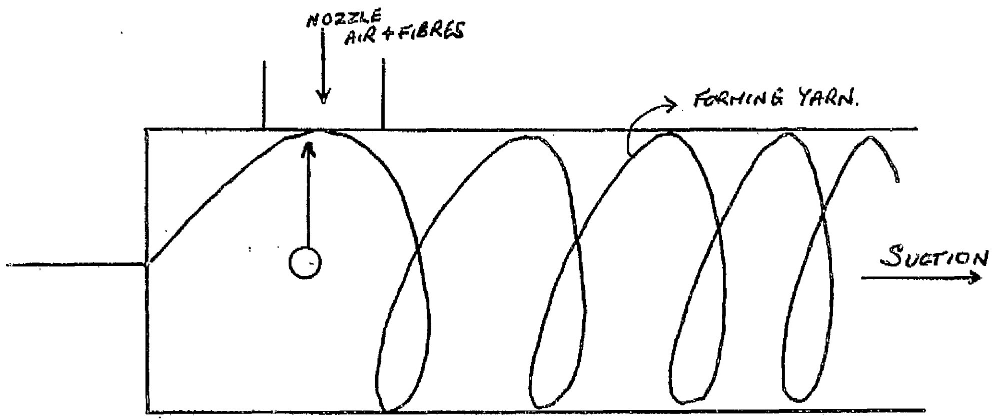



Fig. 9.4 (c)

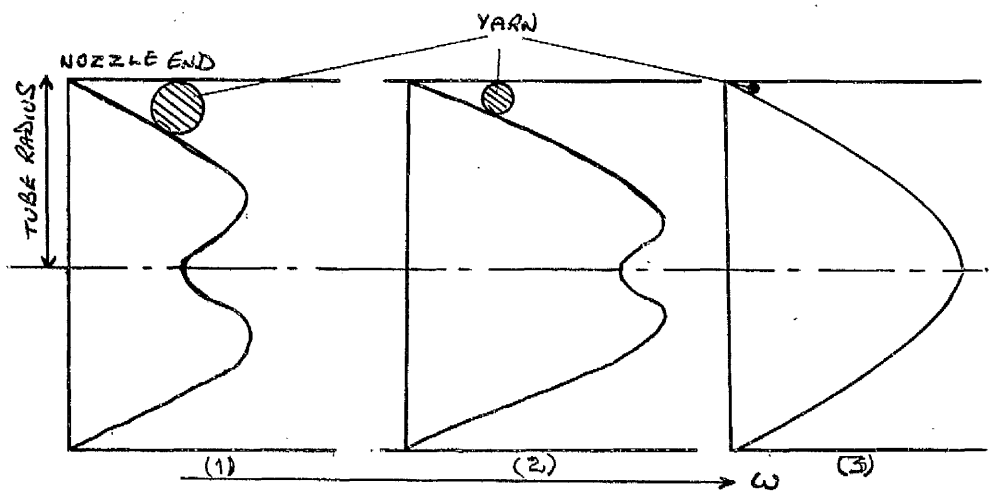



Fig. 9.4 (d)

ASSUMED VELOCITY PROFILE OF AIR AT DIFFERENT DISTANCES

FROM NOZZLE END

Since both terms in the torque expression are positive, the torque direction is in the same direction as that of vortex flow.

Case 2:

If the angular velocity varies inversely as the square of the radius, then

$$\omega_1 > \omega_2 > \omega_y$$

Working out the torque in the same way as in case 1 above, it can be found that the terms are negative. This indicates that the torque direction in yarn is opposed to that of vortex flow. Thus in this case the state of torsional shear existing between the streamlines will tend to roll the yarn on its axis in a direction opposite to that of vortex flow.

(b) Rest of the forming yarn

Consider the remaining length of yarn inside the tube.

Since the yarn rubs on the tube surface, a frictional force $\mu_y F_{cy}$ acts on the yarn tending to retard the yarn movement, where

$\mu_y$ is the co-efficient of friction between yarn and tube wall

and $F_{cy}$ is the normal force acting on the yarn.

A drag force $F_y$ acts on the yarn tending to keep the yarn rotating. Please see Fig. 9.4.(b).

$$\text{Torque} = -\mu_y . F_{cy}(R_1 + r_y) + F_y(R_1 - b), \text{ where}$$

b is a constant dependent on velocity gradient.

At equilibrium conditions,

$$\mu_y . F_{cy} = F_y$$

$$\text{Therefore the torque} = -F_y(R_1+r_y) + F_y(R_1-b)$$
$$= -F_y(b+r_y)$$

Since the expression for torque is negative, the direction of torque in this yarn will tend to be opposite to that of vortex flow. Thus, in Fig. 9.4.(c), the torque up to point O will tend to be in the same direction as that of vortex but will tend to change its direction from point O throughout the remaining length of the forming yarn.

If the air velocity profile inside the tube is assumed to be as shown in Fig. 9.4.(d), then since the forming yarn is tapered towards the free end it may be readily seen that the air force acting on the yarn tends to tail off towards the open end because of

(i) the decreasing diameter of the yarn

and (ii) the increased distance of the yarn from the tube axis.

The direction of twist in the yarn depends upon the result of the combination of torque directions in the drive element and the remaining length of the forming yarn. It is not known to what extent the shearing effects of air vortex contribute towards the yarn twist. However it appears that the frictional properties considerably affect the twisting behaviour of yarn. If the frictional force acting on yarn is high, then there will be a tendency to cause the yarn to roll on the tube wall. This will cause the twist in yarn to be in a direction opposite to that of vortex. When the frictional force prevalent in the system is low, the yarn will tend to rotate in the same orbital direction as that of vortex. There will be a tendency for the yarn to slide bodily (without turning on its axis) between the yarn and the tube wall and this will cause the twist in the yarn to be in the same direction as that of vortex flow.

## 9.5. TORQUE REQUIRED FOR TWISTING YARN

Let $r$ be the radius of the vortex tube

and $r_y$ be the radius of the yarn.

Let $r - 2r_y = r'$.

Let $V_a$ be the velocity of air,

$V_y$ be the velocity of the yarn,

$F_\mu$ be the frictional force between the yarn and the tube wall,

$\rho_a$ be the density of air,

$\rho_y$ be the density of the yarn

and $\mu$ be the coefficient of friction.

Consider an element $\delta l$ of yarn length, as shown in Fig. 9.5.

$$F_\mu = \frac{V_y^2 . \rho_y . \pi r_y^2 . \delta l}{r - r_y}$$

Torque due to solid friction

$$= -\mu \frac{V_y^2}{r - r_y} . \rho_y . \pi r_y^2 . \delta l (r - r_y)$$

$$= -K r_y^2 . V_y^2 . \delta l, \text{ where } K = \mu . \pi . \rho_y .$$

Torque due to fluid friction on the yarn at the tube wall

$$= K_1 \rho_a r_y (\bar{V}_a - V_y)^2 . \delta l . (r - r_y) \text{ where } K_1 = \mu . \pi .$$

Torque due to fluid friction in the balloon part of yarn tail

$$= K_1 \rho_a r_y (V_a - V_y)^2 . l' . r', \text{ where}$$

$l'$ is the length of the yarn in the balloon portion of yarn tail.

Therefore torque available to insert twist

$$= K_1 \rho_a r_y (V_a - V_y)^2 . 1'.r' + K_1 \rho_a r_y (\bar{V}_a - V_y)^2 . \delta l(r - r_y)$$

$$- K r_y^2 . V_y^2 . \delta l.$$

Considering the full length (l) of forming yarn inside the tube, the above expression may be rewritten as follows:

$$K_1 \rho_a r_y (V_a - V_y)^2 . l'.r' + K_1 \rho_a \bar{r}_y (\bar{V}_a - V_y)^2 . l.(r - r_y) - K\bar{r}_y^2 . V_y^2 . l ,$$

$$= K_1 \rho_a r_y (V_a - V_y)^2 \; l'.r' + l \left\{ K_1 \rho_a \bar{r}_y (\bar{V}_a - V_y)^2 (r - r_y) - K\bar{r}_y^2 . V_y^2 \right\}$$

where $\bar{r}_y$ is the average thickness of yarn.

If yarn tail is tapered to zero thickness, then

$$\bar{r}_y = \frac{r_y}{2} .$$

Therefore torque

$$= K_2 r_y \left\{ (V_a - V_y)^2 . l'.r' + \frac{(\bar{V}_a - V_y)^2}{2} . (r - r_y).l. \right\} - K . \frac{r_y^2}{4} . V_y^2 .$$

where $K = \mu . \pi . \rho_y .$ and $K_2 = K_1 . \rho_a .$

## 9.6. RELATIONSHIP BETWEEN THE YARN LINEAR DENSITY AND ITS ANGULAR VELOCITY

By replacing the subscript 'f' in the symbols mentioned in section 8.2. by 'y' for application to a yarn element and then working out in a similar way to that followed in the same section, the following relationship may be obtained

$$r_y . \omega_y^2 = \text{constant},$$

$$\text{or,} \quad \sqrt{tex_y}\, \omega_y^2 = \text{constant}.$$

Thus under conditions of a given spinning tube design and material and constant air flow rate, the rotational speed of yarn varies inversely as the fourth root of the linear density of yarn(tex). This relationship seems to agree fairly well with the graph shown in Fig. 12.41.

# CHAPTER 10

# THEORY OF YARN FORMATION

# CHAPTER 10

## 10.1. YARN FORMATION IN A VORTEX TUBE

In air vortex spinning, the mechanisms of fibre assembly onto the yarn and twist insertion seem to be performed almost simultaneously. These two mechanisms are different and distinct from each other. Hence it was thought that for the sake of simplicity in theoretical discussions that these two mechanisms should be treated separately. Thus the formation of a vortex spun yarn may be broadly divided as shown below.

(a) Fibre assembly to form a strand

and (b) Twist insertion to form the strand into a yarn.

## 10.2. FIBRE ASSEMBLY

In the case of fibres assembling in an air vortex spinner the factors that have to be taken into consideration are:-

(a) the movement of fibres,

(b) the movement of the seed yarn,

(c) the interaction between them,

(d) the continuous formation of the fibre assembly resulting in a forming yarn

and (e) the continuous removal of the forming yarn.

It is necessary to point out at this stage that the term "helix" occurring throughout this work does not mean a uniform helix but refers only to an approximate helical shape taken by the fibre path or yarn inside the vortex tube.

10.2.1. The movement of fibres

When fibres are introduced into a vortex tube, they are subjected to the action of various forces and this has been dealt with in detail in Chapter 8. However it may not be out of place to mention briefly the principal factors.

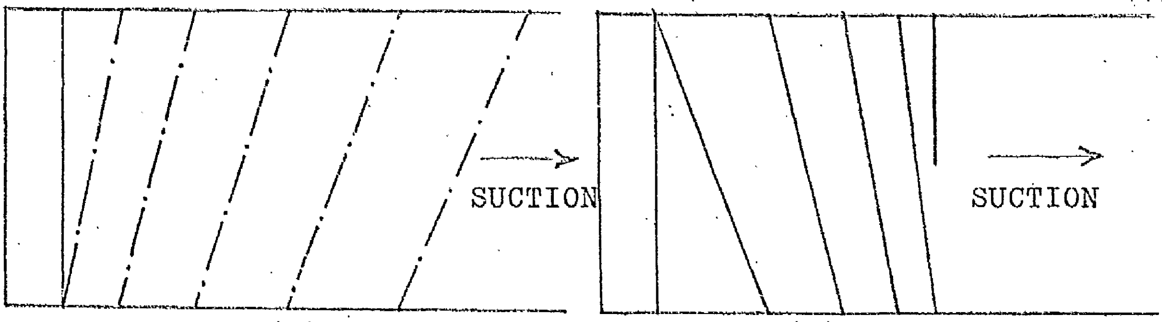
In the vortex tube, air flows along the tube wall in a helical path with the helix tending to open out as the flow proceeds towards the suction end. The aerodynamic forces acting on fibres tend to make the fibres follow this air path closely. The fibres (because of their curvilinear path in the tube) experience a radial acceleration and this tends to keep the fibres in contact with the inner tube surface. As a result of this contact during movement, the fibres experience solid frictional forces and those due to electro-static charges. These forces tend to offer a resistance to the movement of fibres.

Thus the aerodynamic forces tend to create a propulsive drag but the solid friction and static charges tend to produce a retarding drag. The net effect of these forces are:—

(a) the fibres tend to move in a helical path identical to that of air flow, i.e., the helical path of fibre flow tends to open out as the flow proceeds along the tube

and (b) the fibre velocity will be less than that of the air stream.

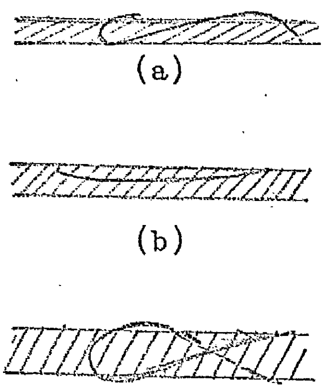
From the above conclusions, it follows that the fibre flow in the vortex tube may be represented as shown diagrammatically in Fig. 10.1. Consider the circumferential




(a) FIBRE TRAJECTORY

(b) YARN TRAJECTORY

Fig. 10.1.



(a) Leading end of the fibre forms a hook

(b) Trailing end caught by the forming yarn

(c) Fibre caught in between its two ends

Fig. 10.2.

ASSUMED FIBRE CONFIGURATIONS DURING FIBRE ATTACHMENT TO THE FORMING YARN

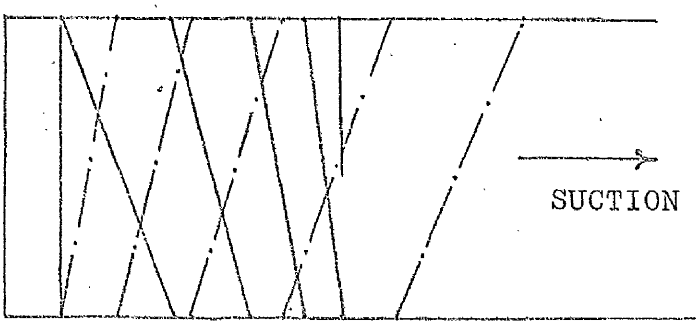



Fig. 10.3.

FIBRE ASSEMBLY DIAGRAM

surface of the vortex tube to be developed into a single plane. Then the fibre trajectory can be represented by the broken lines shown in Fig. 10.1. The width and shape of this trajectory will vary with the nozzle parameters. A small circular fibre inlet in the nozzle is likely to produce a narrow band trajectory. Alternately, a rectangular slit gives a band width related to the width of the fibre inlet slit. The shape of the helical path depends upon the dimension of the axial hole and also on the dimensions of the tangential inlets. However it is to be borne in mind that the helical path of fibre flow for any given nozzle design parameter is independent of the rate of air flow inside the tube, i.e., the fibre flow path is not influenced by the variation in air inlet pressures. Thus the fibre trajectory is a fixed path for a given nozzle design.

10.2.2. The movement of a seed yarn in the vortex tube

Consider a seed yarn introduced into the vortex tube through the axial hole in the nozzle. This seed yarn is subjected to the action of many forces as described in Chapter 9. However it may be relevant to give briefly the behaviour of seed yarn.

It is considered important at this stage to lay particular emphasis on the basic differences existing between the fibres and yarn movements in the tube. Unlike the fibres which are not attached to each other during their movement, the seed yarn is a continuous element. Also the seed yarn is anchored at the axial hole in the nozzle. Hence any rotary movement imparted to any part of the seed yarn will result in a rotation of the whole yarn about the hole as its axis. Thus while the fibre trajectory is a fixed path, the yarn trajectory constantly rotates about the axis on the tube.

The aerodynamic forces acting on a portion of the seed yarn lying in the air entry region tends to cause the yarn to move circumferentially along the tube surface. The direction of rotation is the same as that of the vortex flow. The frictional and inertial characteristics of the remaining length of yarn lying inside the vortex tube tends to make it to lag behind in its rotary movement. The amount of lag tends to increase towards the free end.

Moreover the main body of the seed yarn is subjected to a rotational force and an axial force exerted by the vortex flow.

The ultimate effect of these forces combine to make the seed yarn follow an approximately helical shape. This yarn helix is of the opposite hand to that of the fibre helix. Furthermore this helix is bodily rotated in the same direction as that of the air flow.

Bearing in mind that the yarn is rotated about the axis of the hole, it may be seen that the yarn trajectory is constantly moving about the axis so as to sweep the whole of the relevant tube surface. Therefore, unlike the fibre trajectory, the yarn trajectory is not fixed with respect to the tube although the helical shape assumed by the yarn will tend to remain fairly constant under given conditions of air pressure, nozzle and tube design and the yarn count.

The seed yarn is rotated at high speeds. Hence the yarn balloons and the ballooning of this yarn is contained by the tube wall. The seed yarn is, therefore, subjected to the action of centrifugal forces tending to keep the yarn well in contact with the tube wall. As a result of this behaviour, frictional forces are exerted due to solid friction and electro-static generation. These frictional forces will tend to oppose the yarn movement. In addition to these, the effect due to variation in tension along the length of yarn is also to be taken into account. The net result of all these factors, taken into consideration as a whole, is to make the yarn helix progressively tighten towards its open end, i.e., the helix path will tend to decrease towards the free end of yarn.

The above may be summarised as follows:-

Under steady conditions of air flow with a given design of spinning tube and for a yarn of constant linear density and of a given material

(a) the seed yarn takes up an approximately helical shape; this helix will be of the opposite hand to that of fibre helix (or air helix),

(b) the yarn helix rotates bodily in the same direction as the vortex flow and with a constat speed; the yarn helix in the course of time sweeps all the relevant tube surface

and (c) the yarn helix tends to tighten up towards the open end.

Thus the yarn trajectory at any instant of time may be represented diagrammatically as shown in Fig. 10.1.

and by the continuous lines in Fig.10 , where the vortex tube is developed into a single plane.

## 10.3. THE INTERACTION BETWEEN THE FIBRES AND THE SEED YARN

The movement of fibres and the seed yarn have been dealt with separately in the previous sections. It may, therefore, be apt to consider now both these movements together. The various possibilities that may occur during this interaction are discussed in this section. However, it must be pointed out that the actual mechanism of fibre assembly, i.e., the mechanism by which the fibres are trapped and then assembled on to form a yarn, is still not fully known. An attempt has been made to put forward a hypothetical fibre assembly mechanism.

In order to make a hypothesis study of the mechanism of fibre assembly it is necessary to make certain assumptions. These assumptions are as follows:-

(a) the fibres remain straight (free from kinks and bends) during their presentation to the fibre inlet and also during their movement inside the tube,

(b) the fibres are well-oriented towards the direction of their movement,

(c) the fibres are presented as individuals and not as tufts,

(d) the length of the seed yarn (or the forming yarn) lying in the tube remains constant,

(e) the helical shape assumed by the yarn remains the same throughout the period of fibre assembly

and (f) the effects of solid friction and static charges on the movement of fibres and yarn may be ignored for the sake of simplicity during the initial stages of discussion.

Consider a nozzle with a small circular fibre-cum-air inlet placed tangentially to the tube and with an axial hole.

Consider the attachment of a single fibre to the seed yarn. Assuming that the fibre is fairly long, the seed yarn has a good chance of catching the fibre at any point along its length. Thus the fibre may be caught either near its leading end, trailing end or at any point in between these two positions. The different fibre configurations that may arise due to the attachment of the fibre to the yarn are discussed below.

(a) If the leading end of the fibre is trapped by the seed yarn, then the remaining length of fibre will tend to bend itself at the point of attachment. This bending of the free length of the fibre may be caused by its inertia which acts when the fibre is caught by the yarn. It is also due to the movement of high speed air over the fibre. It should be remembered that the linear velocity of fibre is much greater than that of yarn. Again, because of this factor, the the chances of the fibre being caught at the leading end are great. The angle of fibre bending may be as high as 180°, thus causing the trailing end to become the leading end now. This configuration of fibre is shown in Fig. 10.2.(a).

(b) In the case of the trailing end of fibre becoming attached to the yarn, the configuration of the fibre will not be much changed from its original configuration during its movement. This fibre configuration is shown in Fig. 10.2.(b). In this case, the trailing end may or may not be hooked.

It seems that the chances of a complete absence of hook formation in this method of attachment are quite high.

(c). If the fibre is caught at any other position other than that at (a) or (b), say, midway along the fibre length, then the fibre will tend to bend around at the point of attachment for the same reasons as mentioned in (a) above. Both the fibre ends are likely to orient themselves in the direction of air flow and wrap around the yarn as shown in Fig. 10.2.(c). Such a configuration may be considered to be a form of hook. When a fibre is caught by the forming yarn, it is wrapped around the tail at a helix angle determined by the relative angles of the fibre and yarn paths. In passing, it is thought pertinent to point out that the effective staple length of a fibre is shortened by the double wrapping mentioned above. This may well be one reason for the relatively low breaking tenacity values of the vortex spun yarns.

Of the fibres captured, if equal proportions of them were to assume the three configurations mentioned in (a), (b) and (c) above, then it can be readily seen that at least two thirds of the total fibres captured will tend to have hooks in their configurations. It seems that the probability of fibre assuming the configurations in (a) and (c) are greater than that of (b) because the chances of the trailing end of fibre attaching to the yarn first are small. It appears that the hooked form of fibre configuration is quite likely to be widely prevalent in the mass of the fibre assembly.

The initial attachment of fibre to yarn is thought to be usually achieved by the gripping of this hook onto the yarn. The remaining length of fibre hanging loosely will tend to wrap around the yarn due to the twisting imparted to the yarn as a whole. This secondary binding due to wrapping attaches the fibre firmly onto the yarn. In those cases, where no hooks are formed as might happen when trailing ends are attached, the binding of the fibre to the yarn is solely effected by the fibre wrapping only.

The fibres in whichever configuration they occur are trapped in position by other fibres being wrapped over them. This overlapping of fibres tends to bind the yarn together. In passing, it should be mentioned that if the layering of fibres is too perfect, then there will be little or no migration of fibres and, therefore, the yarn will tend to fail by fibre slippage rather than by breakage.

The nature of the fibre wrapping depends on the type of yarn movement, i.e., the sliding or rolling movement of yarn inside the tube. The direction of fibre wrapping will tend to be coincident with the direction of vortex flow in the case of yarn sliding on the tube wall and reversed in the case of yarn rolling. The sliding and rolling movements of yarn is dealt with in detail in section 9.4.

It must be emphasized that not all the fibres trapped by the yarn are wrapped around in the way mentioned above. There are always some fibres which are not wrapped or perhaps partially wrapped around the yarn. They protrude from the yarn surface and thereby contribute to the hairiness of the resultant spun yarn. Any protruding hair will tend to leave the surface at an oblique tangent and the point of contact with the yarn surface will tend to run along the yarn as it rotates. Fresh fibres approaching this zone will tend to be trapped by this moving nip and licked into the yarn. This mechanism will tend to trap individual fibres rather than tufts. These fibres then will tend to communicate their motion to the approaching fibres since the yarn formation point oscillates in the tube, i.e., the point where the fibres first come under this influence varies from instant to instant and oscillates along the length of the forming yarn. The rotary action of the yarn will tend to cause the attached fibres to be thrown out of the system. At very high spinning speeds, this effect could be considerable. If the fibres are not firmly held or are not recollected after separation, then this could lead to high waste. Furthermore if the fibres were recollected and allowed to drift back into the system in an uncontrolled manner, this could cause irregularities in yarn.

Having so far considered the assembly mechanism of a single fibre, the next step is to proceed onto the mechanism of a number of fibres assembling onto the seed yarn. Suppose, for instance, the fibres are caught by merely fouling outstanding loops and hairs on the seed yarn, then there is a likelihood of a build up of fibres only at these zones of protrusion. The greater is the amount collected at a point, the greater would its collecting power be. In a system like this, slubs will be produced at these attachment points. The other places in the yarn would present thin spots which would be subjected to frequent breakages. The yarn produced would be highly irregular and the whole system of fibre attachment would be unstable. However this does not happen in reality and fairly good quality yarn is produced during vortex spinning. Other alternatives have thus to be considered.

A simple study of the fibre assembly mechanism consists in superimposing the yarn and fibre trajectories, shown in Fig. 10.1.(a) and (b). Fig. 10.3. which shows this superimposition represents a fibre assembly diagram. It is to be remembered that in all the figures appearing in this section from now onwards, unless stated otherwise, the circumferential surface of the vortex tube is geometrically developed into a single plane.

The seed yarn and the fibres tend to travel along the same surface, i.e., the inner wall of the tube. Hence it may be reasonable to assume that the trajectories of fibre and yarn will cross over each other. It is observed in Fig. 10.3. that the yarn and fibre trajectories intersect each other at a number of places. It is precisely at these intersections that the yarn has the chances of gathering the fibres. It might be expected that at the first intersection some fibres will be picked up by the yarn and those fibres which fail to assemble will proceed onto the next intersection. Amongst these fibres, some of them will not assemble and these will move further onto the next intersection and so on. It is assumed that some fibres will always assemble onto the yarn at each intersection. The amount of fibres attaching to the seed yarn seems to depend upon many factors. These will be taken up in a later section. It may be sufficient to mention here that the efficiency of fibre capture appears to be largely influenced by the nozzle design parameters and also by the method of fibre presentation to the vortex system.

Since the yarn trajectory is constantly changing with respect to the tube surface (because of the rotation of yarn about the axial hole), it was thought necessary to consider at least a few different positions of the yarn during its movement. Accordingly, four different positions of yarn (each of them corresponding to a successive movement of a quarter of a revolution of the yarn end in the tube) are shown in Figs. 10.4.(a) to (d), inclusive. As far as the fibre trajectory is concerned, the path is constant and, therefore, in all these figures the fibre trajectory is shown lying in the same position in the tube. The yarn trajectory is represented by continuous lines and the fibre trajectory is shown by broken lines.

It is seen from Fig. 10.4.(a), intersection point coincides with the fibre inlet A. There are nine intersection points in this case. Referring to Figs. 10.4.(b), (c) and (d), it is observed that the total number of intersections is eight at any other instant of time. Thus, the number of intersections does not vary much. In practice, the variations in the number of intersections at any instant of time would be small if the length of forming yarn is reasonably long, i.e., about 20 cm. Thus the number of intersections would seem to remain fairly constant.

Let the efficiency of fibre capture be defined as

$$\frac{\text{amount of fibres captured at an intersection}}{\text{amount of fibres approaching this intersection}}.$$

If it is assumed that this fibre capture efficiency at each intersection point along the yarn length remains the same,

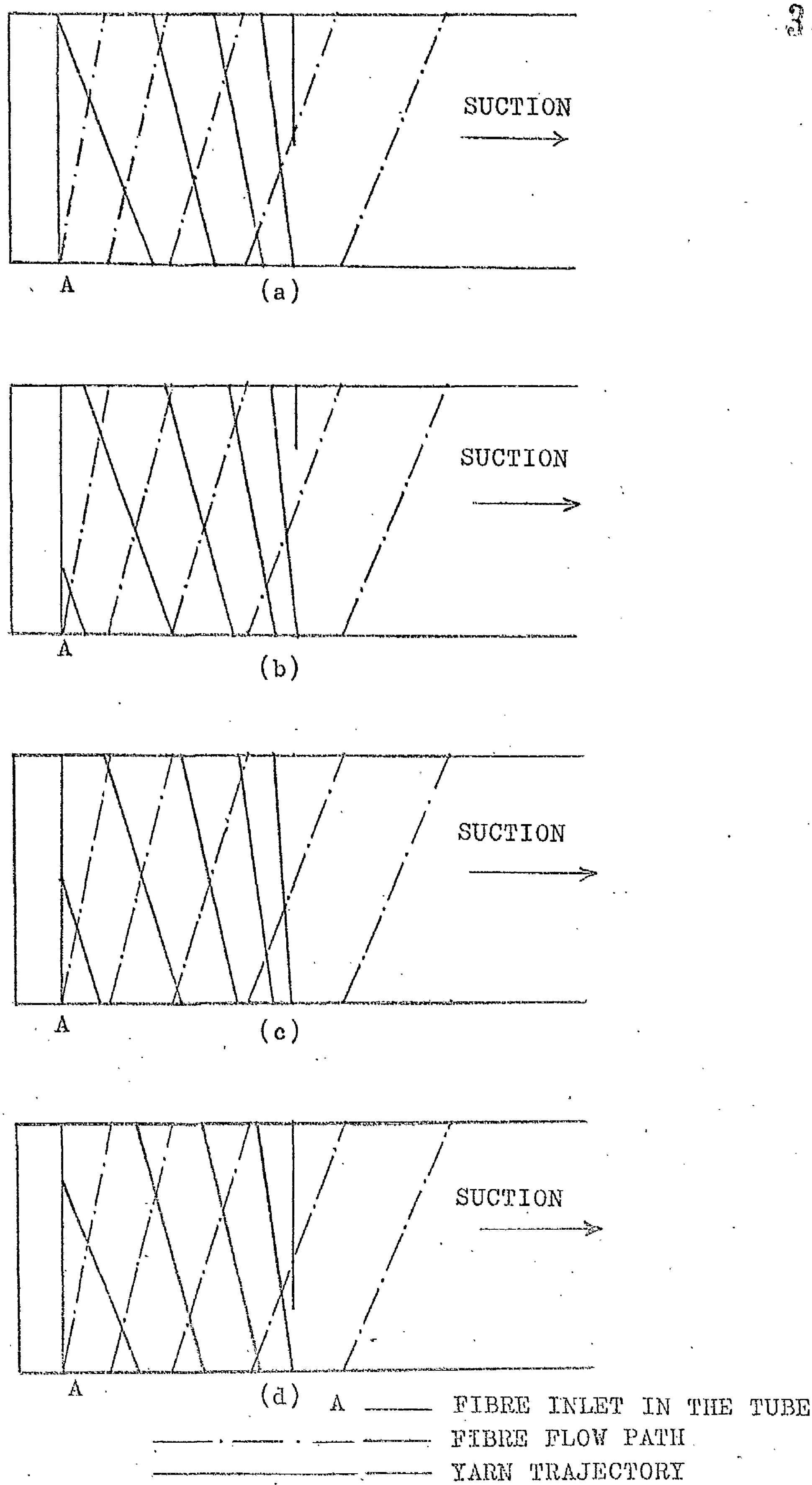



Fig. 10.4.

FIBRE ASSEMBLY DIAGRAMS FOR ONE YARN ROTATION IN THE TUBE the similar number of intersections at any instant of time suggests that the amount of fibres captured by the yarn during each revolution of the yarn is quite likely to remain almost the same. Moreover with a constant efficiency of fibre capture, the amount of fibres that attach to the seed yarn will vary along the yarn length. Since the number of fibres for each subsequent intersection point progressively decreases, the density (or the population) of fibres attaching to the seed yarn will also progressively diminish towards the free end of yarn. Thus the tail of the yarn will tend to be tapered to the point where it can no longer substain fibre assembly.

In order to make the above point more clear, it is thought necessary to give the following method of approach to this problem:-

Assume that the rate of fibre capture by an element of yarn is X% of the fibres approaching that element. Consider a batch of 100 fibres fed into the tube. At the first intersection, X fibres will be captured. The remaining (100-X) fibres will continue to move along. Of these (100-X)X will be captured at the next intersection. If there are n intersections, then the number of fibres that would not be captured at all and find their way into the suction pump would be $(1-\frac{X}{100})^n.100\%$. Thus if one third of the fibres were captured at each intersection, there would be a 32% waste percentage if there were only three intersections. If half of the fibres were captured, then the wastage after the three intersections would be only 12%. The possibility of the yarn breaking just after the third intersection would then be increased because the amount of fibre capture would have been reduced from 22% to 6%. The yarn would have been correspondingly thinner and weaker at that point. Thus the number of actual intersections will depend upon the assembly efficiency and will decrease as the assembly becomes more efficient.

The assembly efficiency at each intersection point will be offset to some extent because with inefficient assembly, the population of the fibre stream decreases slowly down the tube and there is likely to be many successive contacts before the yarn becomes so thin and weak at the tail that it cannot hold together. Any fibres left after this point will go to waste. With more efficient assembly the number of intersections would be decreased because the population would decrease more quickly. At 100% assembly efficiency, there would be only one intersection and no waste.

Let the distance measured along the length of yarn between any two consecutive intersections of fibre and yarn trajectories be termed as the "assembly distance". It is evident from the assembly diagrams shown in Figs. 10.4. (a), (b), (c) and (d) that the assembly distances increase towards the free end of yarn. This is because the fibre trajectory opens out and the yarn trajectory closes in as they proceed towards the suction end. This increase in assembly distances suggests that the number of fibres that get attached to a unit length of yarn might progressively reduce towards the open end.

## 10.4. THE CONTINUOUS FORMATION OF THE FIBRE ASSEMBLY RESULTING IN A FORMING YARN

With a continuous supply of fibres fed into the system, the process of fibre assembly proceeds on. When a seed yarn is allowed to rotate(without being withdrawn), it might be expected that a large population of fibres would be trapped at the first assembly point. The population of fibres attaching at the subsequent assembly points will gradually decrease as explained in the previous section. Therefore a gradual reduction in the density of attached fibres takes place. This produces a tapered shape. The yarn at the free end will be usually of the thickness of a few fibres only. The formation of the taper end will tend to be controlled by the following factors:-

(a) the cohesive force exerted by the fibres of the forming yarn due to the interaction of the inter-fibre friction, entanglement and twisting,

(b) the aerodynamic force acting on the fibre assembly; this comprises of

(i) the radial component which rotates the yarn

and (ii) the axial component which exerts a tensile force on the emerging yarn,

(c) the tension created in the yarn due to the free ballooning of the small portion(drive element) of the yarn lying near the axial end of the tube

and (d) the frictional drag due to the constraint of the remaining length of the yarn in contact with the tube wall.

The cohesive force tends to keep the fibres of the yarn together but the tensions exerted on the yarn tend to break the yarn. It would be precisely at that point along the yarn where the tensile force exceeds the cohesive force that a break will occur and this will determine the end of the forming yarn.

During spinning, the yarn within the tube is built up in a partly discontinuous process because of the variations in fibre supply rate, yarn irregularity and the way in which the fibres become attached to the forming yarn. When large tufts are attached to the weak end of the yarn the air drag acting on this portion of the yarn increases and this imposes an additional tension to that already existing in the yarn. Such tufts may not contain very well oriented fibres and may contribute little to the yarn strength at the point of attachment. Thus a break at or upstream of the tuft becomes more likely because of the capture of the tuft. Thus the taper end will move to a different place in the yarn. However the subsequent building up of the yarn tail will tend to restore the length of the yarn and thus there is a fluctuation in yarn tail length with its consequential changes in yarn speed etc.

An important deduction that can be made from this is that the waste is likely to consist partially of twisted fibres which cannot be used again without some some form of reopening process and this was observed to be so. A simple recirculation system for the fibres may not be, therefore fully successful.

Consider the process of continuous fibre addition to the seed yarn held stationary at the axial end. As explained earlier, this process will increase the linear density of the yarn. Under steady air flow conditions, the increase in the yarn linear density will tend to increase the air drag acting on it and other things being equal, the rotational speed would increase. The combined effect will tend to increase the centrifugal force on all elements of the yarn within the tube. This will tend to increase the size of the balloon of the drive element if it were not for the constraint of the tube. A small portion of the drive element is transferred from the free balloon to the portion constrained by the tube wall, as shown in Fig. 10.5. This tends to increase further the frictional drag on the yarn which, in turn, tends to cause the rotational speed to decrease. The increased centrifugal forces acting all along the constrained portion of yarn within the tube increases and the frictional drag increases with it and this too tends to cause the rotational speed to decrease. Eventually a stage could be reached when the drive element, as defined here, will cease to exist because the whole of the forming yarn will be in contact with the tube wall. Under these conditions, the rotational speed is likely to be very low because of the absence of any substantial amount of drive. The overall effect of an increase in yarn mass is likely to lead to a reduction in the yarn speed.

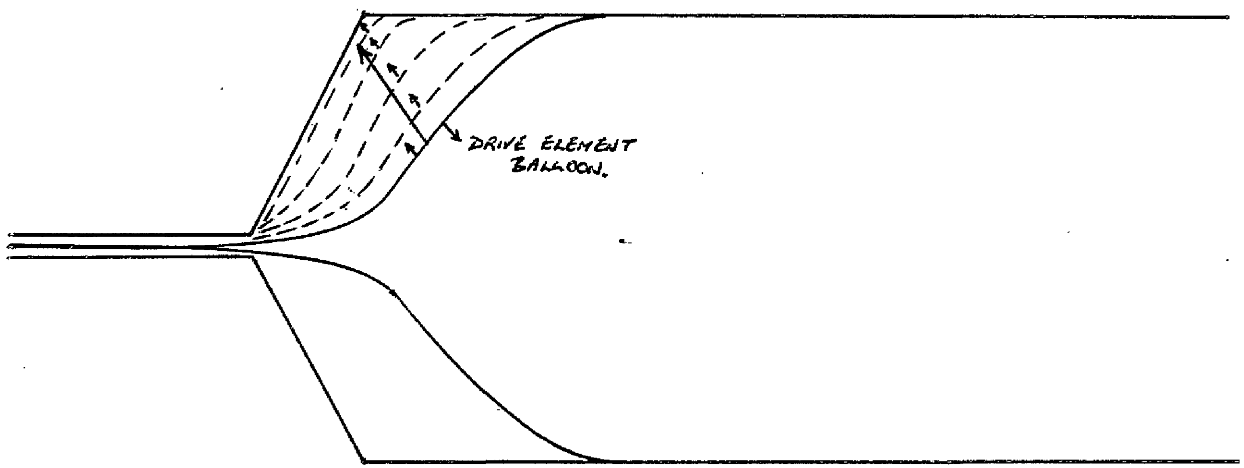



Fig.10.5

# SECTION IV

# F U R T H E R   T E S T S

## CHAPTER 11

## FURTHER TESTS TO OPTIMIZE THE SPINNING TUBE

# CHAPTER 11

## 11.1. INTRODUCTION

The optimum geometry of the spinning tube when using Egyptian fibres(1 7/16 in. staple length) was arrived at earlier(please see Chapter 6). It was, therefore, thought appropriate to proceed further with experimentation on spinning performance of the same tube. These experiments were mainly confined to spinning with fibres of different materials and various staple lengths. It was also considered necessary to find the optimum air pressure within the tube, yarn take-up rate etc., in order to produce a reasonably good yarn with low fibre loss.

Before proceeding with these experiments, it was felt that a fibre feed device should be selected in order to make it standard.

## 11.2. SELECTION OF FIBRE FEED DEVICE

The drafting unit employed by Hirway was rather of a crude construction and, therefore, had certain limitations. The absence of a break draft zone made the use of a drawn sliver compulsory. The draft in the unit could not be varied and, therefore, the range of yarn counts that could be spun was also restricted.

The choice of fibre feed apparatus lay either in the use of a card cylinder or a SKF drafting unit fitted on SKF spintester.

In a revolving flat card used for this purpose, the form of back stuff material was also varied. Yarns were made from both lap and drawn sliver which were fed to the taker-in of the card. However in the SKF drafting unit a roving was used.

Table 11.1. shows the results obtained in spinning with both types of feed on the card as well as from the SKF drafting unit. When working from the card, the results prove the superiority of the drawn sliver feed over that of lap. On the other hand, the results of the former did not differ much to those obtained with the SKF drafting apparatus. The SKF drafting unit was selected for fibre feeding in this tests series because

(a) the flexibility and ease of variation of draft gave the advantage of spinning a relatively wide range of counts from a given backstuff material,

(b) a given spinning draft ratio could be always maintained constant at all yarn take-up rates by a positive link up of the yarn take-up mechanism with the drafting appratus,

(c) when the spinning tube was applied to the card cylinder the fibres needed to be stripped from the cylinder surface. In order to obtain an efficient stripping, it would be necessary to maintain a certain minimum air pressure across the tube. However with the drafting method of fibre supply, this lower limit on air pressure could be considerably reduced.

and (d) it appeared that with the drafting apparatus, the fibres supplied to the spinning tube would be better oriented than those from the card surface, but the fibres from the drafting unit might have been in tuft form.

TABLE 11.1.

COMPARATIVE RESULTS OF VORTEX YARNS SPUN FROM SCUTCHER LAP AND CARD SLIVER IN A CARD AND FROM A ROVING IN A SKF DRAFTING UNIT.

Processing Conditions

Material - Fibro 1 7/16 in. staple and 1.5 denier.

Air pressure difference across the tube - -30 in$H_2O$.

Yarn take-up rate - 10 m/min.

Spinning tube - ¾ in. tube bore; ¾in.X3/16 in. inlets.

| Yarn properties | Scutcher lap feed | Card sliver feed | Roving feed in SKF unit |
|---|---|---|---|
| Linear density of yarn | 295 tex | 147 tex | 147 tex |
| Twists per cm.(approx.) | 2.6 | 4.0 | 4.1 |
| Twist constant | 45 | 48 | 50 |
| Breaking elongation(%) | 18.4 | 20.7 | 16.4 |
| Breaking tenacity(gf/tex) | 6.0 | 8.6 | 9.0 |
| Yarn irregularity(P.M.D.) | 10.2 | 10.8 | 9.9 |
| Fibre assembly efficiency (%) | 76 | 79 | 86 |

The drafting mechanism used was a SKF pendulum weighting arm type PK211E1. The diameter of the bottom roller was 1 inch. This drafting unit was capable of drafting fibres up to $1\frac{3}{4}$ in. staple length. The yarn take-up mechanism was linked to the front roller so as to give a spinning draft ratio of 0.9.

## 11.3. PROCESSING CONDITIONS

The following apparatus were worked under the stated processing conditions in this series of tests:-

(a) A spinning tube with two $\frac{3}{4}$in. X $\frac{3}{16}$ in. tangential slit inlets and an axial hole of $\frac{1}{8}$ in. diameter.

(b) A spinning draft ratio of 0.9 was maintained when spinning in conjunction with the SKF drafting apparatus.

(c) A roving of 1.25 hank (0.472 ktex) was usually used in the creel.

(d) The electrode of a static eliminator was placed at about 6 in. away from the nozzle end of the spinning tube.

(e) Air pressure inside the tube was kept at -25 in.$H_2O$. Please see section 11.5.

and (f) The atmospheric conditions of the spinning room were maintained at $70^{\circ} \pm 2^{\circ}$ F and 55% ± 1% relative humidity.

Most of the work was done with Egyptian cotton of 1 7/16 in. staple length and Fibro of 1 7/16 in. staple length and 1.5 denier.

## 11.4. EVALUATION OF THE YARN PROPERTIES

Unlike the preliminary tests, sufficiently long lengths of yarn were spun during each test.

The yarn evenness was measured in the way outlined in section 5.4.5.2.

The Uster automatic single thread strength tester was used to measure the breaking strength and elongation of these yarns. Sixty tests were made from each yarn sample. The linear density of yarn was determined from the broken threads of each yarn sample.

The measurement of twist in the yarn posed a problem because of the very different nature of the twist structure in these yarns as compared to that of the conventional ones. This did not permit the use of the normal method of twist measurement. Hence a 'twist to break' method was followed. In this method, a 10 in. length of yarn was mounted at a tension of 0.5 g/tex between the jaws of a conventional twist tester. This yarn was slowly rotated in one direction (say, S-way) by the rotating jaw until the yarn snapped. Let the number of twists added to the yarn to cause this break be A. The twist test was repeated but this time the yarn was rotated in the opposite direction (Z-way). Let the number of twists needed to break this yarn be B. Then the twist per inch of yarn is given by $\frac{1}{2}(\frac{A-B}{10})$. Forty such tests were carried out for each yarn sample and the average was obtained.

The twist direction in the yarn was also known from these tests.

The fibre waste loss was measured as described in section 5.4.5.5. However, instead of the term fibre waste loss, a term "fibre assembly efficiency" was used. These two terms are complementary to each other.

## 11.5. EFFECT OF AIR PRESSURE DIFFERENCE ON SPINNING PERFORMANCE OF THE TUBE

It was felt essential that the effect of air suction on the yarn properties and fibre loss should be investigated in order that an optimum pressure could be found. This pressure could then be used to standardise the subsequent tests.

With a low air pressure, the rotational speed of yarn would be also low. The twist in yarn might, therefore, be low too and this would result in a weak yarn. On the other hand, high air pressure differences might cause highly turbulent air flow inside the tube and this might be unfavourable to fibre assembly. Moreover the higher the air consumption, the higher will be the power consumption too. The economics of this system would be greatly affected.

The air pressure difference across the spinning tube was varied from −12 $inH_2O$ to −35 $inH_2O$. It was difficult to spin below −12 $inH_2O$ and about −35 $inH_2O$ was the maximum pressure that could be obtained with the vacuum pump. The pressure was varied by the movement of a sleeve over a series of ports in a tube connecting the spinning tube with the vacuum pump.

Fibro was used in this experiment. The yarn take-up rate was kept constant at 12 m/min .

Fig. 11.1. shows the relationships between the air pressure difference and

(a) fibre assembly efficiency,

(b) yarn irregularity,

(c) breaking tenacity,

(d) twist constant.

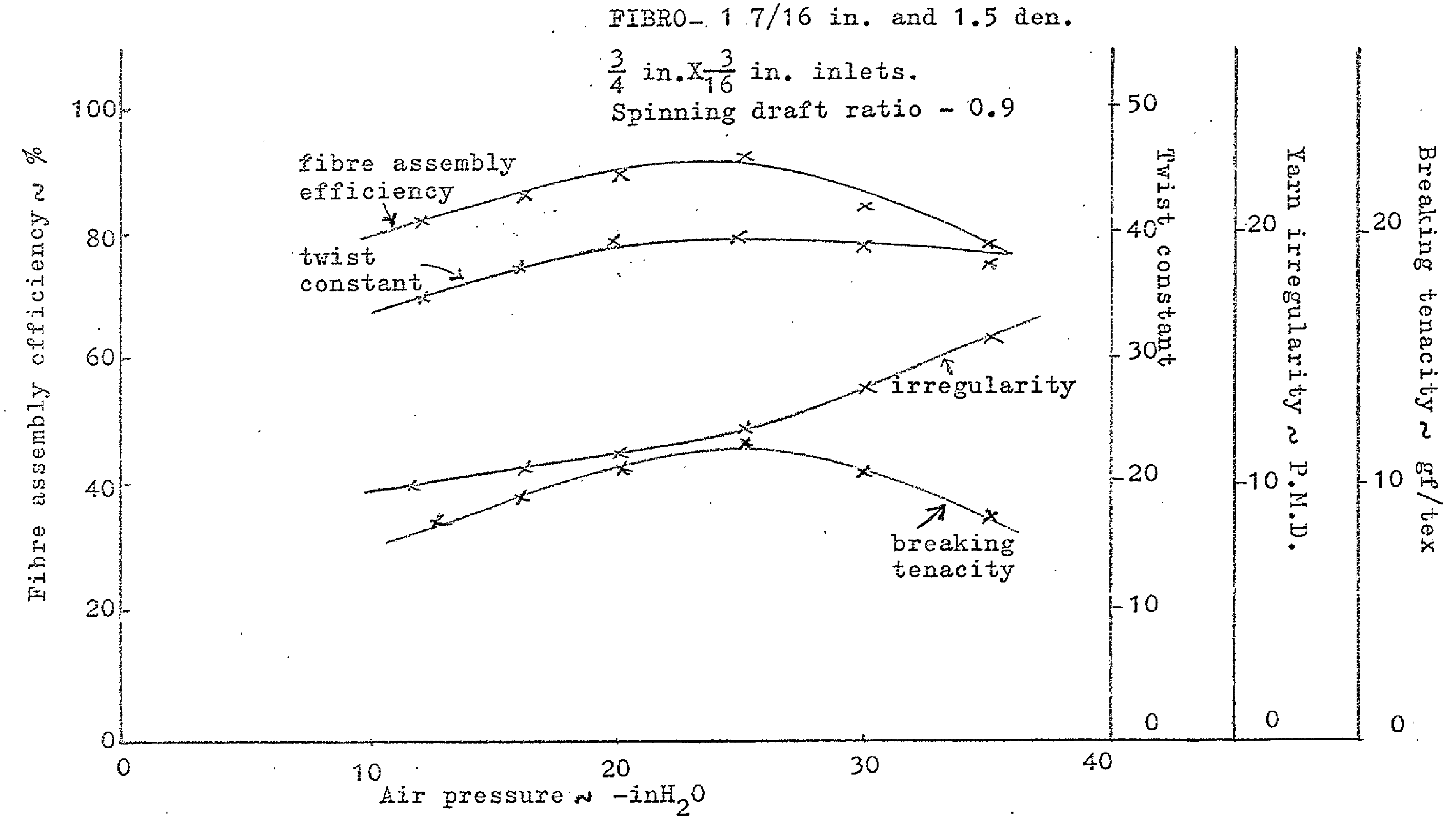



Fig. 11.1.

EFFECT OF AIR PRESSURE DIFFERENCE ON YARN PROPERTIES

The tendency for the fibre assembly efficiency and the twist constant to increase with air pressure up to −20 $inH_2O$ suggests that the twist insertion rate tends to increase with air pressure. Any additional twist gained by the forming yarn will tend to increase the yarn tail strength. Perhaps this increase in strength may reduce the tendency of portions of the forming yarn to detach themselves and thus assist it to maintain a consistent length. A fairly uniform length of forming yarn may give consistently good fibre assembly efficiency.

However at air pressures over −25 $inH_2O$ the fibre assembly efficiency decreased rapidly with air pressure although the twist constant tended to remain at a fairly constant level. This indicates that the air suction becomes sufficiently strong to snatch portions of yarn tail from the forming yarn, adding to the waste. It was observed that, at air pressures over −25 $inH_2O$, the waste collected in the pump contained relatively large number of short twisted yarn lengths. This seems to prove the above hypothesis. Furthermore the fluctuations in yarn tail end tended to vary the fibre capture efficiency. All these led to a high fibre waste and a low fibre assembly efficiency.

There was no substantial twist gain at high air pressures. In fact, the twist constant seemed to remain at a fairly steady level. Perhaps this twist constant was the maximum attainable under the stated working conditions. At very high air pressures, any additional twist inserted into the forming yarn above a certain limit would tend to form incipient snarls in the yarn tail. (This limit would be determined by the linear density, the nature of material and the torsional rigidity of the yarn). The snarl formation due to over twisting would tend to take the yarn away from the tube wall. This tends to reduce the twist flow rate into the yarn because the twist due to rolling would become reduced and also the yarn will tend to move in lower velocity air as it approaches the tube axis and, therefore, the drive to insert twist will be reduced. Although such a mechanism tends to maintain the twist constant of the yarn, it was observed that the yarn in the tube under these conditions formed balloons constrained by the tube and the balloon shapes pulsed with respect to time. A photographic evidence of this behaviour is shown in Fig. 13.5.

It should be also noted that the snarl formation in yarn would tend to decrease the fibre assembly efficiency.

The behaviour of the breaking tenacity and the irregularity curves above −25 $inH_2O$ suggested that the higher the irregularity, the lower was the breaking tencaity of yarn. Perhaps this was due to the increased number of thin places occurring in the yarn.

It is evident from Fig. 11.1. that the optimum air pressure consistent with fibre assembly efficiency, yarn tenacity and evenness was about −25 $inH_2O$.

## 11.6. EFFECT OF YARN TAKE-UP RATE ON THE PERFORMANCE OF THE SPINNING TUBE

The yarn take-up rate was varied from 5 m/min to 20 m/min. Egyptian cotton and Fibro were used and an air pressure difference of about −25 $inH_2O$ was maintained.

Fig. 11.2. shows the relationships between yarn take-up rate and

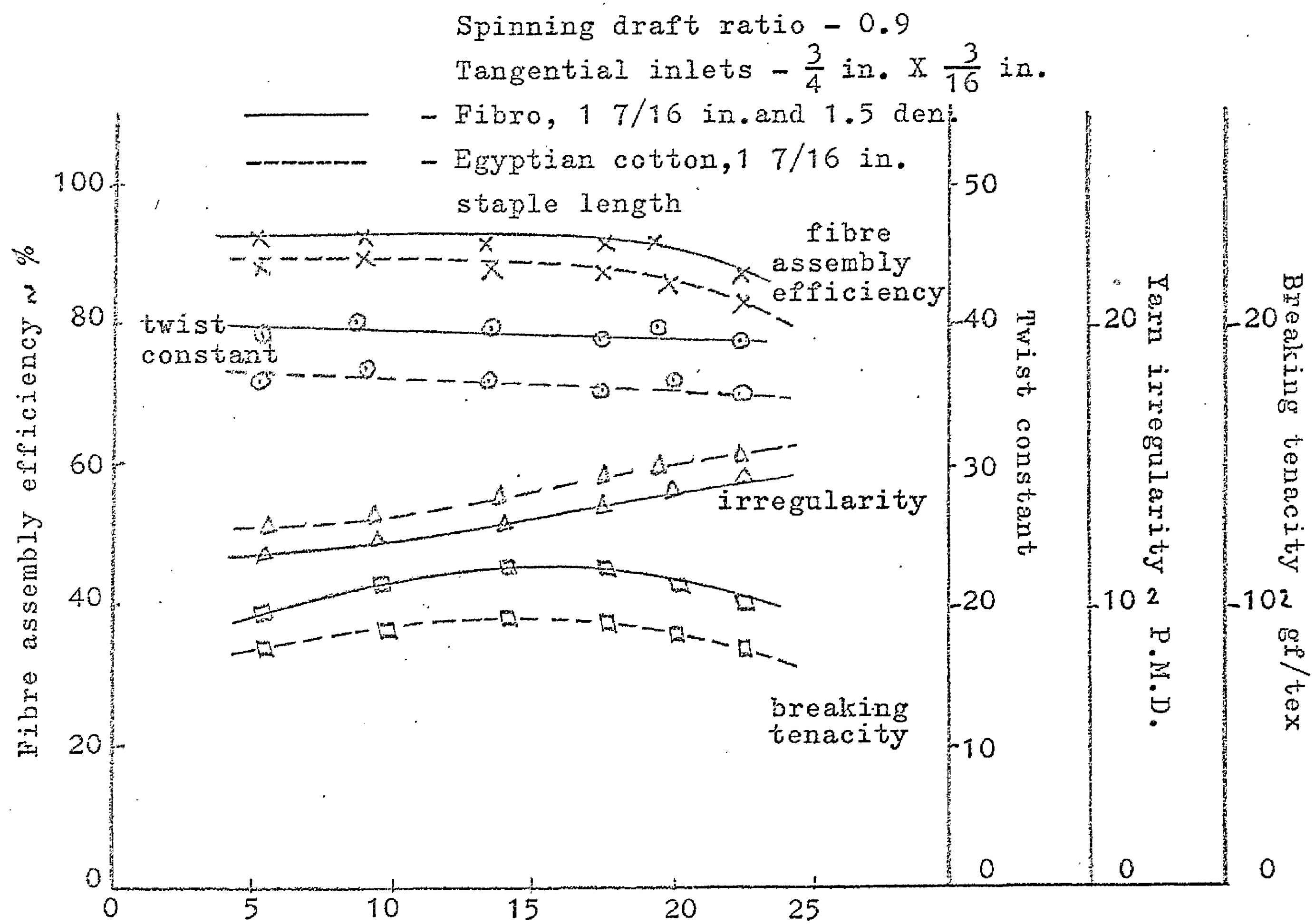



Fig. 11.2.

EFFECT OF YARN TAKE-UP RATE ON YARN PROPERTIES

(a) fibre assembly efficiency,

(b) yarn irregularity,

(c) yarn tenacity,

(d) twist constant.

It might be noted that the fibre assembly efficiency remained virtually constant up to about 15 m/min and 18 m/min for cotton and Fibro respectively. Under a given yarn take-up rate,Fibro gave a higher fibre assembly effciency than cotton. The surface nature of Fibro fibres help to cause the yarn to roll more easily on the tube wall than the cooton yarn. It was observed with a stroboscope that with an increase in the take-up rate of the yarn, the length of forming yarn gradually reduced. This behaviour explains the decrease in fibre assembly efficiency with increase in yarn take-up rate.

The increased inter-fibre frictional characteristic of Fibro fibres in comparison with cotton fibres might have accounted for the greater breaking tenacity of Fibro yarns. The yarn regularity seemed to go hand in hand with fibre assembly efficiency. In general, the yarn tenacity was almost a reflection of the yarn evenness.

## 11.7. RELATIONSHIP BETWEEN STAPLE LENGTH OF FIBRES AND SPINNING TUBE BORE

In this experiment, the following fibres were used:-

(a) Egyptian cotton, 1 7/16 in staple length,

(b) American cotton, $1\frac{1}{8}$ in. staple length,

(c) Peruvian cotton, 11/16 in. staple length,

(d) Comber waste, $\frac{1}{2}$ in. staple length approximately,

(e) Courtelle fibres, 1 7/16 in. staple length and 2 denier,

(f) Asbestos fibres, about $\frac{1}{2}$ in. to $\frac{3}{4}$ in. long,

(g) wool fibres about 6 in. long

and (h) jute fibres about 6 in. long.

Spinning tubes of the following bores were used to spin these fibres:-

(a) $1\frac{1}{4}$ in. bore,

(b) $\frac{3}{4}$ in. bore

and (c) $\frac{1}{2}$ in. bore.

A yarn take-up speed of 10 m/min for Egyptian cotton, American cotton, Peruvian cotton, comber waste and Courtelle fibres and a speed of about 5 m/min for asbestos, wool and jute fibres was used.

Table 11.2. shows the result obtained with spinning different fibres with the various tube bores.

Comber waste, asbestos and, to a certain extent, Peruvian cotton spun reasonably well with the $\frac{1}{2}$ in. tube whilst the Egyptian and American cotton performed better with a $\frac{3}{4}$ in. tube. This seemed to suggest that the shorter the staple length, the smaller should be the tube bore and vice versa. Spinning of long fibres (wool and jute) even with the $1\frac{1}{4}$ in. tube was very unsatisfactory. A 2 in. tube (or larger) might have produced good yarns.

Spinning with asbestos fibres was encouraging although the stickiness of the asbestos binding medium presented problems at the drafting rollers.

The yarn spun with the highly crimped Courtelle fibres produced a full yarn but the handle of the yarn was harsh. The yarn was highly irregular and its strength was low. However the breaking elongation was the highest of all the yarns spun. This is because in addition to the folds and entanglements introduced into the yarn structure due to

TABLE 11.2.

EFFECT OF TUBE BORE SIZE ON THE SPINNING PERFORMANCE OF FIBRES OF DIFFERENT STAPLE LENGTHS.

| Type of Fibres | Tube bore (in.) | Fibre assembly efficiency (%) | Yarn irregularity (P.M.D.) | Breaking tenacity (gf/tex) | Twist constant |
|---|---|---|---|---|---|
| Egyptian cotton | $\frac{1}{2}$ | 88 | 14.6 | 8.0 | 38 |
| | $\frac{3}{4}$ | 92 | 10.6 | 9.2 | 44 |
| | $1\frac{1}{4}$ | 84 | 11.2 | 8.3 | 42 |
| American cotton | $\frac{1}{2}$ | 86 | 13.8 | 7.4 | 36 |
| | $\frac{3}{4}$ | 88 | 12.4 | 7.6 | 39 |
| | $1\frac{1}{4}$ | 82 | 14.3 | 6.7 | 32 |
| Peruvian cotton | $\frac{1}{2}$ | 88 | 13.2 | 7.0 | 34 |
| | $\frac{3}{4}$ | 84 | 14.6 | 6.5 | 32 |
| | $1\frac{1}{4}$ | 80 | 15.8 | 6.1 | 29 |
| Comber waste | $\frac{1}{2}$ | 86 | 13.0 | 6.0 | 28 |
| | $\frac{3}{4}$ | 83 | 14.7 | 5.5 | 27 |
| | $1\frac{1}{4}$ | 77 | 15.8 | 4.9 | 25 |
| Courtelle fibres | $\frac{1}{2}$ | 90 | 14.5 | 6.0 | 32 |
| | $\frac{3}{4}$ | 88 | 13.8 | 6.1 | 32 |
| | $1\frac{1}{4}$ | 81 | 16.1 | 4.8 | 26 |
| Asbestos fibres | $\frac{1}{2}$ | 91 | 14.2 | 4.6 | 26 |
| | $\frac{3}{4}$ | 84 | 15.9 | 4.4 | 22 |
| | $1\frac{1}{4}$ | 78 | 16.9 | 3.9 | 19 |

It was not possible to spin continuous lengths of yarn from wool and jute fibres with the three spinning tubes.

Nozzle dimensions: $\frac{3}{4}$ in. X 3/16 in. tangential inlets.
Yarn take-up rate: 10 m/min.

TABLE 11.3.

EFFECT OF TUBE CRAZING ON THE SPINNING PERFORMANCE

Material used for spinning : Fibro 1 7/16 in. staple and 1.5 den.
Spinning tube : $\frac{3}{4}$ in. tube with $\frac{1}{2}$ in. X 3/16 in. tangential inlets.
Yarn take-up rate : 12 m/min.

| | Fibre assembly efficiency (%) | Yarn irregularity (P.M.D.) | Breaking tenacity (gf/tex) | Twist constant |
|---|---|---|---|---|
| Normal tube without crazing | 88 | 11.8 | 9.6 | 44 |
| Crazed tube | 87 | 12.0 | 10.8 | 50 |

vortex spinning, the crimpiness of the fibre also acted to give extensibility to this yarn.

It was not possible to spin wool and jute fibres from the drafting system because the short length of the nozzle fibre guide used. It was necessary to keep the fibre inlet close to the roller nip to allow the air suction to transport the fibres. Unfortunately this did not allow a break in fibre flow and a false twisted fibre assembly was the result. However when the fibres were hand fed into the spinning tube, spinning of yarn was possible. The yarn was very irregular and weak. The lap length of these fibres was greater than the tube circumference. This might have resulted in the movement of the fibres being restricted within the tube. The presence of grease from wool fibres on the tube wall appeared to hinder the spinning process.

It is interesting to note[98] that a finer fibre gave a higher fibre assembly efficiency, a better yarn evenness and a higher breaking tenacity and all these at a higher yarn take-up rate than those obtained with a coarser fibre of the same material. The finer fibres tended to behave slightly differently to a coarser fibre during their movement in the air stream. They were more likely to move along the tube wall surface because of their reduced stiffness and this might have given better chances of fibre assembly with the forming yarn. On the other hand, a crimped stiff fibre would only touch the tube wall at only a few points along the fibre and, therefore, the bulk of the fibre would travel in an air stream of lower velocity along a surface not traversed by the forming yarn.

## 11.8 . EFFECT OF CRAZING OF THE TUBE ON THE SPINNING PERFORMANCE

In the Perspex tube, "crazing" refers to multiple hair-line surface cracks on the tube wall. The presence of these cracks will tend to increase the coefficient of friction between the yarn and the tube wall.

Two similar vortex tubes with $\frac{1}{2}$ in. X $\frac{3}{16}$ in. tangential inlets were used in this experiment. One of the tube was crazed while the other was not. The results of spinning with the two tubes are given in Table 11.3. It was observed that the crazed tube gave improved twist insertion rate and the yarn was more highly twisted than that obtained with the smooth tube. Thus, it would appear that, under identical conditions, a crazed tube should be preferred to a smooth tube when a high twist insertion rate was needed.

# CHAPTER 12

## MEASUREMENTS OF TORQUE, TENSION AND AIR FLOW IN IN VORTEX SPINNING

# CHAPTER 12

## MEASUREMENT OF TORQUE, TENSION AND AIR FLOW IN VORTEX SPINNING

### 12.1. INTRODUCTION

It is now known that the production of a good yarn is governed by several factors, such as, the spinning tube design, the air pressure difference in tube(or air flow rate) etc. Of the various spinning tube designs experimented upon, the slit inlet nozzle gave a reasonably good spinning performance. However, even in this design, only some performed well at a certain optimum air pressure difference. The question arose as to how these factors influence the formation of a good yarn. It was considered necessary to know the effect of these factors on the torque generation in yarn. This is because torque is usually related to twist and twist to strength. It should be noted that throughout this chapter, emphasis is laid mainly on yarn strength and the effective twist insertion rate of the spinner.

In a conventional yarn, the following relationships hold good:-

(a) In general, below an optimum twist limit, the strength of the yarn depends largely on the amount of twist it contains per unit length.

(b) The amount of twist introduced is a function of the torque applied on the yarn.

The relationship (a) is equally applicable to vortex spun yarns because it has been found in vortex yarns that at any given count, the yarns with high twist are always stronger than those with low twists. The optimum twist in these yarns is different from that usually found in conventional yarns spun with the same material.

In vortex spinning, the net torque inserted into the final yarn differs from the available torque in the spinner. The lack of sufficient restraint at the open end of yarn allows a certain amount of twist to run out and be lost. Thus not all the torque applied to the yarn is necessarily transformed into twists. In other words, unlike conventional spinning, a twist loss mechanism exists in vortex spinning and in fact, the twist loss mechanism is such that even with moderate changes in linear density of yarn and yarn take-up rate the twist factor of the resultant yarn remains fairly constant. However the greater amount of torque available, the greater is the twist factor likely to be all other things being kept equal.

Thus it is essential to know the effective torque introduced into a yarn under different working conditions. Once the optimum conditions are known, it might then be possible to obtain the maximum torque generation and possibly the effective retention of it in the yarn. This would fulfill one of the basic shortcomings of the vortex type of break spinner and thus pave the way for the production of a strong yarn.

During the torque measurement tests, the values of yarn rotational speeds and tensions were also recorded. In addition to these tests, a few more tests were performed separately to find if any relationships existed between the following factors:-

(a) Rotational speed of yarn,

(b) Spinning tension,

(c) Yarn take-up rate,

(d) Linear density of yarn

and (e) Air pressure difference in the tube.

For the sake of clarity, this chapter is divided into three parts. Part I deals mainly with the torque measurements, Part II with yarn speed and tension measurements and Part III with the measurements of air flows.

## PART I

## MEASUREMENTS OF TORQUE ON YARN IN SPINNING TUBES

### 12.2. INTRODUCTION

It was the object of the torque tests to determine the net torque applied to a yarn. It was difficult to measure torque in the yarn during the spinning process but a fair idea of its value could be obtained by experiments on a stationary seed yarn(stationary in the sense that the yarn was not withdrawn from the spinner). It was fully realised that torque values obtained with a stationary seed yarn would differ from those obtained with an almost similar yarn under actual spinning conditions due to the following reasons:-

(a) the lack of fibre flow in tube,

(b) the linear density of the seed yarn was almost constant throughout its length, whereas under normal spinning conditions it would not be,

(c) the length of seed yarn inside the tube was maintained constant whereas under normal spinning conditions it would vary

and (d) the seed yarn was not withdrawn from tube.

12.3. EXPERIMENTAL SET-UP

The net torque introduced into a yarn was determined as follows:-

The angular displacement of a bar of known moment of inertia was measured. A monofilament yarn was used for the suspension of the bar to avoid any defects in torsional characteristics due to the use of staple yarns. This yarn was chosen so as to be just sufficiently sensitive to the torque applied by the spinner. A nylon monofilament yarn of 0.010 in. diameter was suspended from a screw vice held vertically such that the vice centre was in the axis of the vortex spinning tube, as shown in Fig. 12.1. The yarn passed into the tube through the axial hole and was twisted by the vortex action. It was assumed that the vertical disposition of the spinning tube would not affect the torque characteristics of the tube.

A thin, long Perspex bar was attached to the monofilament yarn by passing the yarn through a hole at the bar centre and fixing it by means of a small screw in the bar. The Perspex bar was kept at a distance of 2 cm. from the point of suspension. This bar carried a vertical pointer mark engraved on one of its ends. To measure the angle through which the yarn moved and hence the bar during the tests, a 360° protractor was placed horizontally beneath the Perspex bar. The changes in pointer positions with reference to the protractor readings gave "torsional deflection" of the yarn.

The monofilament yarn was passed through the central hole of the protractor disc. Care was taken that the yarn did not foul the protractor. The short length of

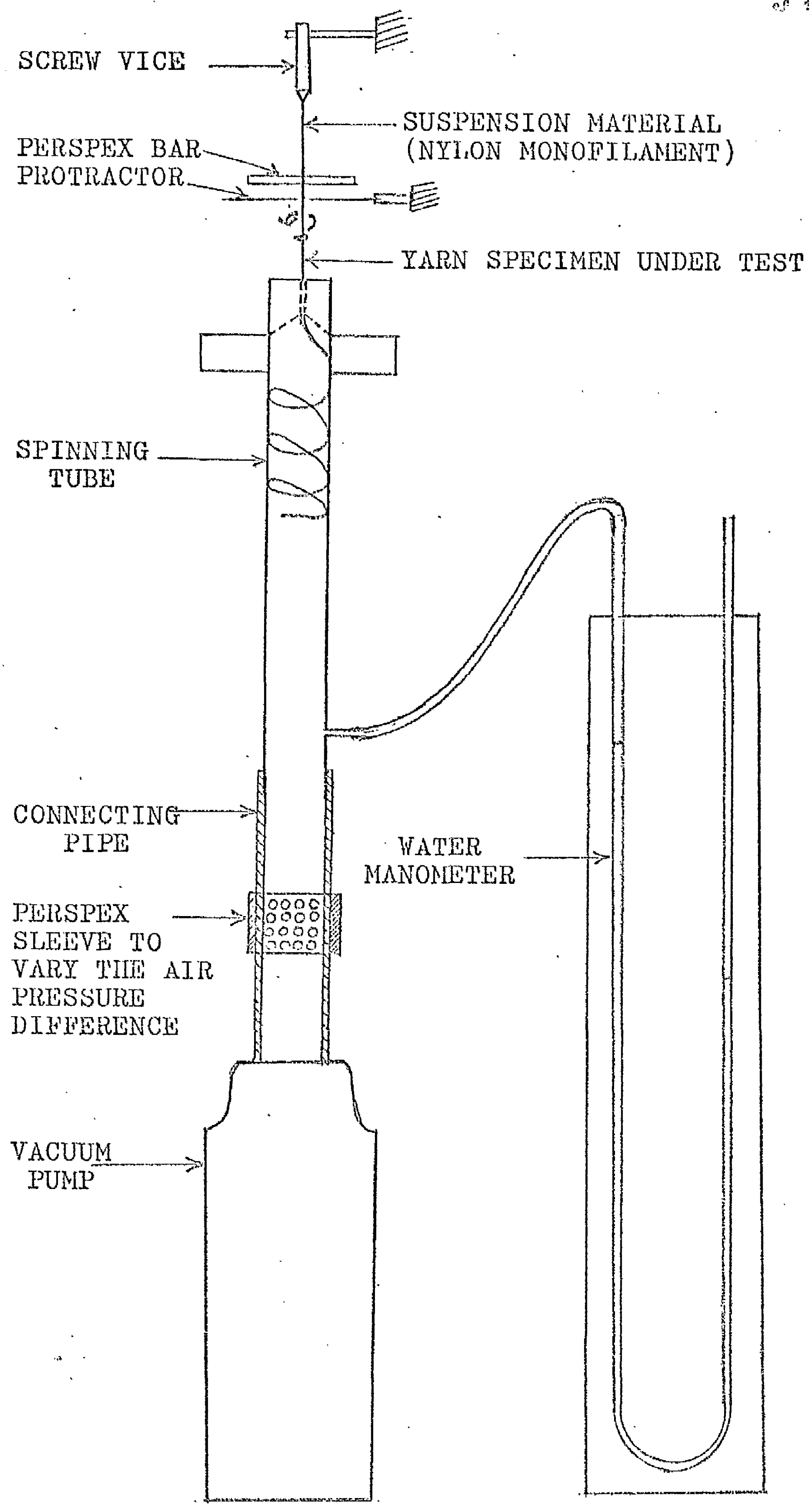



Fig. 12.1.

EXPERIMENTAL SET-UP FOR THE TORQUE TEST

the monofilament yarn which passed through the protractor was used to attach the seed yarn under test. Again, care was exercised such that this joint did not contact the spinning tube.

## 12.4. MEASUREMENT OF TORSIONAL STIFFNESS OF SUSPENSION

Let n be the natural frequency of suspension in oscillations per second,

q be the torsional rigidity of suspension, i.e., the torque required to produce an angular displacement of the bar of one radian from the equilibrium position

and I be the mass moment of inertia of the bar.

Then the torsional rigidity of the suspension is given by the relationship

$$n = \frac{1}{2\pi}\sqrt{\frac{q}{I}}$$

$$\text{or } q = 4\pi^2 n^2 I \quad \ldots\ldots\ldots\ldots(1)$$

Moment of inertia of a thin long bar(I) = $\frac{1}{12}ML^2$, where

M = mass of the bar and L = bar length.

Substituting the value of I in equation (1),

$$\text{the torsional stiffness } (q) = \frac{4\pi^2 n^2 ML^2}{12} \quad \ldots\ldots(2)$$

Therefore, torque = torsional stiffness X torsional deflection .

## 12.5. CALCULATION OF TORQUE

Before the seed yarn was attached, the natural torsional frequency of the suspension system was determined. The Perspex bar was set into small torsional oscillations by a slight twist. Care was taken not to produce pendulum type oscillations. The torsional rigidity of the suspension system was then calculated from equation (2).

From the experiment the following values were obtained.

$$n = \frac{1}{3} \text{ oscillation per second,}$$

$$L = 8.89 \text{ cm.}$$

$$M = 5.125 \text{ gm.}$$

From equation (2),

$$q = 0.15617 \text{ gf.cm/radian}$$

$$\text{or } q = 0.002725 \text{ gf.cm/degree.}$$

The product of the torsional stiffness of the suspension and the torsional deflection gave the torque on the yarn under test. Torque was expressed in gf.cm.

12.6. TORQUE MEASUREMENTS

First of all, it was considered necessary to obtain an idea of hysteresis behaviour of the monofilament suspension under the test conditions. An understanding of this behaviour might be valuable in avoiding any serious errors that might arise in torque measurements.

A nylon monofilament yarn was used both as a suspension material and also as the seed yarn. This was done to avoid any deviation in torque characteristics that might be caused by the presence of any joints in the torque measurement system. The air pressure difference across the tube was first increased to 14 in. and then onwards in steps, as shown in Table 12.1., until it finally reached 45 in. The torsional movement of the bar at each air pressure reading was recorded. A similar procedure was repeated as the air pressure was decreased. The results are shown in Table 12.1. A 2 X $\frac{1}{4}$ in. diameter inlet nozzle and a 1 in. tube was used in this experiment.

From Fig. 12.2., it is obvious that there is a

TABLE 12.1.

NYLON MONOFILAMENT(0.010 in. dia.) - 58 tex

| Air Pressure | Torsional deflection of bar measured from 0° | |
|---|---|---|
| | Increasing air pressure | Decreasing air pressure |
| $(-inH_2O)$ | (degrees) | (degrees) |
| 0 | 0 | 94 |
| 14 | 128 | 202 |
| 16 | 158 | 210 |
| 20 | 182 | 241 |
| 25 | 228 | 262 |
| 30 | 250 | 280 |
| 35 | 270 | 289 |
| 40 | 287 | 293 |
| 45 | 295 | 295 |

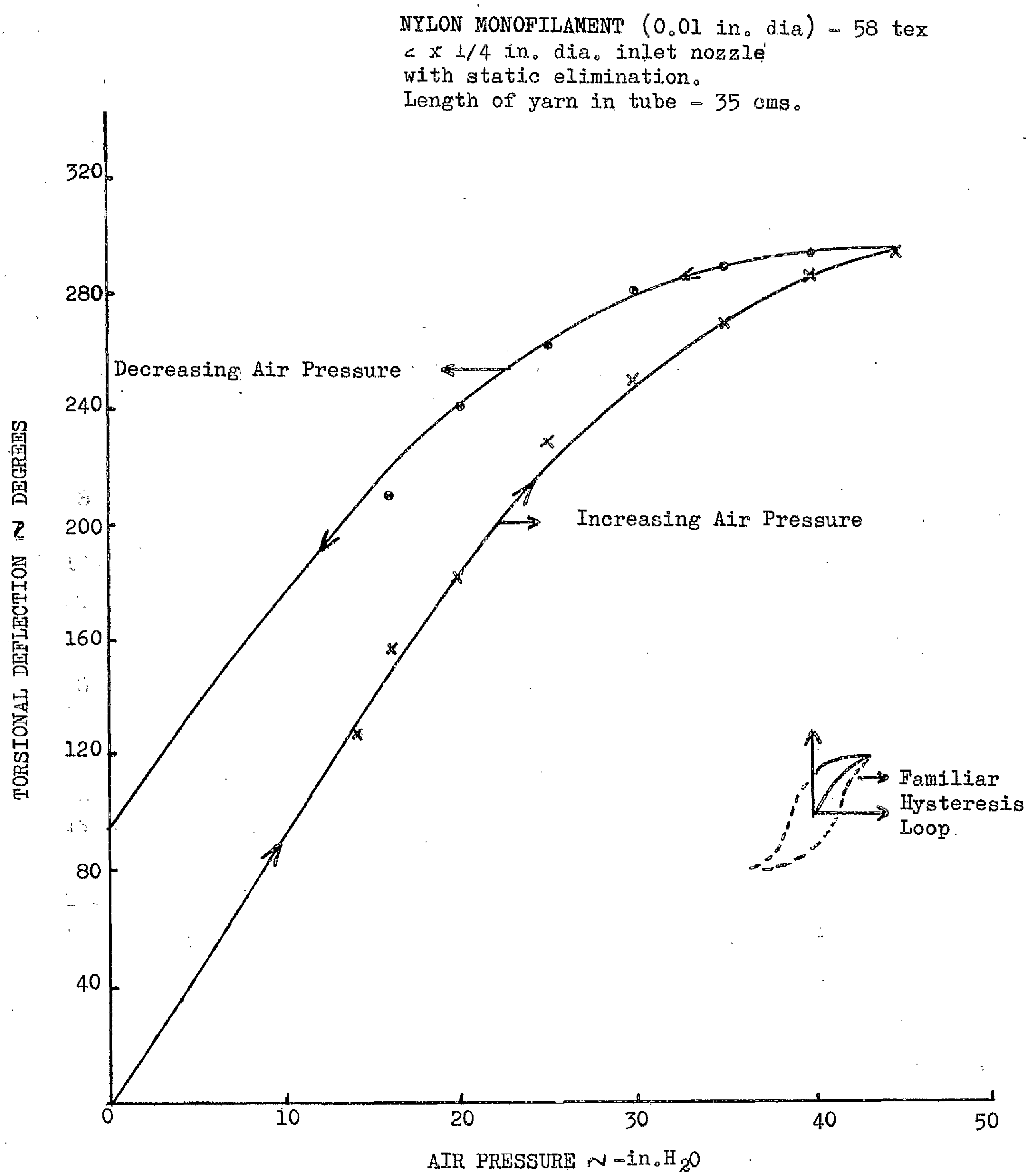



Fig. 12.2

HYSTERESIS OF THE SUSPENSION MATERIAL IN THE TORQUE SET-UP.

hysteresis pattern. This behaviour might be due to (a) the nature of the suspension material and (b) the influence of static charges present in tube which act on the yarn under test. The attraction of the yarn to the tube wall due to static electrification would tend to exercise some restraint on the yarn and this would tend to reduce the amount of twist leakage.

To eliminate the effects due to static, the seed yarn was removed from the spinning tube and allowed to hang loosely in air. The suspension was allowed to come to rest on its own. In this context, it should be mentioned that it took quite some time for the suspension system to attain an equilibrium position. It was assumed that a time interval of 5 minutes would be sufficient for the system to reach its equilibrium condition. It was observed that the suspension moved slowly towards the starting position($0^\circ$). However it finally settled down to a position somewhere between $0^\circ$ and the rest position before the yarn was taken out of the tube. This indicated that the torque retention in the yarn during decrease of air pressure was partly due to the influence of static charges and partly due to the torsional deformation experienced by the suspension material.

The lessons learnt from this experiment were as follows:-

(a) After each test was over, the suspension material needs to be discarded and replaced by a new piece. This was because of the partial torsional deformation of the monofilament yarn. This was considered to adversely affect the stiffness values.

(b) Static charges in tube tend to exercise some influence on twist leakage in yarn.

(c) The better procedure for torque measurement during each test would be to gradually increase the air pressure difference(or quantity of air flow) rather than decrease it so that every specimen was subjected to similar strain history.

In all the subsequent torque experiments, the following parameters were varied:-

(a) Material of the seed yarn,
(b) Length of the seed yarn in the spinning tube,
(c) Air pressure difference in the tube,
(d) Shape of the tangential inlet,
(e) Size of the tangential slit inlet,
(f) Yarn exit hole dimensions
(g) Tube bore size.

The last four mentioned above constitute the spinning tube parameters.

The effect of static elimination on torque behaviour when some of the above parameters were changed was also studied.

<u>12.6.1. Material of yarn</u>

The different materials of yarns that were experimented were cotton, viscose(Fibro), wool and nylon. The first three were staple yarns but the nylon was used as a monofilament only. A cotton ply yarn of 5/12s c.c.(245 tex),and a Fibro ply yarn of 3/6s c.c.(295 tex) ~~and a 2 ply woollen yarn of 140 tex~~ were used in these tests. The nylon monofilament was 0.010 in. in diameter and was about 10s c.c. (59 tex). The ready availability of the above yarns was the only consideration in favour of their choice. Yarns of different materials but of the same linear density and construction would have been ideal choices for this series of tests but this was not available in the laboratory.

It was difficult to use single yarns of staple fibres because these yarns tended to break away during the course of the test due to constant rubbing against the tube surface.

12.6.2. Length of seed yarn in tube

The developed length of the yarn from the open end up to the point lying at the yarn exit hole was taken as the length of seed yarn. Usually six different lengths of yarn of the same material was tested. These lengths varied from 60 cm. to 10 cm, in steps of 10 cm. Due to constant abrading action of the yarn against the tube wall, the yarn showed a tendency to disintegrate. This tendency was more pronounced near the open end than in the body. Constant watch was kept on the yarn condition since any changes in yarn mass would upset the torque test. Furthermore by adopting a procedure of reducing the yarn length from the open end onwards enabled even the slightly damaged yarn end, if any, to be discarded in the subsequent tests.

12.6.3. Air pressure difference

The air pressure differences usually maintained in the tube during the various experiments were equivalent to 16, 20, 25, 30, 35, 40 and 45 in. of water column. These readings were obtained from a U-shaped manometer, one arm of which was connected to the spinning tube and the other left open to the atmosphere. The pressure in the tube was always lower than the atmospheric pressure, hence the air pressure readings were always expressed with negative signs.

The maximum and minimum air pressure differences employed in the test were equivalent to -45 in. and -16 in. of water column respectively. The optimum air pressure difference required with an optimum nozzle design to give a good spinning performance was found to be about 25 in. of water column (please refer to section 11.5. ).However it was thought necessary to cover as wide a range of air pressure differences as possible with the vacuum pump available.

It should be mentioned that the air pressure difference in any one tube is a measure of the quantity of air flowing through it but different nozzles had different total air inlet areas. Again, the velocity of air flow can differ widely with different nozzles although the quantity of air flow passing through them remains the same. The measurement of air flow in different spinning tubes at different air pressure differences is given in Part III of this chapter.

The abrading action on yarn due to constant rubbing against the tube wall was more pronounced at high air flow rates than at low rates. This was because the yarn speed increased with the air flow rate. Moreover, sufficient time was needed for the torque measuring suspension system to come to an equilibrium position at each torque test. This time was sometimes as high as 5 min. Even the strong ply yarns showed some tendency to disintegrate, especially towards their open ends.Since the yarn wear tended to be greater at high air flow rates than at low rates, it was decided to begin the torque tests from low air flow rates and then increase it in steps after each test till the maximum rate was finally attained.

12.6.4.Shape of tangential inlet.

The slit inlet nozzle design gave improved spinning performances and, therefore, this type of nozzle was used mostly in the later spinning experiments. Hence it was thought reasonable to confine the torque tests mainly to the slit inlet type of nozzle design. However a cylindrical inlet nozzle was also included. This was because this inlet design was used in the early part of the present research. Moreover, this nozzle design is still met with in many of the devices relating to air vortex spinning tried elsewhere.

12.6.5. Size of tangential inlets.

The problem associated with the manufacture of numerous spinning tubes with different tangential inlets was solved by the use of a Perspex tube which was provided at one end with an arrangement capable of making a snug fit with any of inlets used. During any test, this tube always carried two tangential inlets of the same dimensions. The various dimensions of inlets, mainly of the slit type, that were experimented upon are given below. In the following, unless stated, the first dimension referred to the length of the inlet and the second to its width. The length of the inlet was always placed parallel to the tube axis.

| | |
|---|---|
| 1/4 in. X 1/16 in. | 3/4 in.X 1/16 in. |
| 1/4 in. X 1/8 in. | 3/4 in.X 3/16 in. |
| 1/4 in. X 3/16 in. | 1 in.X 1/16 in. |
| 1/4 in. X 1/4 in. | 1 in.X 1/8 in. |
| 1/2 in. X 1/16 in. | 1 in.X 3/16 in. |
| 1/2 in. X 3/16 in. | 1 in.X 1/4 in. |
| | 1/4 in. diameter. |

The following spinning tube parameters were, however, kept constant when the inlets were varied.

Nozzle bore - $\frac{3}{4}$ in.

Yarn axial hole - $\frac{1}{8}$ in.

Tube bore - $\frac{3}{4}$ in.

12.6.6. Size of yarn exit hole

The yarn exit hole(also called the axial hole of nozzle) was varied from $\frac{1}{8}$ in. to $\frac{3}{8}$ in., in steps of 1/16 in.

Five circular Perspex blocks with the dimensions mentioned above were made so as to fit the end of the spinning tube. The taper at the base end was kept at about 60° in all these blocks.

12.6.7. Tube bore size

Most of the torque experiments were performed with a spinning tube of ¾ in. bore. This was because the bore size of ¾ in. gave the best spinning performance when spinning staple fibres of about 1½ in. This staple length was generally used in this research. However the size of the tube bore was later changed from ¾ in. to 1 in. to obtain an idea of the effect on torque due to change in bore size.

12.7. EFFECT OF STATIC CHARGES ON TORQUE INPUT IN YARN

12.7.1. At constant air pressure

During the preliminary study on Hirway's nozzle (Chapter 5), it was found that the presence of static charges adversely affected the spinning performance of the tube. It was thought that the answer to this behaviour of the spinning tube might perhaps be revealed in the torque tests. Moreover if the presence of static in tube was found to be detrimental to the torque insertion, as it was likely to be, then steps could be taken to reduce its deleterious influence in the subsequent torque tests. This would greatly assist in maintaining a reasonable standard in the test conditions. Accordingly, the first test series involved the study of torque behaviour under static control and under static build up situations.

The placement of the electrodes of a static eliminator close to the spinning tube(about 6 in. away from the tube near the nozzle end) tended to control the static present. Hence when conditions of static control were required for the tests, the above arrangement was adopted. It should, however, be stressed that the static eliminator does not completely eliminate the static generated in the tube although it does reduce its effect to a considerable extent.

Torque measurements were conducted with cotton, Fibro and nylon yarns under conditions of static accumulation and also under controlled static charge level in the tube.

From Fig. 12.3., it may be noted that the torques on yarn generally tended to increase with the length of yarn lying in the tube. Again it appeared that a higher linear density yarn almost always tended to suffer higher torque. These two relationships seemed to hold good in both the cases of static control and static accumulation. However the significant fact that emerged from these tests was that the torque applied to yarns was always larger when static was under control than when it was not. The torques introduced into all types of yarns were greatly reduced under conditions of static build up in the tube. The reason for this behaviour was not far to seek. Stroboscopic measurements showed that substantial decreases in yarn speed occurred when static charges were allowed to build up. This is clearly shown in Fig. 12.4.

Referring to Fig. 12.5., it may be noted that the percentage loss in yarn speeds varied widely between 2 % and 35% depending upon the yarn length in tube. All the three different yarns exhibited an almost similar pattern in the behaviour of yarn speed loss. The maximum loss occurred with short yarn lengths. This was rather interesting because with control exercised on static build up, a shorter length of

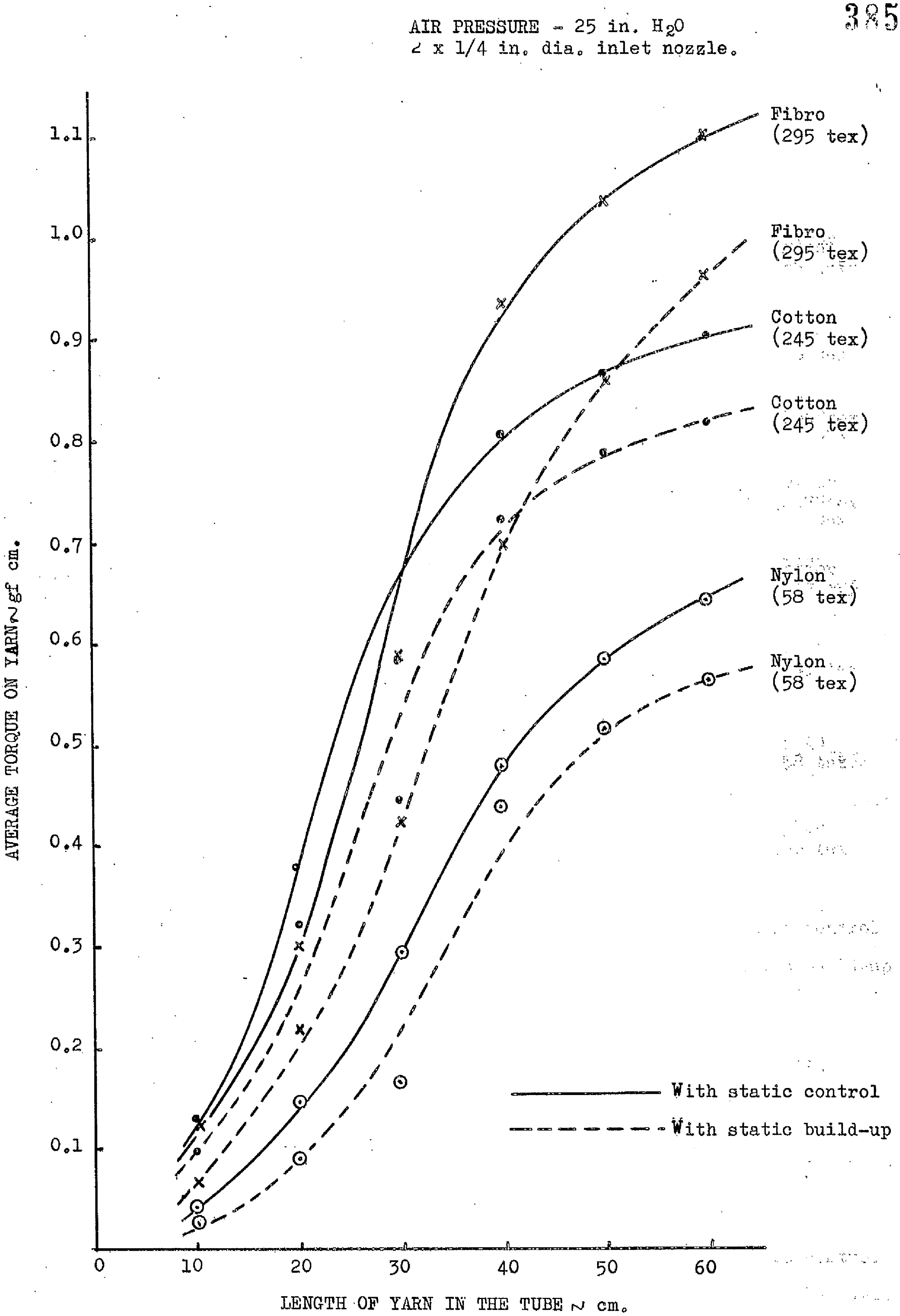



Fig. 12.3

RELATIONSHIP BETWEEN YARN LENGTH AND TORQUE ON YARN IN THE TUBE.

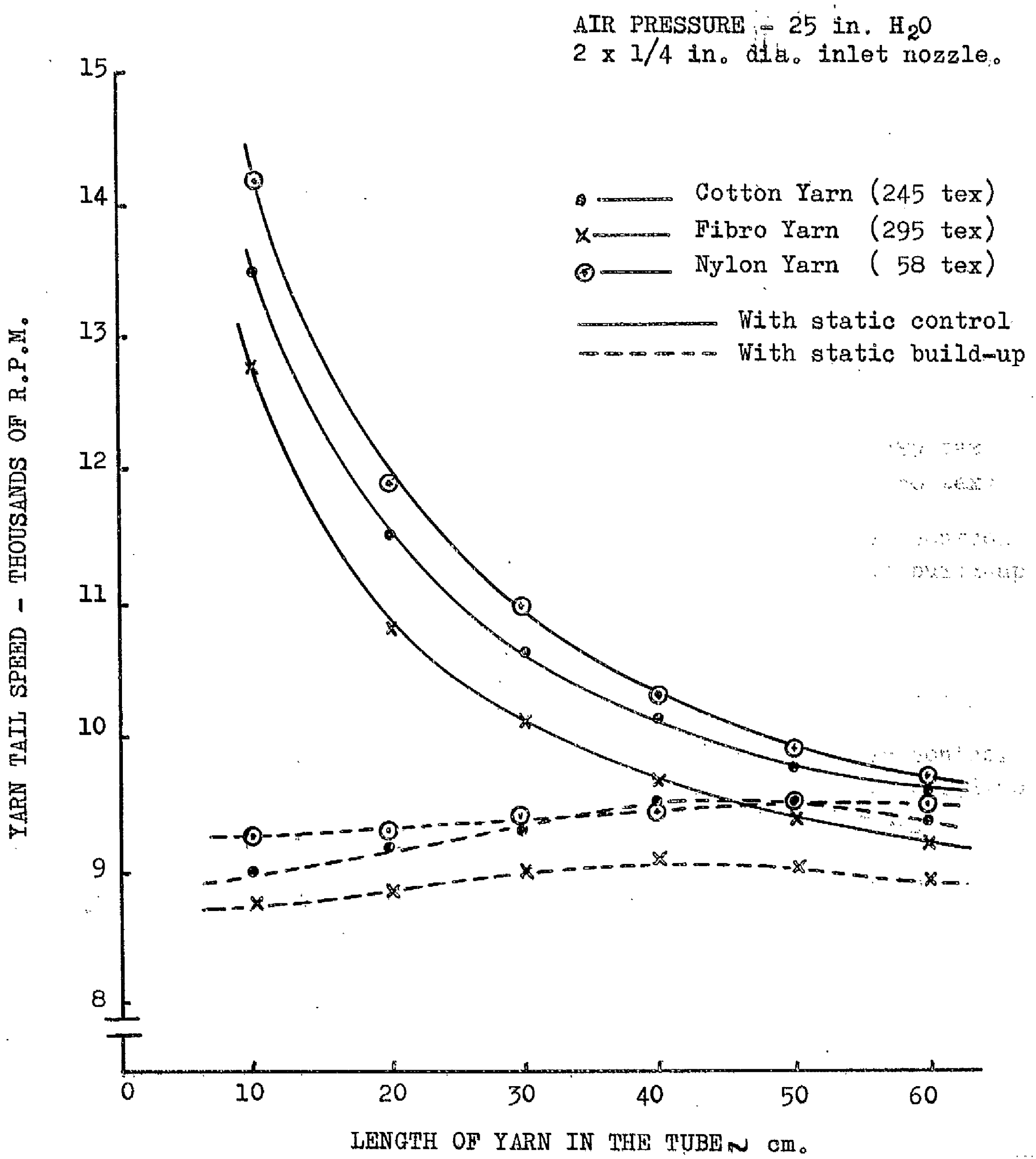



Fig. 12.4.

RELATIONSHIP BETWEEN YARN LENGTH AND YARN SPEED WITH AND WITHOUT STATIC CONTROL.

AIR PRESSURE - 25 in. $H_2O$
2 x 1/4 in. inlet nozzle.

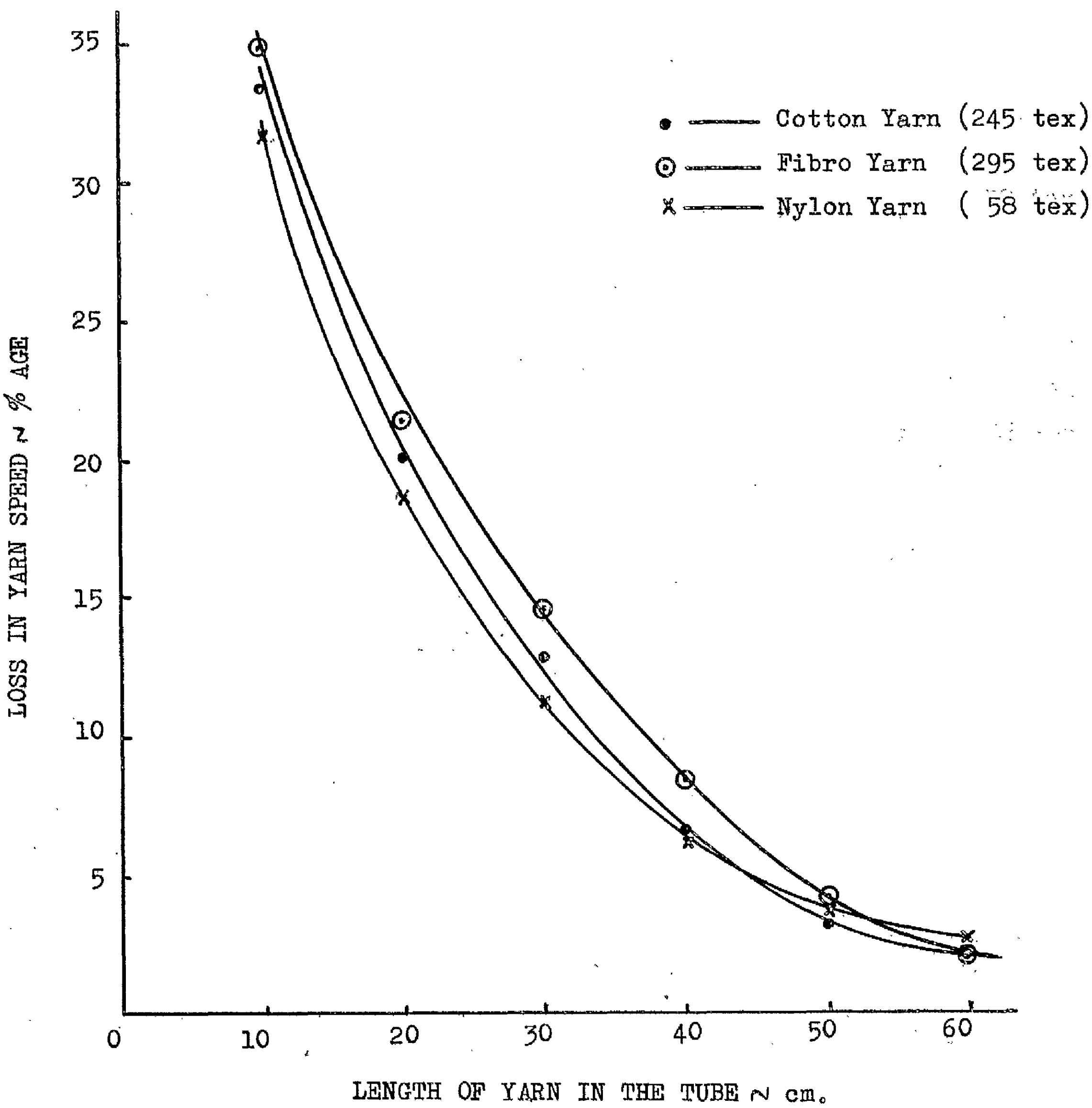



Fig. 12.5.

RELATIONSHIP BETWEEN YARN LENGTH AND LOSS IN YARN SPEED DUE TO STATIC BUILD-UP IN THE TUBE.

FIG. 4

yarn was always associated with higher speed and vice versa. In fact, the relation between yarn length and speed appeared to be nearly hyperbolic. This can be seen in Fig. 12.4. However the yarn length-speed behaviour was quite different from the above when no control was made on static accumulation. Perhaps this might be due to the relatively greater restraint exercised by charges on yarn rotation on shorter yarn lengths.

From Fig. 12.6., it was evident that the torque applied on a unit length of yarn was always higher with static control than without. Moreover it was noticed that an optimum torque per unit length was achieved with about 40 cm. lengths of yarn for all the three yarns under the conditions of static control and accumulation. This optimum value seemed to be well pronounced in the case of Fibro yarns under the static control conditions.

The inherent characteristics of some fibres make them more prone to static generation than others. Therefore it may be reasonable to expect that the rate of static build up in uncontrolled conditions will tend to become high with static prone fibres. Even with fibres like cotton which are supposed to be less prone to charging, the time factor seems to play an important role. The static accumulation tends to increase with time. Assuming that the capacity of the static eliminator is only able to neutralise a certain amount of charges per unit time, it is conceivable that if the rate of static generation is high, then the equilibrium level of charge accumulation will also be high. Control of static formation became less effective at yarn lengths over 40 cm. and this was irrespective of the

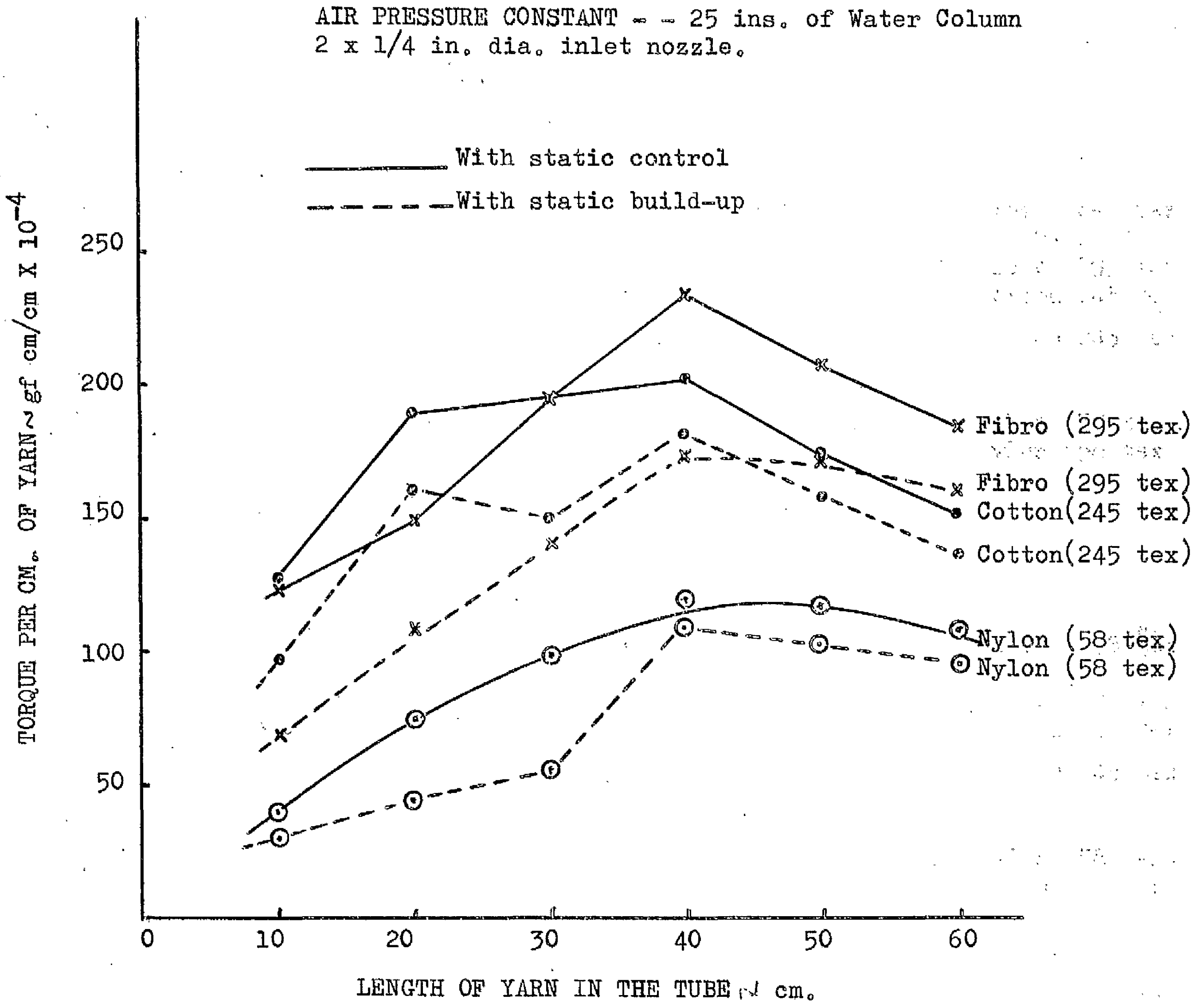



Fig. 12.6.

RELATIONSHIP BETWEEN YARN LENGTH AND TORQUE PER UNIT LENGTH UNDER CONDITIONS OF STATIC CONTROL AND STATIC BUILD-UP.

nature of fibres used. Perhaps this is one of the possible explanations for the general decline in torque input at lengths over 40 cm. The following is another explanation of this behaviour.

It is known that air flows in a fixed helical path in the spinning tube and the pitch of this helix tends to increase downstream. On the other hand, the yarn moves over the entire surface of the tube length covered by the yarn. Since it is only the movement of the material that causes static generation, it may be readily seen that the entire tube surface covered by the yarn will tend to become charged (assuming that fibres are not flowing in the tube). The positive and negative ions released from the electrodes of static control device will tend to be carried along the helical path of the air stream. This flow of ions will tend to de-electrify the helical track. Such a selective de-charging of the tube surface will tend to create a situation when the rest of the tube surface will tend to retain its charges. Since the pitch of the helical path of air tends to open out towards the suction end, the area of tube surface de-electrified per unit length of tube will tend to gradually reduce downstream. The effectiveness of the ionised air stream will also diminish. This will tend to give rise to increased static accumulation per unit tube length at the downstream portions of the tube. Such a build up will tend to affect the movement of longer lengths of yarn. The reduced yarn speeds will eventually result in a lowered torque input. The experimental torque values seemed to indicate that the maximum yarn length up to which proper static control could be exercised was 40 cm.

12.7.2. At varying air pressures

So far the effect of static on torque input under constant air pressure was considered. In the next series of tests, air pressure was varied between -16 in. and -45 in. of water. The yarn length was kept constant during each test. Since the yarn length under the actual spinning conditions usually varied between 20 and 30 cm., it was thought sufficient to confine the tests to only three yarn lengths, viz., 20, 30 and 40 cm. Once again, the tests were carried out with the three yarns, viz., cotton, Fibro and nylon.

From the results obtained with the above tests and shown in Figs. 12.7., 12.8., and 12.9., it was quite obvious that the torque per unit length of yarn tended to increase with air pressure. The torques obtained with static control were definitely higher than those obtained under conditions of static build up.

The decrease in torques might be attributed to the reductions in yarn speed. The yarn speed-air pressure relationship is shown in Fig. 12.10.

It should be also added that the presence of a limited quantity of charge was found to be an asset to spinning(section 5.5.2.4.). Hence the complete elimination of static charges was not desired. Therefore in all the subsequent torque tests a control over static was always exercised.

12.8. RELATIONSHIP BETWEEN TORQUE AND YARN LENGTH

The results of the tests conducted under conditions of static control and included in the previous section could be made use of in supplying additional information.

FIBRO YARN - 295 tex.
2 x 1/4 in. dia. inlet nozzle.

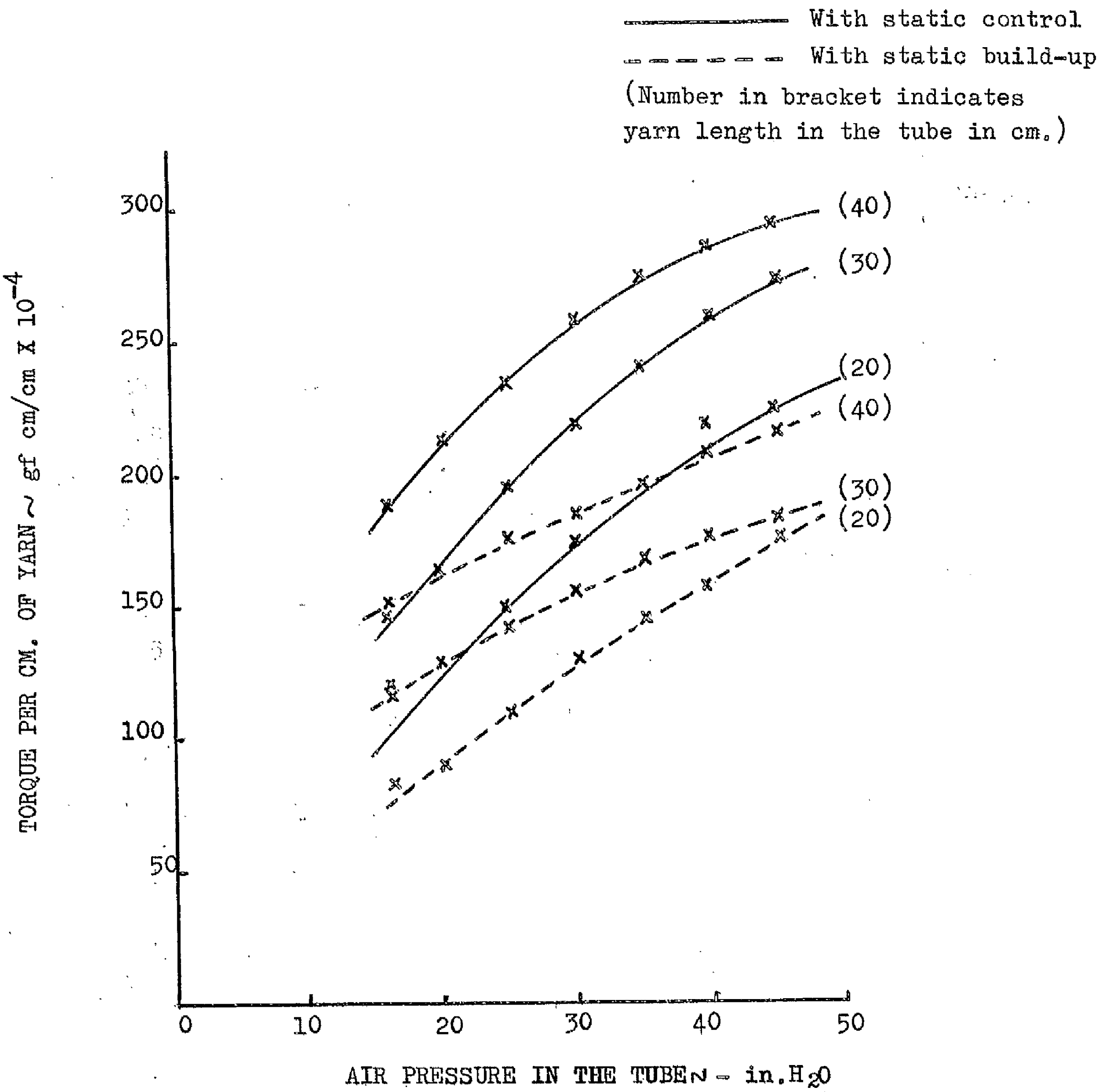



Fig. 12.7

RELATIONSHIP BETWEEN AIR PRESSURE AND TORQUE PER UNIT LENGTH OF A FIBRO YARN WITH DIFFERENT LENGTHS IN THE TUBE.

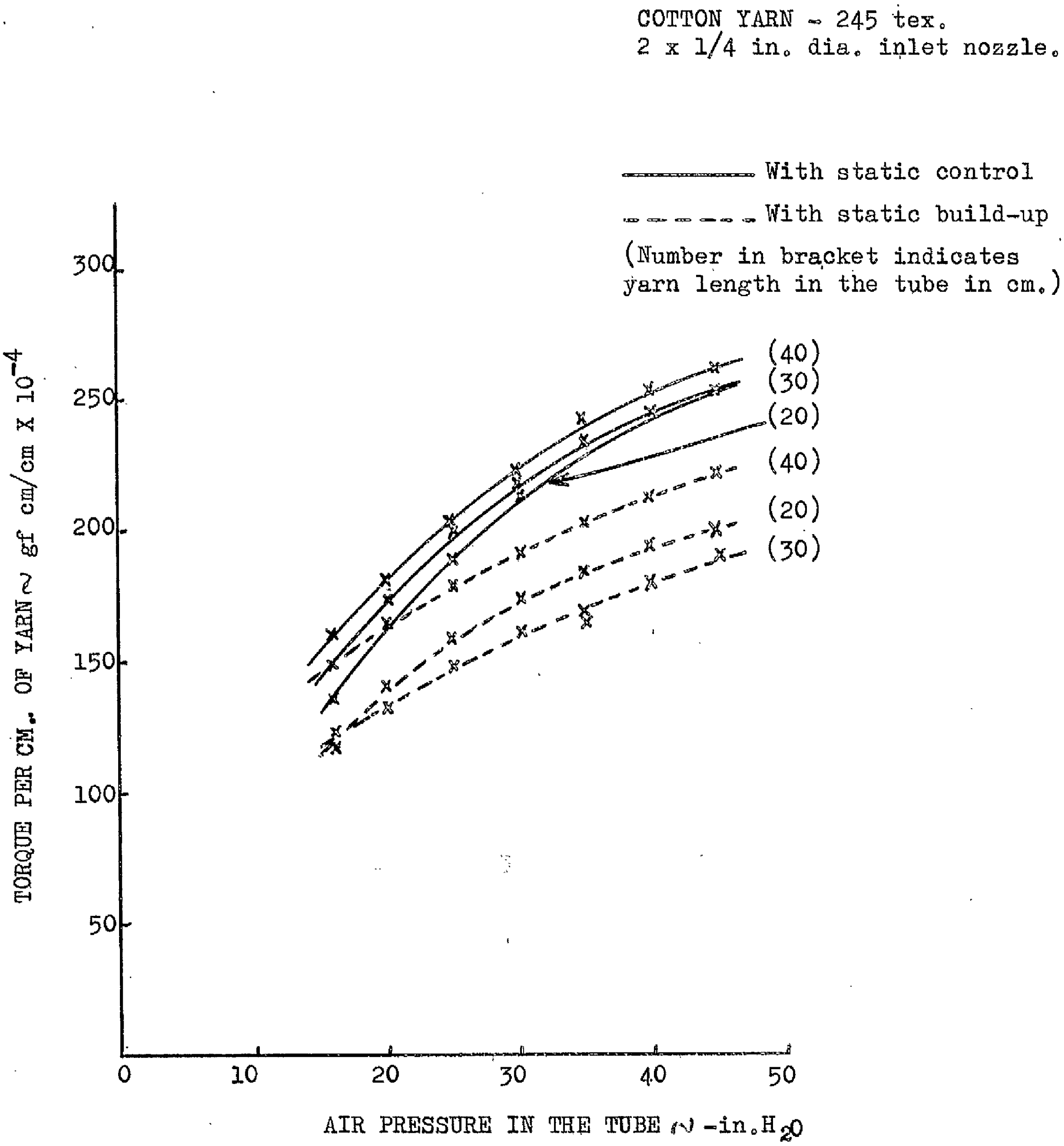



Fig. 12.8

RELATIONSHIP BETWEEN AIR PRESSURE AND TORQUE PER UNIT LENGTH OF A COTTON YARN WITH DIFFERENT LENGTHS IN THE TUBE.

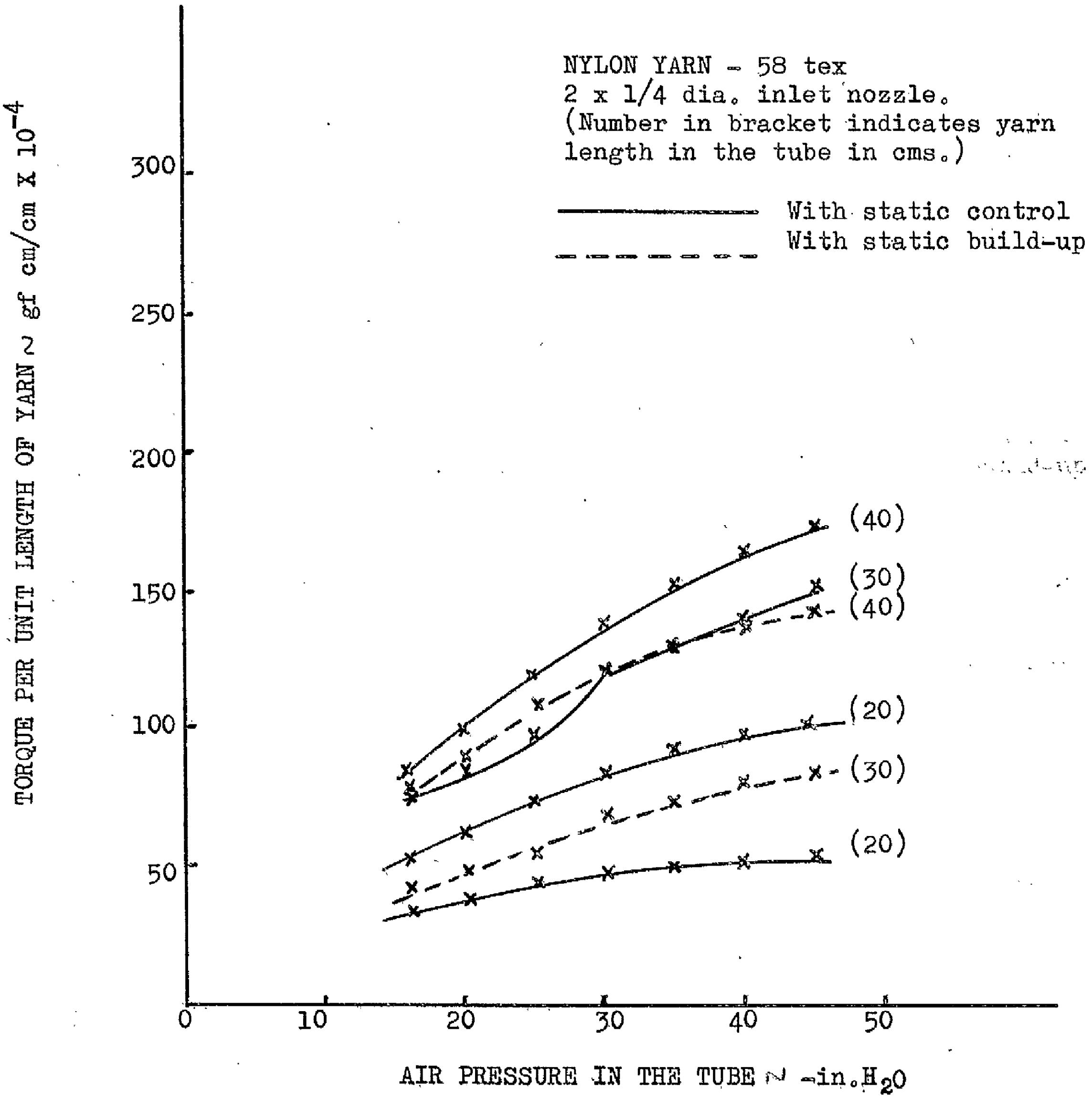



Fig. 12.9

RELATIONSHIP BETWEEN AIR PRESSURE AND TORQUE PER UNIT LENGTH OF A NYLON YARN IN THE DIFFERENT LENGTHS IN THE TUBE.

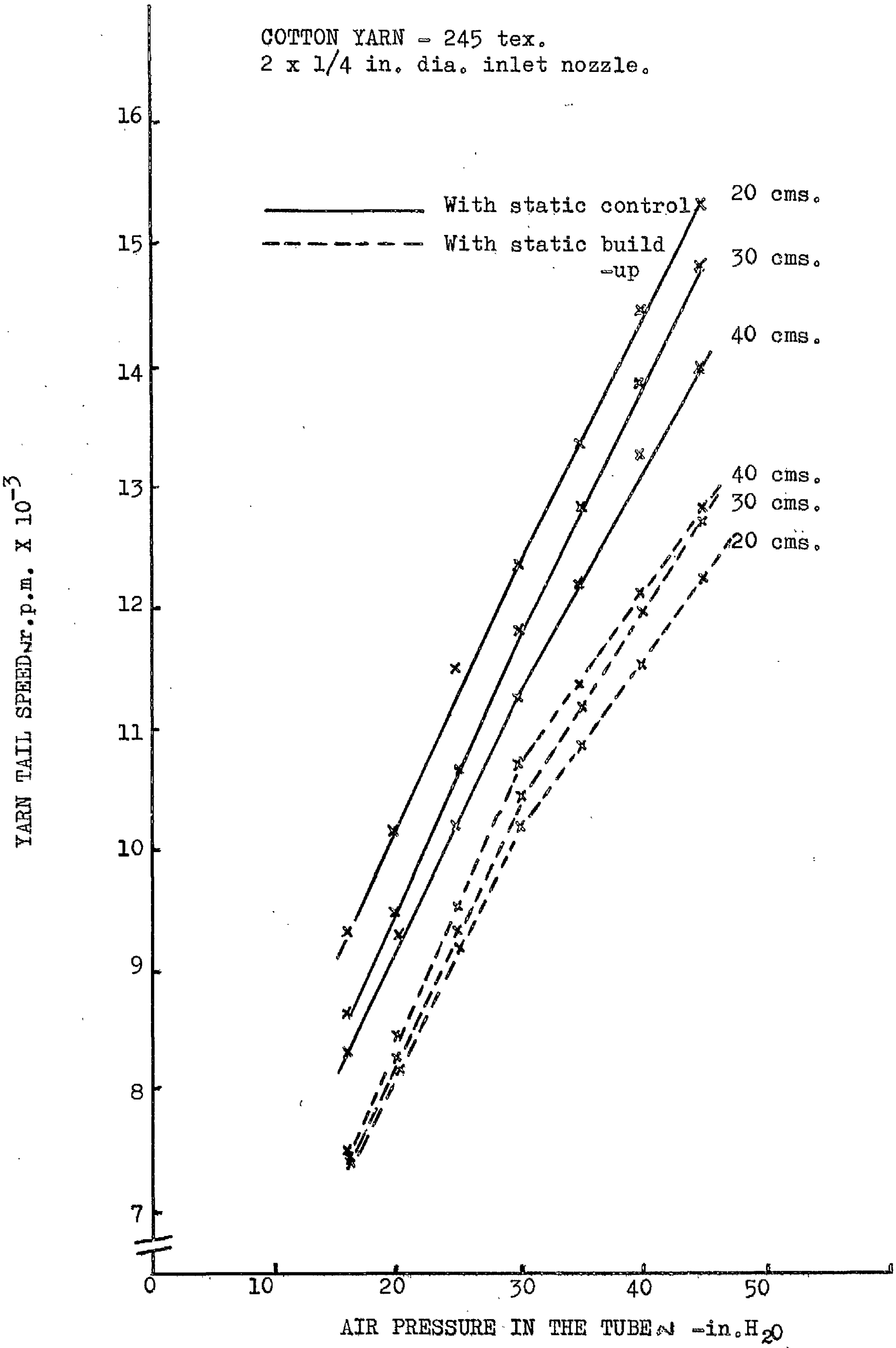



Fig. 12.10

RELATIONSHIP BETWEEN THE AIR PRESSURE AND THE YARN SPEED WITH DIFFERENT YARN LENGTHS.

Reverting to Fig. 12.3., the torques on yarn lengths of 20, 30 and 40 cm. appeared to be a function of yarn lengths. In general, this relationship seemed to be correct at different air pressures as well as for the different materials of yarns tested. However the slope of the curves appeared to vary with each test condition. The results obtained with the two air pressures of -25 in$H_2O$ and -45 in$H_2O$ are shown in Figs. 12.3. and 12.11. respectively.

In general, the torque per unit length fell off rapidly at long yarn lengths (50 and 60 cm.) and less rapidly at short lengths (10 cm.) This indicated that the torque per unit length of yarn was greatest with lengths between 20 and 40 cm.

Approximate relationships between torque and yarn lengths were found when the results were plotted in log-log graphs.

For cotton yarn,

$$\text{torque} = f\,(\text{yarn length})^{0.26} \quad .$$

For Fibro yarn,

$$\text{torque} = f\,(\text{yarn length})^{0.32} \quad .$$

For nylon yarn,

$$\text{torque} = f\,(\text{yarn length})^{0.40} \quad .$$

Presumably these variations were due to the different frictional characteristics of the individual yarns with the tube.

## 12.9. RELATIONSHIP BETWEEN TORQUE AND AIR PRESSURE

A simple torque experiment was conducted with the nylon yarn with various lengths (20, 30 and 40 cm.) and at increasing and decreasing air pressures. The results of this experiment are shown graphically in Fig.12.12. It was

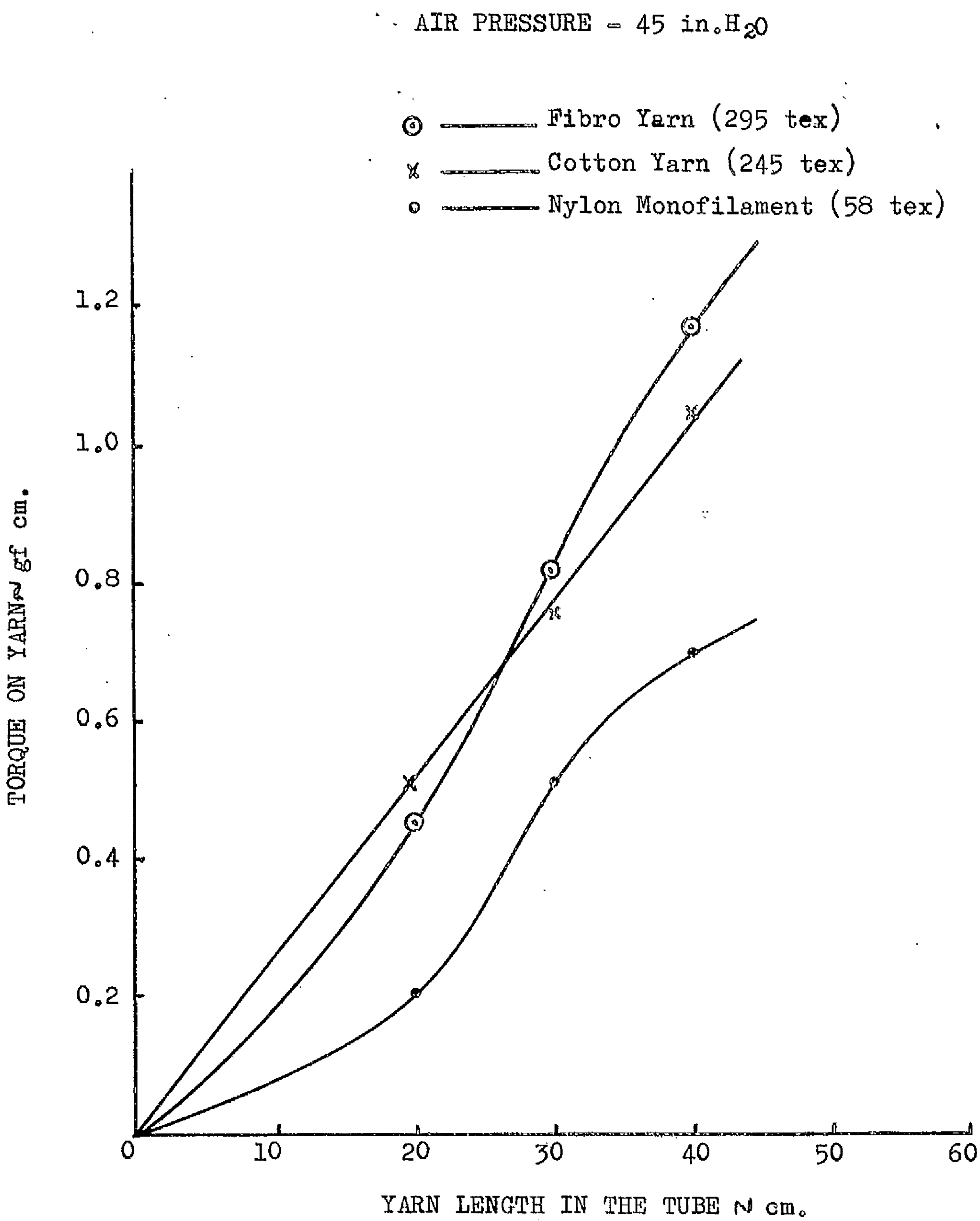



Fig. 12.11

RELATIONSHIP BETWEEN THE YARN LENGTH AND TORQUE WITH DIFFERENT MATERIALS OF YARN

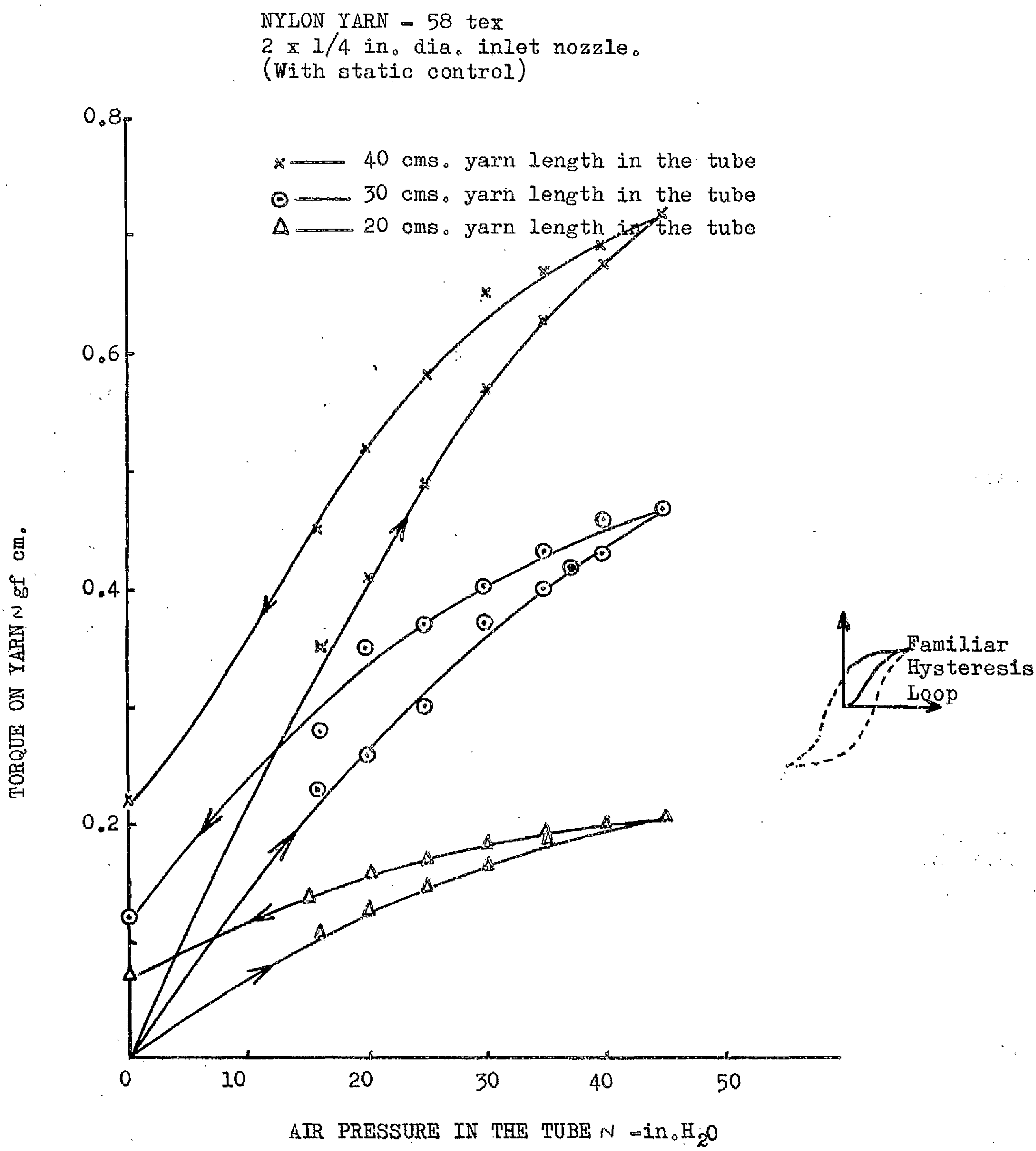



Fig. 12.12

RELATIONSHIP BETWEEN AIR PRESSURE AND TORQUE ON YARN observed that torque tended to increase with pressure.

However the increments in torque per unit air pressure was higher at pressures up to -30 in$H_2O$ than those corresponding to pressures above -30 in$H_2O$. A noticeable deviation in the graph may be noted at the air pressure of -30in$H_2O$.

The torque values tended to increase with yarn length. This is seen in Figs. 12.12. and 12.13. The results shown in these figures show that torque is not a linear function of air pressure. In order to discover what the relationship might be, the results were plotted on log graph paper and the resulting graphs were linear, i.e., torque=k $\Delta p^n$. However it was found that the constants k and n varied with both yarn material and length. The results are shown in Table 12.1(a).

TABLE 12.1(a)

| Yarn length (cm.) | Cotton | | Fibro | | Nylon | |
|---|---|---|---|---|---|---|
| | k | n | k | n | k | n |
| 40 | 0.0008 | 0.31 | 0.0012 | 0.25 | 0.0006 | 0.31 |
| 30 | 0.0008 | 0.22 | 0.0012 | 0.22 | 0.0006 | 0.17 |
| 20 | 0.0008 | 0.15 | 0.0012 | 0.18 | 0.0006 | 0.13 |

Figs. 12.14. and 12.15. show three-dimensional graphs of torque bahaviour at different conditions of yarn length and air pressure for the different types of yarns tested.

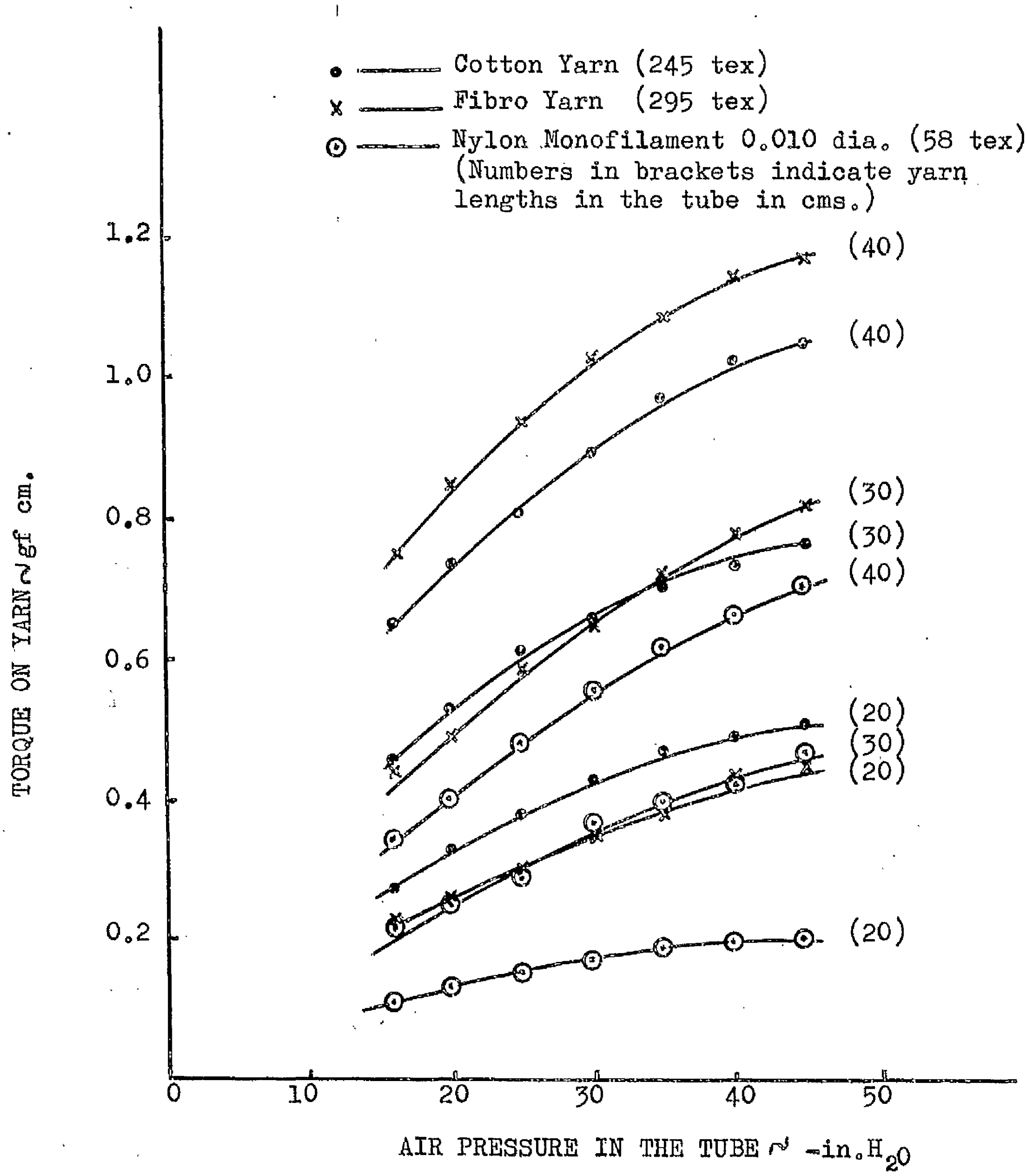



Fig. 12.13.

RELATIONSHIP BETWEEN AIR PRESSURE AND TORQUE ON YARN OF DIFFERENT LENGTHS AND MATERIALS.

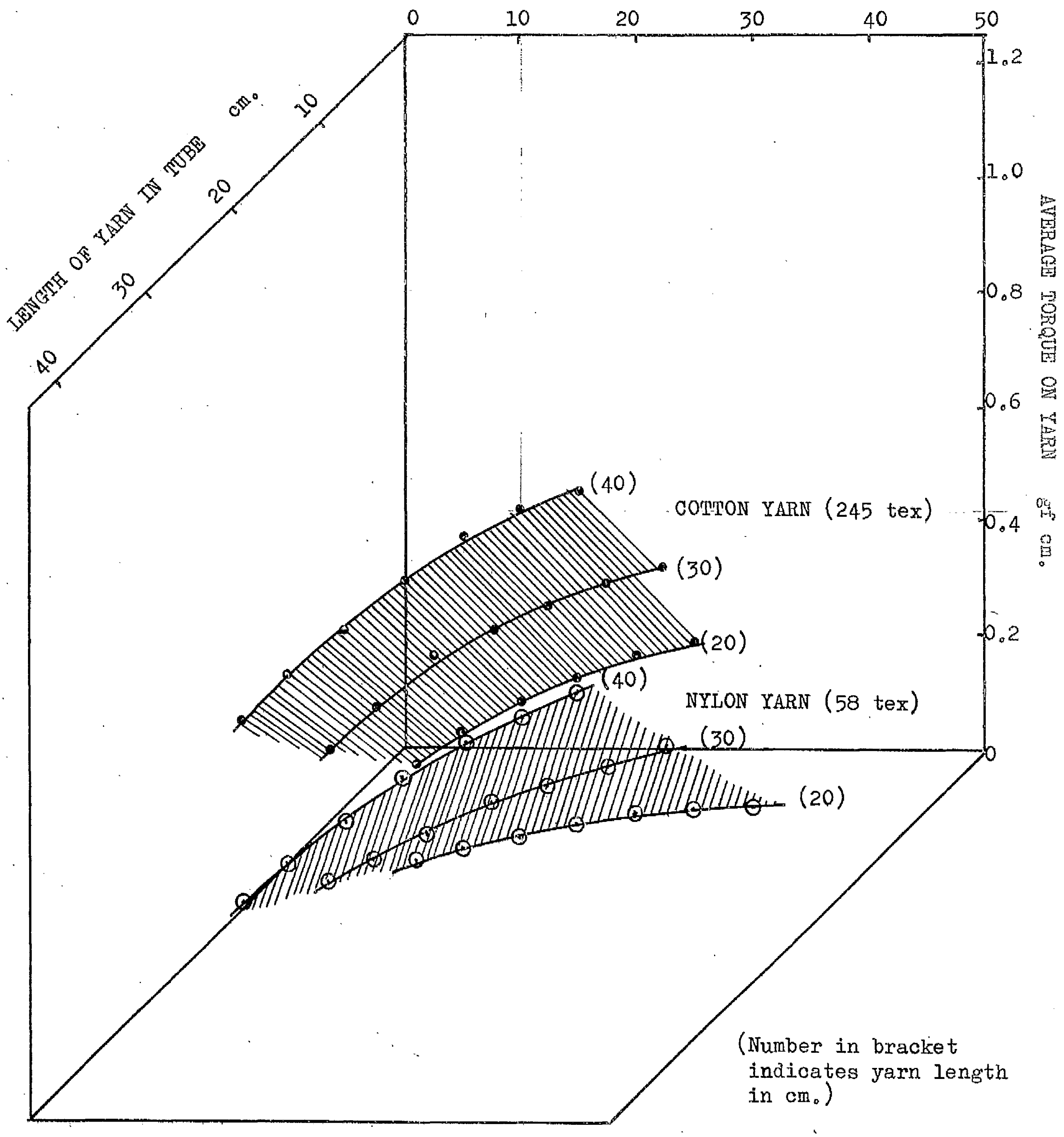



Fig. 12.14

TORQUE BEHAVIOUR WITH YARN LENGTH AND AIR PRESSURE FOR COTTON AND NYLON YARNS

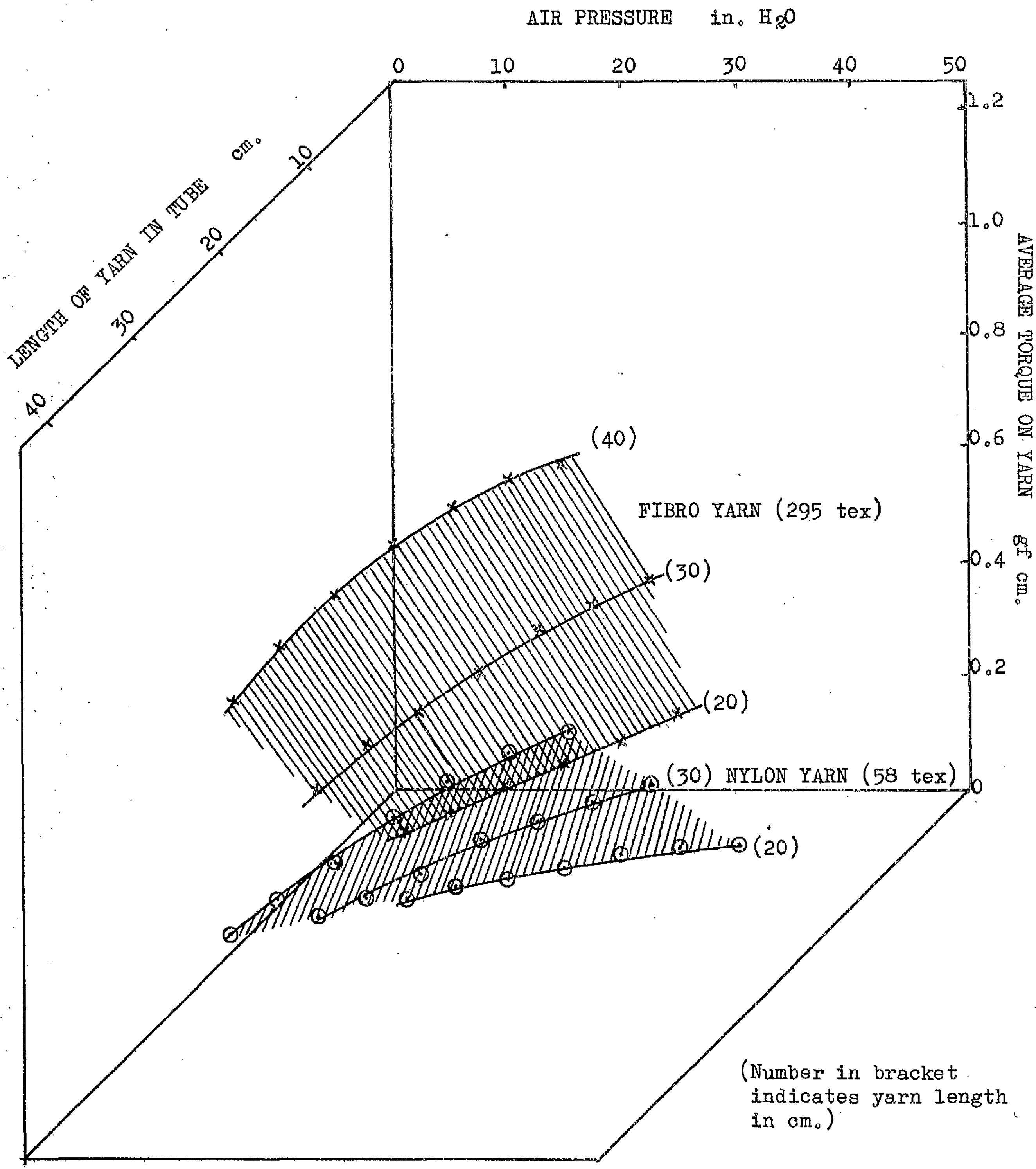



Fig. 12.15

TORQUE BEHAVIOUR WITH YARN LENGTH AND AIR PRESSURE FOR FIBRO AND NYLON YARNS

A fair approximation for the purpose of generalisation is given below:-

$$\text{torque} \propto (\text{air pressure})^{0.30} \text{ for 40 cm. yarn length.}$$
$$(\text{air pressure})^{0.20} \text{ for 30 cm. yarn length.}$$
$$(\text{air pressure})^{0.15} \text{ for 20 cm. yarn length.}$$

It should be pointed out that with the type of nozzle used (2 X $\frac{1}{4}$ in. diameter) in the above test series, the torque insertion was in the same direction as vortex flow. The torque introduced was thus due to sliding on the tube wall. Therefore, the above findings will tend to be valid only under conditions of sliding torque.

## 12.10. SLIDING AND ROLLING TORQUES

The term "sliding torque" was used to represent the type of torque applied to the suspended material in which the torsional deflections were produced in a direction coincident with that of vortex flow. This torque could only be obtained when the yarn in the tube was bodily sliding on the tube wall without much rolling. On the other hand, when the resultant torque introduced into the suspended material was in a direction opposed to that of vortex flow, the torque was termed "rolling torque". The rolling torque was produced when, under certain conditions, the bodily contact of the yarn with the tube wall tended predominantly to roll the yarn rather than to slide it.

It was necessary to introduce these terms because they were needed during the discussion of the effect of nozzle design geometry on torque.

In all the different types of nozzles used in these tests, the tangential inlets were always positioned in such a way as to produce a vortex flow in an anti-clockwise direction when viewed from the suction end of the tube. This direction of vortex flow gave Z twist on yarn subjected to sliding torque and S twist with rolling torque.

In general, the nozzles which had slit lengths of $\frac{1}{4}$ in. but different widths(including that of $\frac{1}{4}$ in. dia. cylidrical inlets) always produced sliding torque in yarn. Rolling torque was, however, predominantly exhibited by nozzles with 1 in. slit length. It was interesting to note that with some nozzles, especially with slit lengths of $\frac{1}{2}$ in. and $\frac{3}{4}$ in., both types of torques were obtained. The transition from one type to another usually occurred with certain yarn lengths. These different behaviours are discussed after the next section.

It should be pointed out that both types of torques tend to exist in a spinning tube. The extent to which they manifest themselves seem to be governed by certain factors which are dealt with later on. Of these two torques, the predominant one would tend to decide the type of resultant torque applied to the yarn. The amount of torque would tend to be influenced by the relative strengths of these two torques.

## 12.11. HYDRAULIC MEAN LENGTH

One of the characteristics of the nozzle inlets, that of their hydraulic mean length , was later found to have a profound controllinginfluence on the torque behaviours of yarn. The term "hydraulic mean length" (or hydraulic radius) is commonly used in fluid dynamics in connection with turbulent flows mainly in non-circular cross-sections.

The hydraulic mean length of a cross-section is equal to $\frac{\text{area of cross-section}}{\text{wetted perimeter of cross-section}}$. In this work, this term was applied to the nozzle inlets.

The purpose of using this term was to find if this parameter had any relation to the air flow rate and the net torque applied to the yarn.

Fig. 12.16. shows the relationship between hydraulic mean length and volume rate of air flow at different air pressures. From this figure, it might be observed that the slope tended to become rather steep between the hydraulic mean length values of 0.15 cm. and 0.20 cm. (It was seen later that in this region of hydraulic mean length, the torque gains in yarn tended to be high).

The volume rate of air flow (V) is proportional to $A \times (\Delta p)^{\frac{1}{2}}$, where A is the area of the opening in the tube and $\Delta p$ is the air pressure difference across the tube.

Then, $V = K.A.(\Delta p)^{\frac{1}{2}}$, where K is a constant.

Friction losses occur in air flows. As the volume rate of air flow increases, it might be expected that the friction losses in the system would also tend to increase and, therefore, the value of K would no longer be constant. It might well be that the value of K would decrease too.

Fig. 12.16(a) shows the relationship between the hydraulic mean length and $\frac{\text{volume rate of air flow}}{\text{area of opening} \times (\text{air pressure})^{\frac{1}{2}}}$ i.e., K. From the graph, it was observed that the value of K decreased when the hydraulic mean length was increased. This agrees with the predicted relationship.

Fig. 12.17. shows the relationship between hydraulic mean length and the product of the area of opening and $(\text{air pressure difference})^{\frac{1}{2}}$.

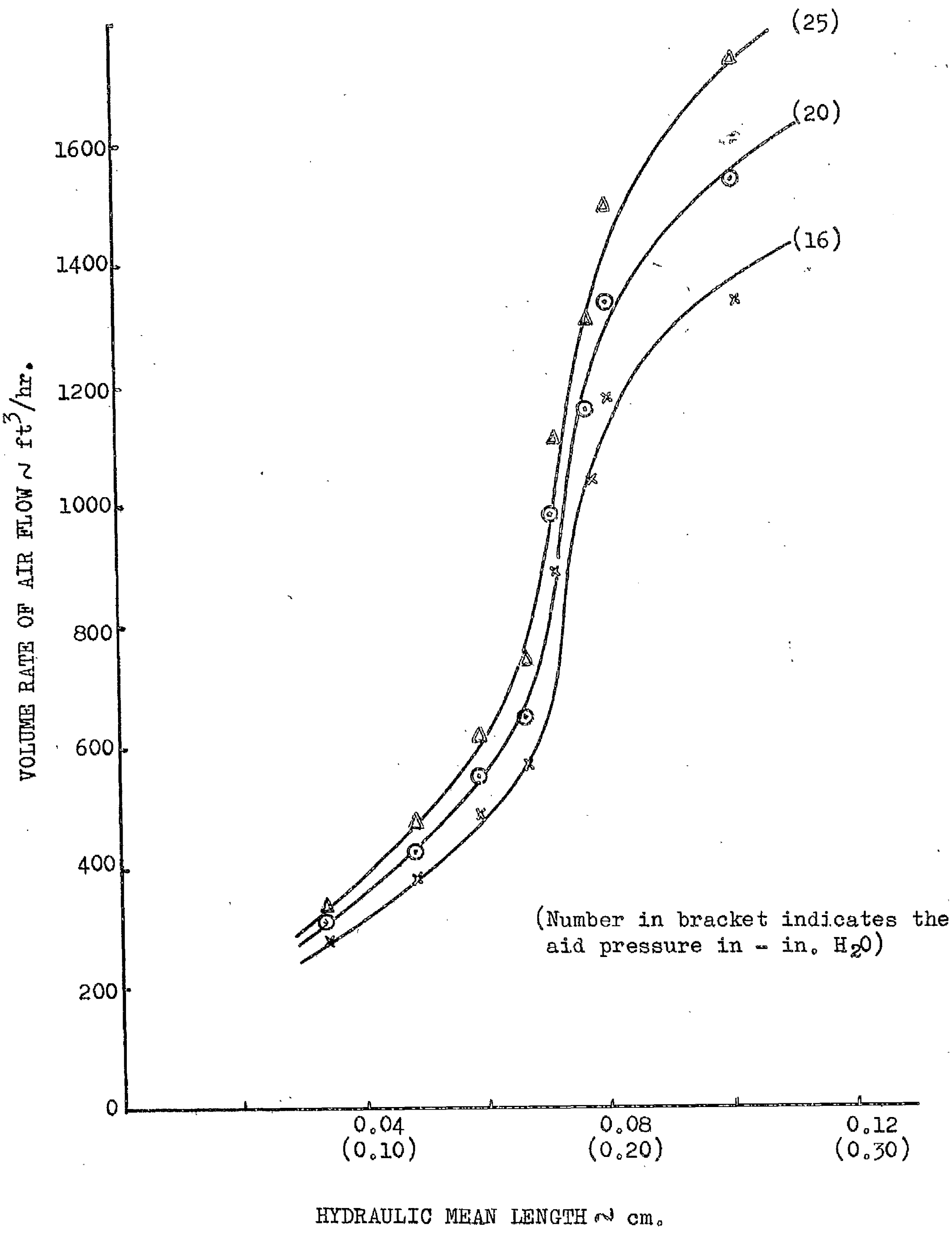



Fig. 12.16

RELATIONSHIP BETWEEN HYDRAULIC MEAN LENGTH AND VOLUME RATE OF AIR FLOW AT DIFFERENT AIR PRESSURES

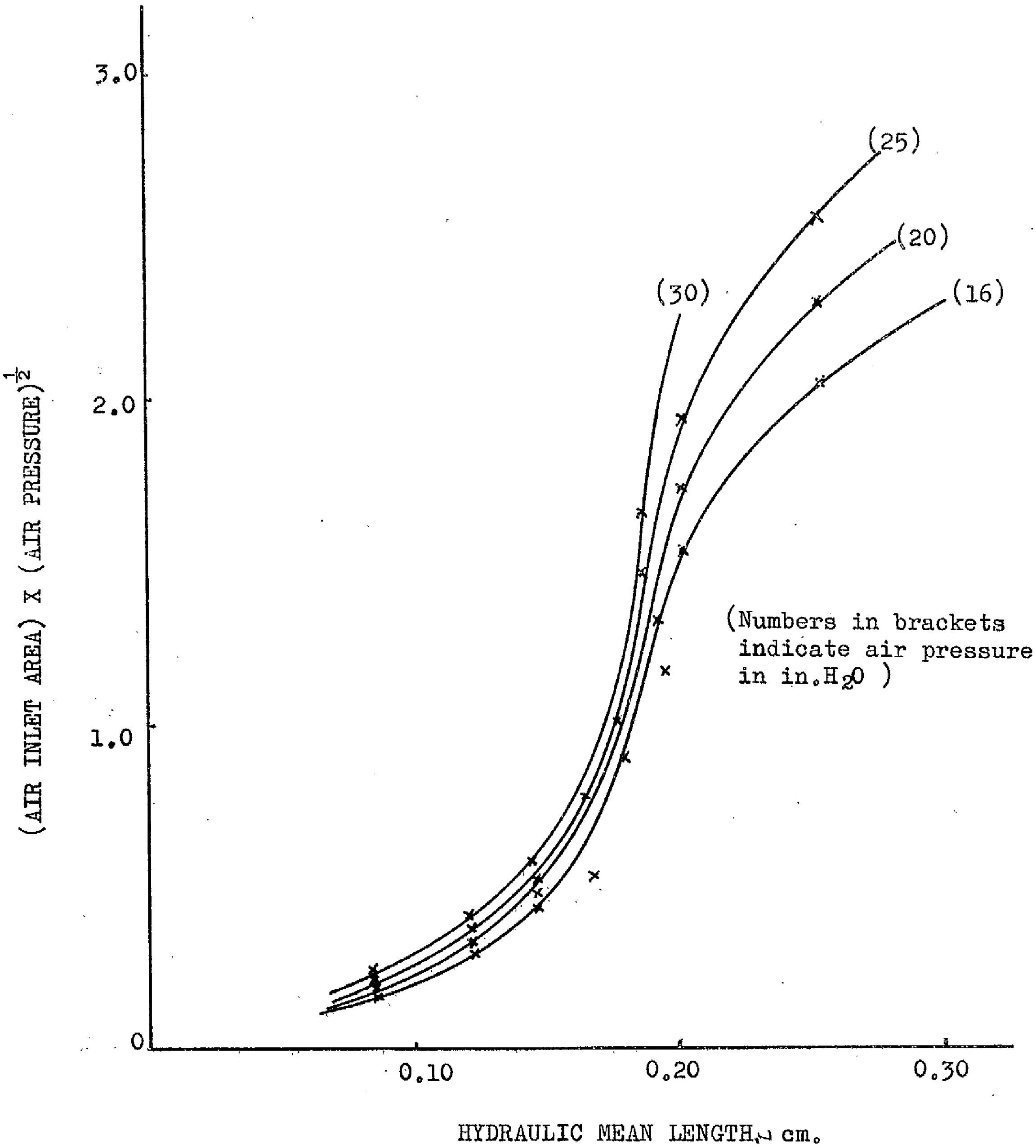



Fig. 12.17.

RELATIONSHIP BETWEEN HYDRAULIC MEAN LENGTH AND THE PRODUCT AIR INLET AREA AND (AIR PRESSURE)$^{\frac{1}{2}}$ AT DIFFERENT AIR PRESSURES

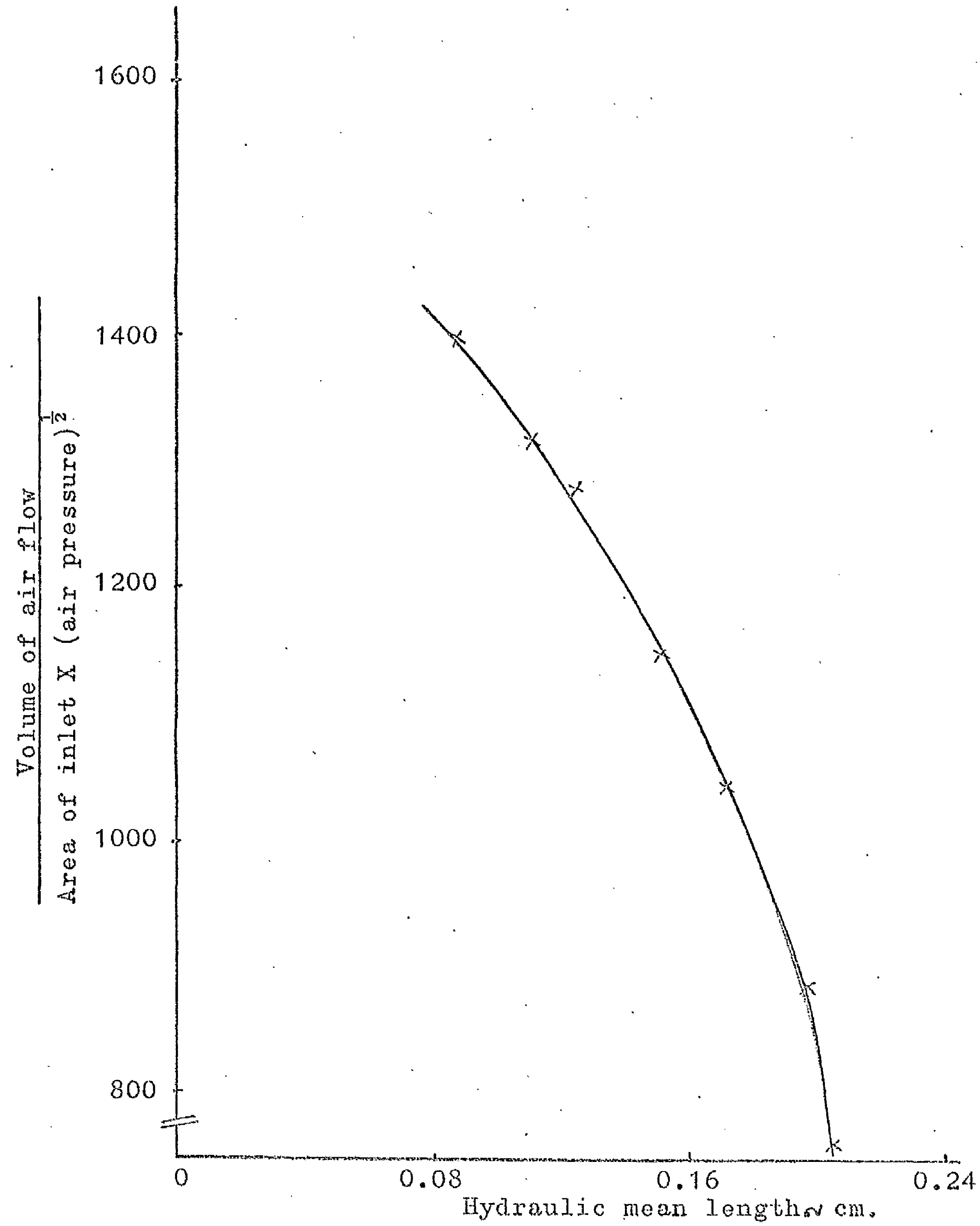



Fig. 12.16.(a)

RELATIONSHIP BETWEEN HYDRAULIC MEAN LENGTH AND

$$\frac{\text{VOLUME OF FLOW}}{\text{AREA OF INLET X (AIR PRESSURE)}^{\frac{1}{2}}}$$

## 12.12. EFFECT OF NOZZLE DESIGN GEOMETRY ON TORQUE

Torque experiments were carried out with various spinning tube designs (18 in all). Torque measurements were made with each nozzle design by varying the yarn length and the air pressure. At each yarn length, torques were obtained with different air pressures. A cotton yarn of 295 tex was used throughout these tests.

The results of these tests are given in Appendix . It was considered unnecessary to go into the results of each test. Only those results which were thought to throw some new and interesting information were picked out for discussion.

As already mentioned earlier, some of the spinning designs exhibited sliding torque while others gave rolling torque. These experiments were classified into the following two groups:-

(a) Those which produced a net sliding torque

and (b) those which produced rolling torque.

### 12.12.1. Torque tests with net sliding torque

Nozzles of $\frac{1}{4}$ in. slit length with widths of 1/16 in., 1/8 in., 3/16 in. and 1/4 in. as well as that of $\frac{1}{4}$ in. diameter inlets have been considered here.

The hydraulic mean length versus torque relationship for different yarn lengths but at a constant air pressure of -25 in. water is shown in Fig. 12.18. From this figure, it might be noted that the longer yarn lengths were usually associated with higher torque values. The torque values, at any particular yarn length, seemed to bear a linear relation with the hydraulic mean length. This relationship is as follows:-

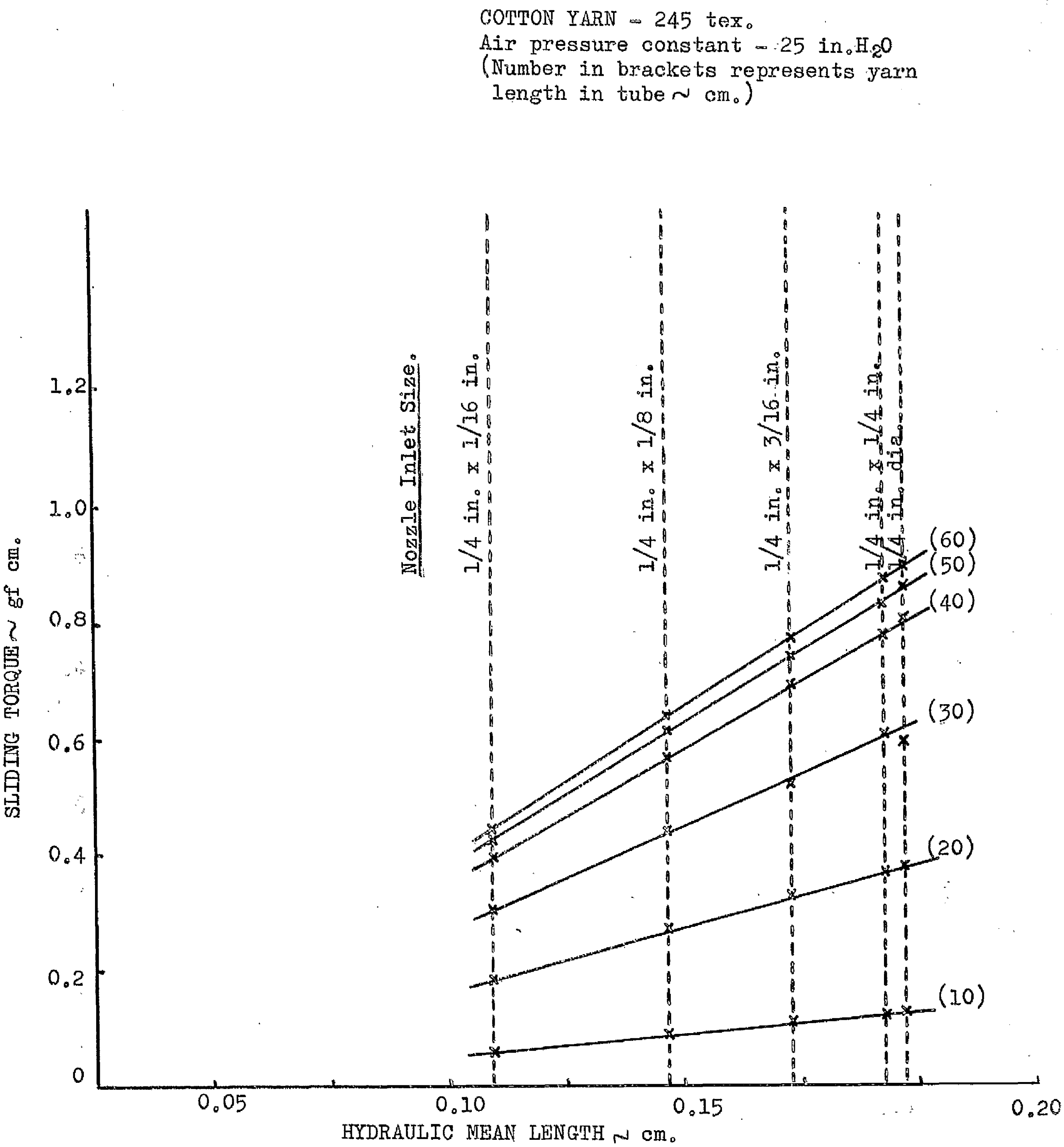



Fig. 12.18

RELATIONSHIP BETWEEN HYDRAULIC MEAN LENGTH AND SLIDING TORQUE WITH DIFFERENT YARN LENGTHS sliding torque = $k_1$ (hydraulic mean length) × yarn length, where $k_1$ is a constant.

The value of $k_1$ was found to be 0.1125 (approx.) with an air pressure difference of -25 in$H_2O$ across the tube.

When the yarn lengths were increased above 40 cm. the torque gains obtained were smaller with increases in yarn length. The above expression is true for yarn lengths up to 40 cm. In other words, there was an ever diminishing value in increasing the yarn length within the tube.

The relationship between hydraulic mean length and torque at a constant yarn length of 40 cm. different air pressures is shown in Fig. 12.19. From this figure, it appeared that at all the pressures, the torque was proportional to hydraulic mean length. However the constant of proportionality varied with yarn length in the tube. The relationship between torque and hydraulic mean length at different air pressures with yarn length of 40 cm. is as follows:-

sliding torque = $k_2$ (hydraulic mean length). $\Delta p$, where $k_2$ = a constant. $k_2$ was found to be 0.175 approx.

Another important relationship is shown in Fig. 12.20. From this figure, it might be observed that the maximum torque per unit length of yarn was obtained in the region of about 30 cm. yarn length. Here again, the torque curves tended to arrange themselves according to the magnitude of the hydraulic mean length of each nozzle.

From the above observations, it was evident that the torque on the yarn increased with the hydraulic mean length, with pressure and also with yarn length. Since the increases in hydraulic mean length were obtained in all the above cases by merely increasing the geometrical dimensions of the slit width, it might be therefore said that the enlargement of slit widths were mainly responsible for the greater input of torque into yarn.

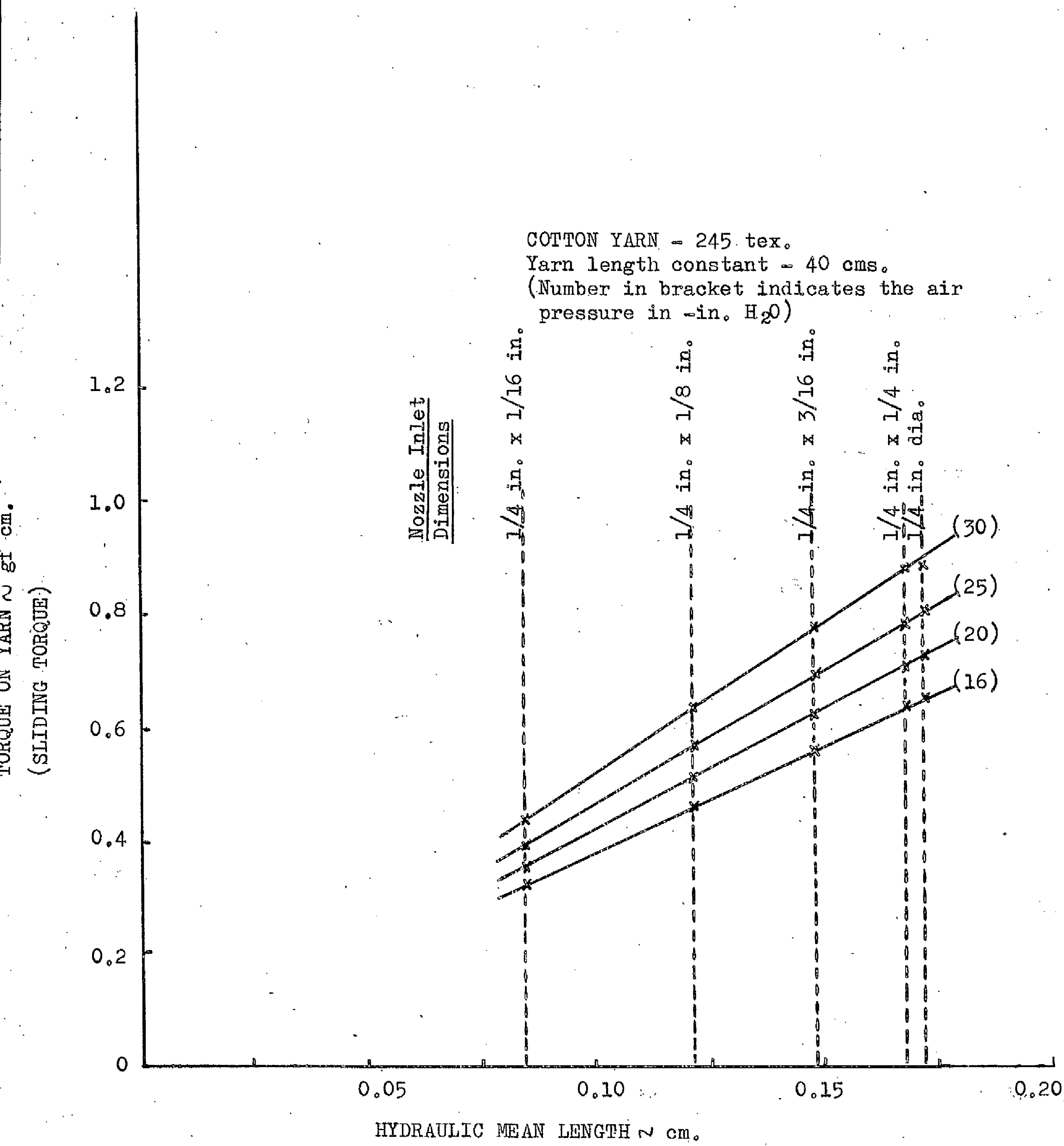



Fig. 12.19

RELATIONSHIP BETWEEN HYDRAULIC MEAN LENGTH AND SLIDING TORQUE WITH DIFFERENT AIR PRESSURES

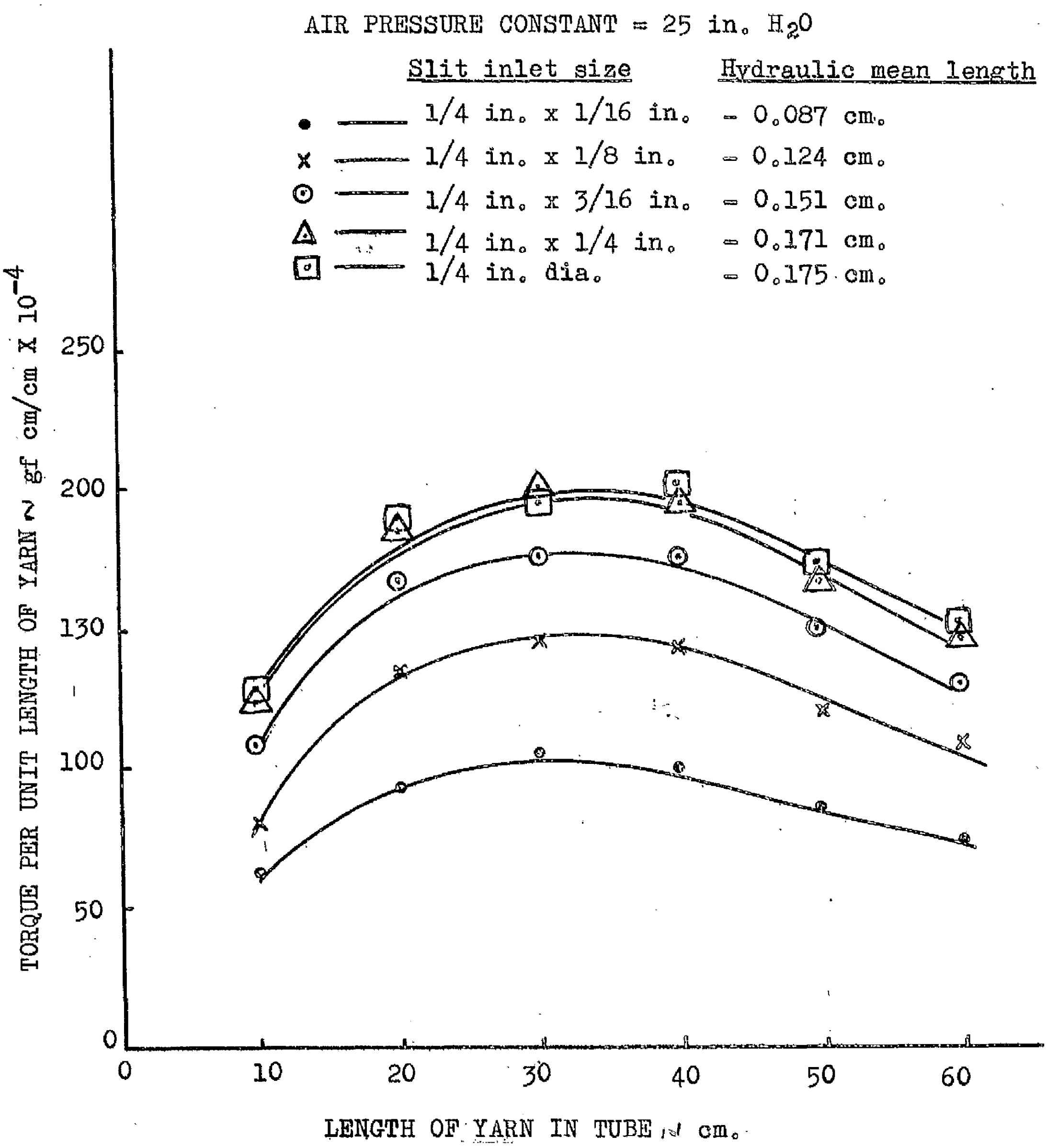



Fig. 12.20

RELATIONSHIP BETWEEN YARN LENGTH AND TORQUE PER UNIT LENGTH OF YARN

DIFFERENT HUDRAULIC MEAN LENGTH OF NOZZLE

All the foregoing relations seemed to be valid for only those nozzles which produced a predominance of sliding torque.

Torque tests on circular tangential inlets were confined to only one dimension, that of $\frac{1}{4}$ in. diameter but these tests even under different air pressures and with different yarn lengths always produced sliding torques. Yarns spun with different dimensions of tangential holes (mentioned in Chapter 6, Part I) were always 'Z' twisted and these results also indicated that torques in yarns were produced mainly by sliding. Since the hole dimensions did not, at any time, exceed $\frac{1}{4}$ in., it might be concluded that the tangential circular inlets up to $\frac{1}{4}$ in. diameter tended to produce sliding torques rather than rolling torques. It is not known what type of torque would be introduced into yarns when inlets larger than $\frac{1}{4}$ in. diameter were used. Perhaps it might be said that the nature of torque might depend upon the effective application of an even pressure distribution on the length of forming yarn.

Circular holes above $\frac{1}{4}$ in. were not tried because spinning with circular inlets produced inferior quality yarns and the fibre assembly efficiency was also less than those obtained with the slit inlets. Hence the main interest was focussed on slit type inlets.

12.12.2. Torque tests with net rolling torque

The nozzles with slit lengths of 1 in. and different widths always tended to produce rolling torques at all the different yarn lengths tested. The relationship between hydraulic mean length of these nozzles and their torque inputs to yarn is shown in Fig. 12.21. From this figure, it appeared that the optimum torque gains were usually obtained at hydraulic mean lengths of about 0.20 cm. Any increase of hydraulic mean length over this value tended to increase the torque to a small extent only.

The pattern of torque curves for different yarn lengths at different air pressures is shown in Fig. 12.22. (a),(b),(c),(d),(e) and (f). All these curves showed a tendency to reach a plateau level over a hydraulic mean length of 0.20 cm. Once again, this behaviour seemed to suggest that the optimum value of torque at each yarn length was attained at a hydraulic mean length of about 0.20 cm. and this was independent of the air pressures used.

Referring back to Fig. 12.21., it might be noted that the torque values obtained at 40 cm. and 20 cm. yarn lengths tended to be higher than those corresponding to 50 cm. and 30 cm. yarn lengths respectively. This indicates that the rolling torque tended to be more efficient at certain yarn lengths.

In the case of rolling torque also, increases in hydraulic mean length of nozzles were obtained by opening the slit widths. Therefore it might be true to say that the dimension of the slit width played an important role, up to a certain limit, in the contribution towards increases in torque inputs to the yarn.

The torque per unit length of yarn versus yarn length was plotted graphically, as shown in Fig. 12.23. It might be noticed that, in general, the shorter yarn lengths tended to produce higher torque values. The exception, however, was in the case of yarn length of 40 cm. which

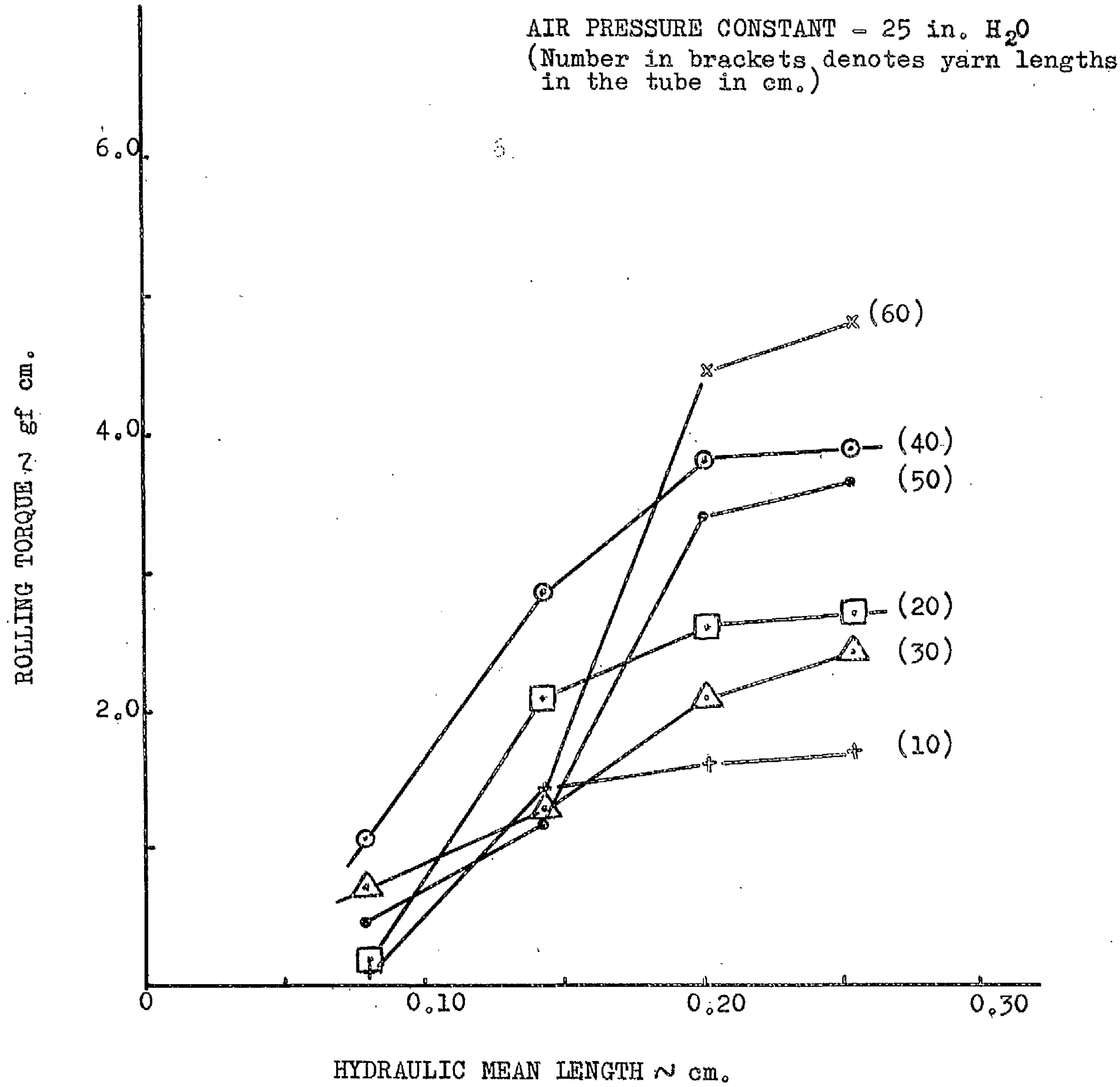



Fig. 12.21

RELATIONSHIP BETWEEN HYDRAULIC MEAN LENGTH AND ROLLING TORQUE

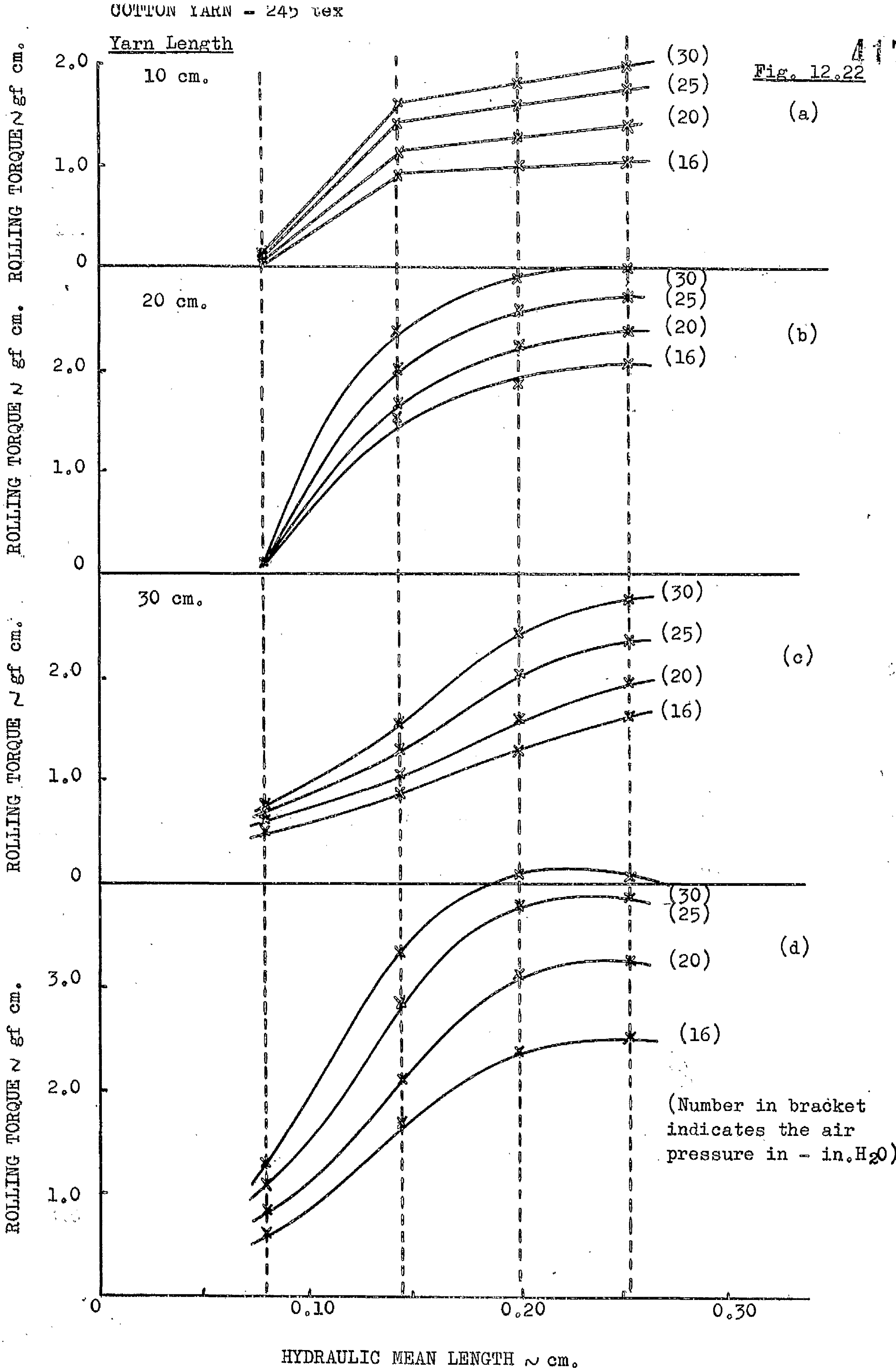



Fig. 12.22

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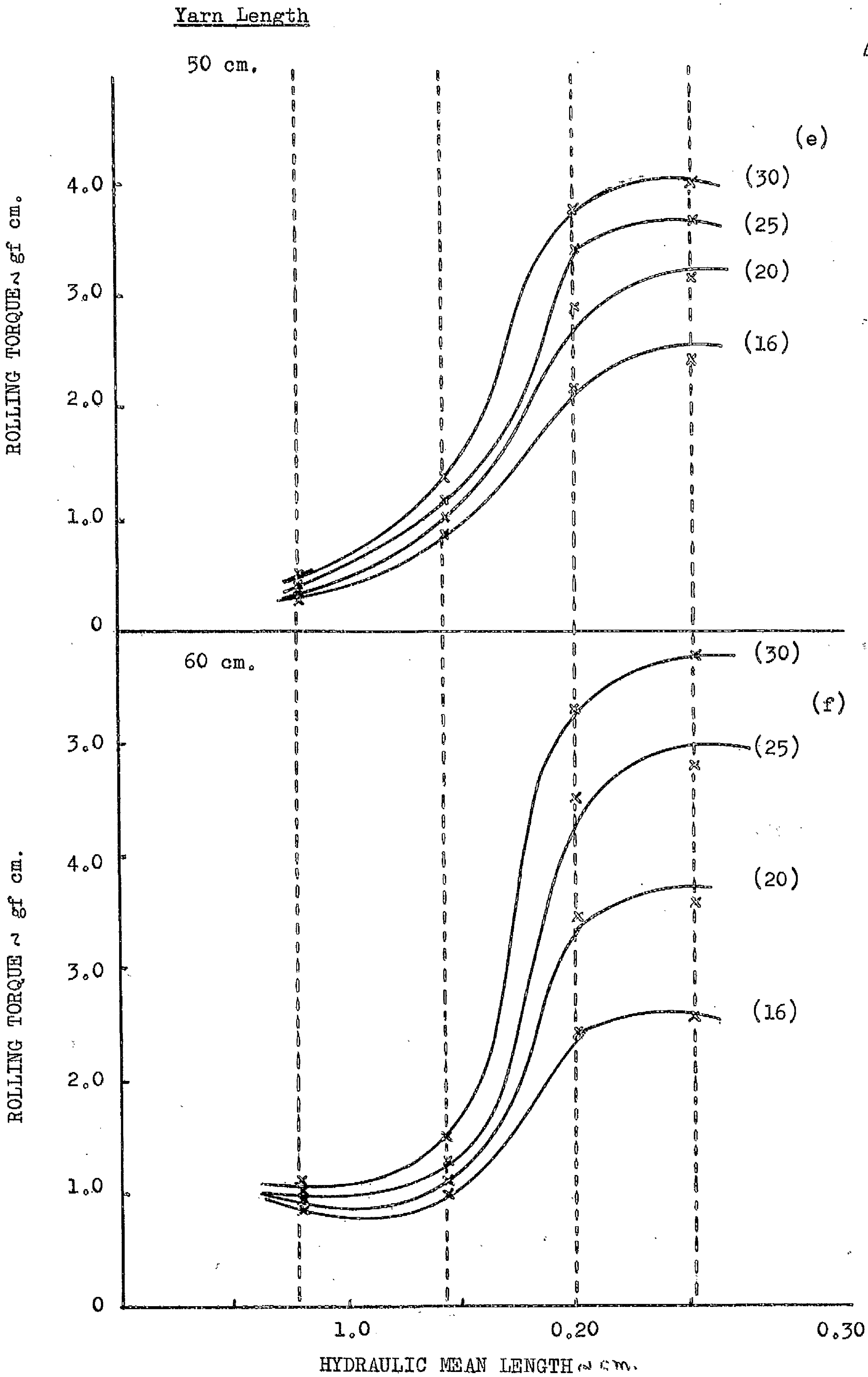



Fig. 12.22

RELATIONSHIP BETWEEN HYDRAULIC MEAN LENGTH AND ROLLING TORQUE WITH DIFFERENT AIR PRESSURES AT (a) 10 cm. (b) 20 cm. (c) 30 cm. (d) 40 cm. (e) 50 cm. AND (f) 60 cm. YARN LENGTH IN THE TUBE

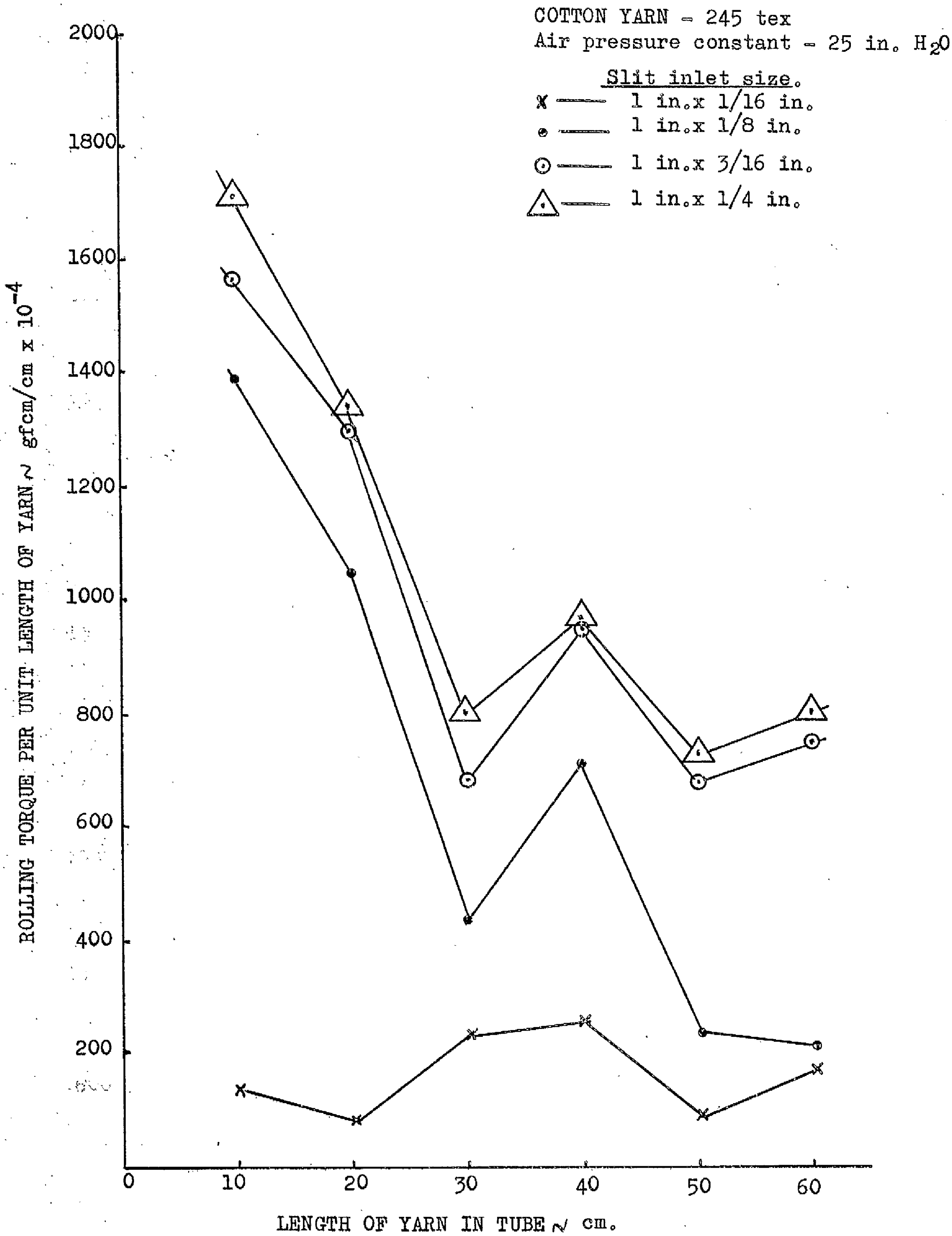



Fig. 12.23

RELATIONSHIP BETWEEN YARN LENGTH AND ROLLING TORQUE PER UNIT LENGTH WITH DIFFERENT SLIT INLETS showed consistently an increase in torque values in comparison with those of its neighbouring yarn lengths of 30 cm. and 50 cm., at all the four different slit sizes.

The general tendency for the torque per unit length to decrease with yarn length might be explained as follows:-

The rolling action of yarn on tube wall will tend to be more effective with short yarn lengths than with long lengths. The amount of sliding torque applied will tend to increase with yarn length up to about 30 cm. to 40 cm., as shown already in Fig. 12.20. Moreover it will be noted that, under constant air pressure conditions, an increase in yarn length decreased the rotational speed of yarn. A combination of reduced rolling torque and increased sliding torque could result in a drastic reduction of the net torque (rolling) applied to the yarn when the yarn length is increased.

12.12.3. Transition in torque direction

Nozzles with slit lengths above $\frac{1}{4}$ in. but below 1 in. tended to exhibit both sliding and rolling torques. The nozzles with $\frac{1}{2}$ in. and $\frac{3}{4}$ in. slit lengths were included in this category.

The nozzles with $\frac{1}{2}$ in. slit length and 1/16 in. and 3/16 in. widths are considered first. The $\frac{1}{2}$ in. X $\frac{1}{16}$ in. slit inlet produced torsional deflections in the Z direction and hence the net torque applied to the yarn was of the sliding type. This result is included in this section because of the rather low torque values. This behaviour was true at almost all yarn lengths (please refer to Table D.12.9a in Appendix D ). At first sight, it appeared that these low values might be due to the low hydraulic mean length (0.07 cm.) but on closer scrutiny it seemed that this might not be the only cause. The torque values generally tended to be a linear function of the hydraulic mean length, but when the torques were calculated on this basis for this nozzle the calculated values were found to be much higher than those actually obtained. The loss in torque was sometimes as high as 40%. This undue decrease in torque seemed to suggest the possibility of the presence of a substantial proportion of rolling torque and this tended to reduce the sliding torque. The results obtained from the $\frac{1}{2}$ in. X $\frac{3}{16}$ in. slit inlet nozzle also seemed to support this latter explanation because the sliding torques applied to the yarn tended to be much too low for its hydraulic mean length(0.18 cm.).

The relationship between the torque and air pressurewith at different yarn lengths with the $\frac{1}{2}$ in. X $\frac{3}{16}$ in. slit inlet is shown in Fig. 12.24. It might be noted that the transition from sliding to rolling torque occurred at 20 cm. yarn length. The value of rolling torque, even at this short length of 20 cm., was much larger in comparison with the values of sliding torques obtained with either 30 cm. or 40 cm. yarn lengths. Moreover, at this yarn length the rolling torque curve tended to rise sharply with air pressure and this behaviour was in contrast to that of the sliding torque under any condition.

Similar patterns of torque behaviour, as outlined above, were demonstrated by nozzles with slit openings of $\frac{3}{4}$ in. X $\frac{1}{16}$ in. and $\frac{3}{4}$ in. X $\frac{3}{16}$ in. However the deviations in behaviours were mainly in those which were concerned with change-over stages. These variations in transitional behaviours

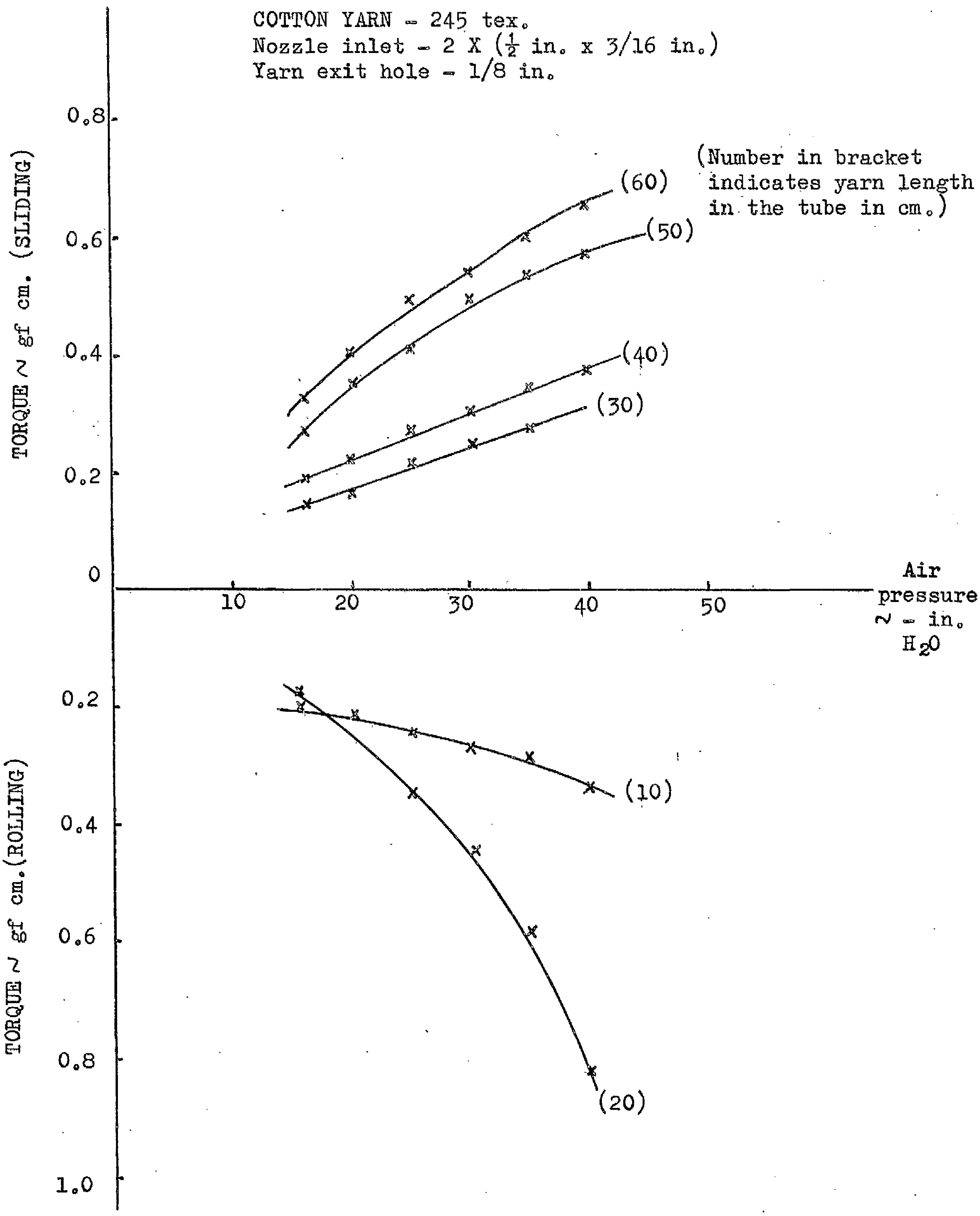



Fig. 12.24

RELATIONSHIP BETWEEN AIR PRESSURE AND TORQUE (SLIDING AND ROLLING) WITH DIFFERENT YARN LENGTHS are shown in the three-dimensional graph in Fig. 12.25. The torque transition in spinning tubes with the lowest hydraulic mean length tended to occur at short yarn lengths. With a rise in hydraulic mean length, the transition tended to take place at increased yarn lengths. In other words, this implied that the higher the hydraulic mean length, the greater will be the tendency for the torque to change its direction at longer yarn lengths. This behaviour seemed to be linked with the increased torque values.

Referring to Fig. 12.31., it might be seen that the optimum values of rolling torques were attained in the region of 0.20 cm. of hydraulic mean length. Since the hydraulic mean length of $\frac{3}{4}$ in. X $\frac{3}{16}$ in. slit inlet nozzle was also about 0.20 cm., it might be fair to assume that this nozzle too would give about the optimum rolling torques. Indeed the torque results obtained with this nozzle, as shown in Fig. 12.26., showed that the values of rolling torques were really high at 20 cm. This length was approximately the length of forming yarn encountered during spinning and, therefore, the yarn length which needed to be considered most from the practical point of view.

From all the foregoing considerations, it was evident that the geometry of the tangential inlet is probably the most important factor in determining the strength and direction of torque applied to the yarn.

Incidentally, it might be of interest to note that Chandarana[10] and Mishra[98] carried out most of their work on a nozzle with a $\frac{3}{4}$ in. X $\frac{7}{32}$ in. slit. This nozzle geometry might be considered as one with slight variation from the above discussed nozzle($\frac{3}{4}$ in. X $\frac{3}{16}$ in.).

OTTON YARN - 245 tex.

umber in brackets indicates
arn length in the tube in cm.)

| Inlet size. | | Hydraulic Mean Length. |
|---|---|---|
| x —— | ½ in. x 3/16 in. | 0.182 cm. |
| △ —— | 3/4 in. x 1/16 in. | 0.082 cm. |
| ⊙ —— | 3/4 in. x 3/16 in. | 0.197 |

- - - - - Transition in Torque Direction

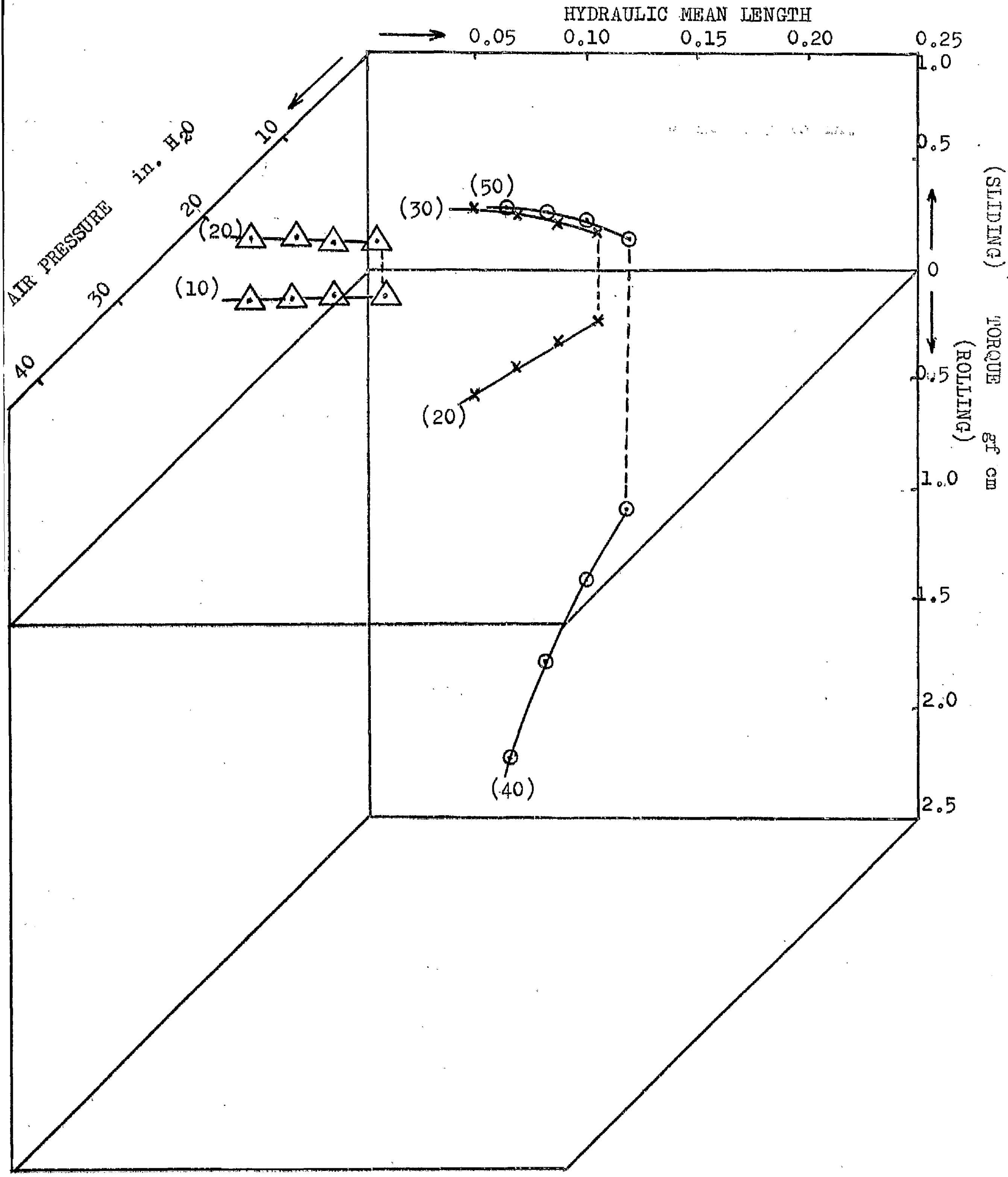



Fig. 12.25

TRANSITIONAL BEHAVIOUR OF TORQUE

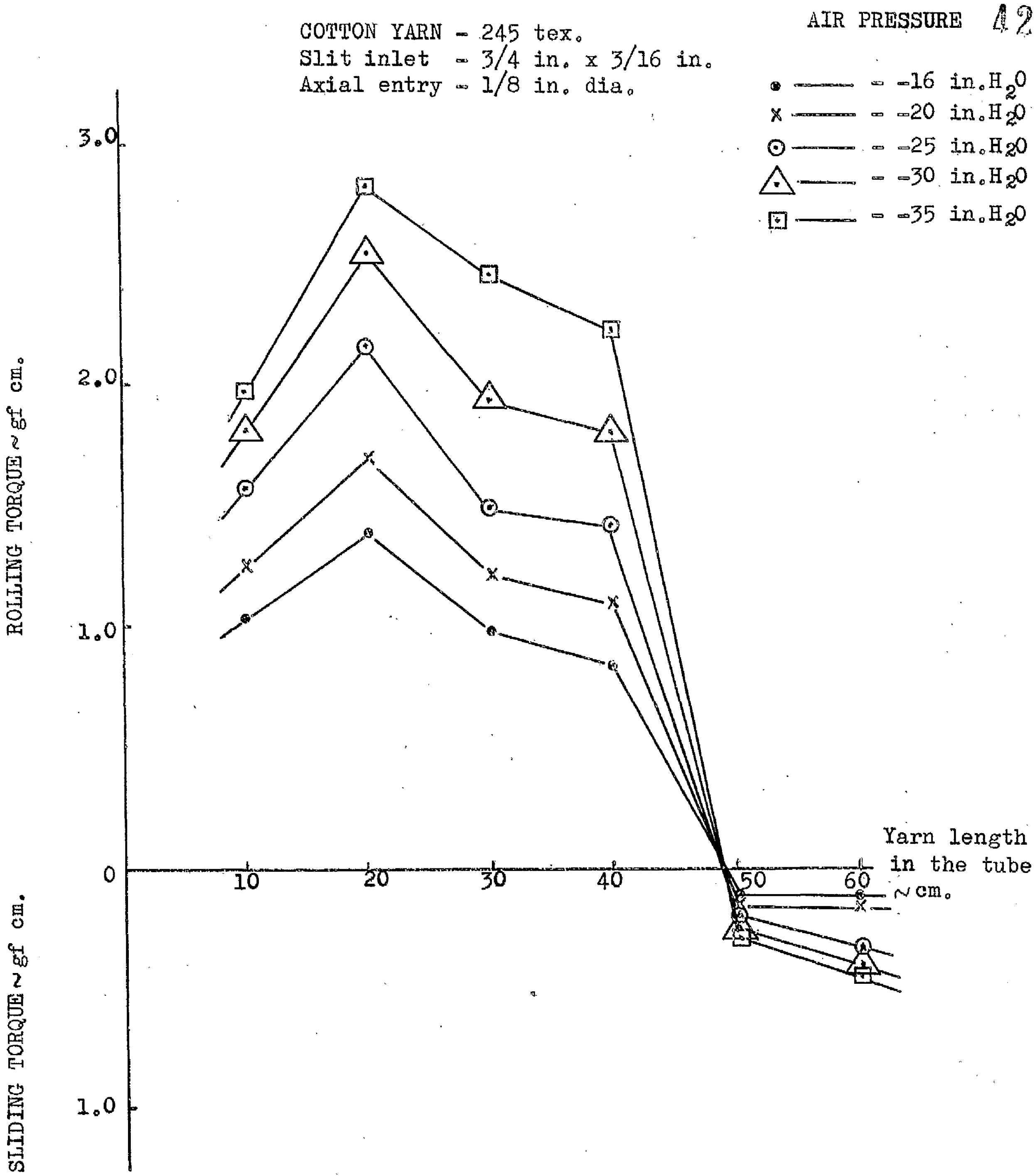



Fig. 12.26

TRANSITIONAL BEHAVIOUR OF TORQUE WITH YARN LENGTH AT THE VARIOUS AIR PRESSURES

The hydraulic mean length of this nozzle was 0.22 cm. This was, therefore, in the region of the optimum hydraulic mean length. Presumably, this was one of the main reasons for the consistently improved spinning performances obtained by these workers.

It might be observed that the diameter of the axial entry($\frac{1}{4}$ in.) used by them was twice that of the dimension($\frac{1}{8}$ in.) normally used. This gave rise to a strong suspicion that this parameter too might have influenced the torque behaviour. Hence the following tests were conducted with a view to study the effect.

12.12.4. Effect of torque behaviour due to changes in yarn exit hole

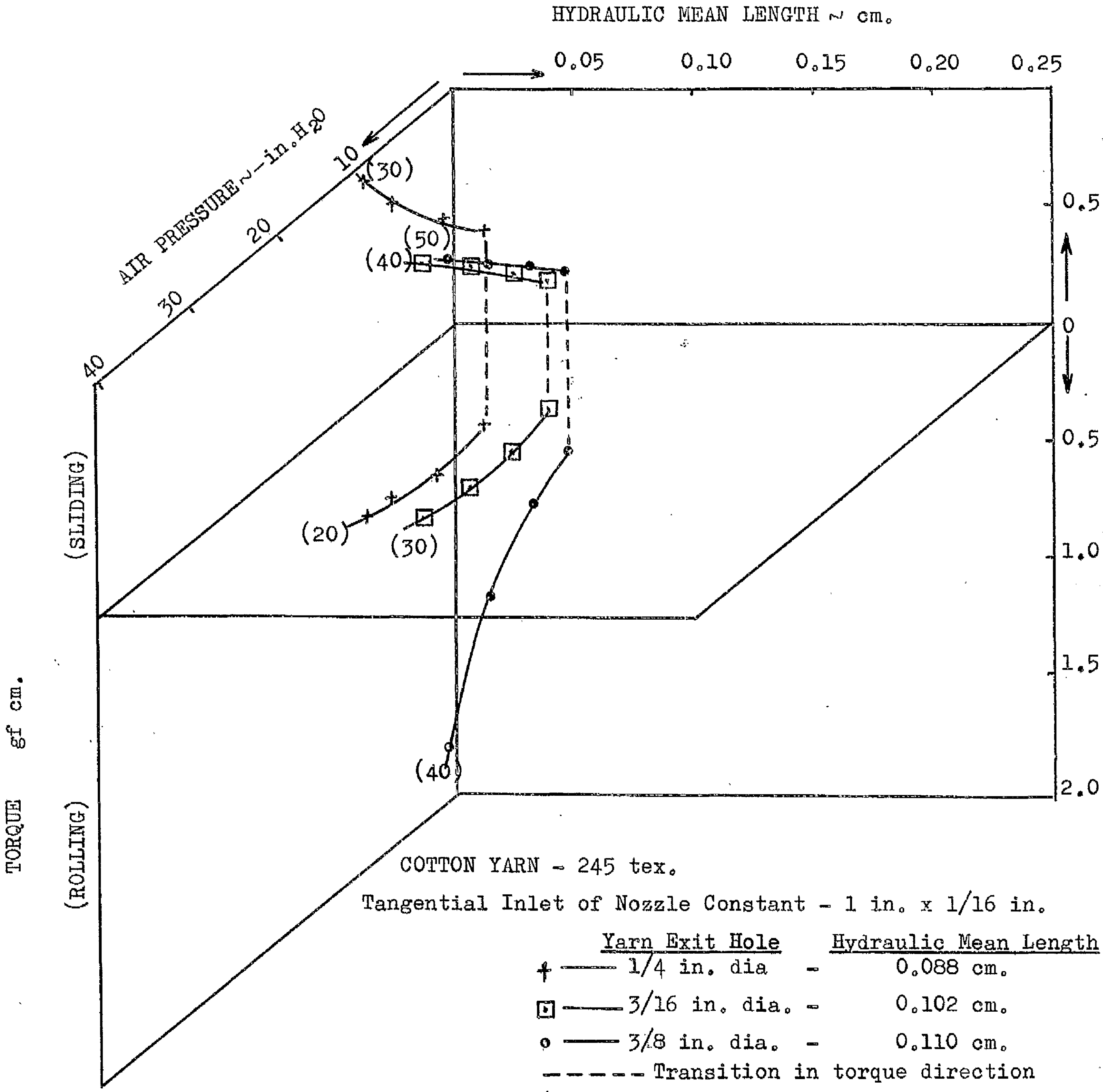
As already mentioned, the dimensions of the tangential inlets were kept constant at 1 in. X $\frac{1}{16}$ in. and the yarn exit hole size was varied from $\frac{1}{8}$ in. to $\frac{3}{8}$ in., in steps of $\frac{1}{16}$ in.

Slit lengths of 1 in. normally tended to produce rolling torques on yarn. A change in the dimension of the axial hole from $\frac{1}{8}$ in. to $\frac{3}{16}$ in. tended to reduce the amount of rolling torque at any given yarn length and air pressure. Please see Tables D.12.18., D.12.19. and D.12.22.

The torque reduction with increase in axial hole dimension seemed to suggest that a gradual transformation in torque direction might occur. Enlarging the axial hole further to $\frac{1}{4}$ in. definitely showed a reversal in torque direction. At yarn lengths above 30 cm., the torques were predominantly of the sliding type but at shorter yarn lengths below 20 cm., the rolling torque was predominant. Increasing the size of the axial entry still further to $\frac{5}{16}$ in.

and $\frac{3}{8}$ in., the torque behaved in a similar way but the actual transition from sliding to rolling torque took place at yarn lengths of 30 cm. and 40 cm. respectively. The transition in torque with the three different sizes of axial entry is shown in Fig. 12.27. From this figure, it might be noted that an increase in the axial hole dimension(and the hydraulic mean length) tended to make the torque transition occur at progressively increasing yarn lengths. Furthermore the rolling torque tended to increase with air pressure rather more sharply at high hydraulic mean lengths than at low lengths.

It might be observed from Fig. 12.28. that the torque generally tended to increase with hydraulic mean length; the increase in hydraulic mean length was brought about solely by increasing the size of axial hole. The areas of axial entries of $\frac{1}{8}$ in., $\frac{3}{16}$ in., $\frac{1}{4}$ in., $\frac{5}{16}$ in. and $\frac{3}{8}$ in. are in the ratio of 1.00 : 2.25 : 4.00 : 6.25 :9.00. The torques obtained with these entries appeared to be somewhat related to their respective area ratios at certain axial entry sizes. Thus, for example, at a yarn length of 20 cm. and an air pressure of -25 in. of water(TablesD.12.18.-22) the torques obtained were found to be in the ratio of approximately 1.00 : 1.25 : 4.00 : 4.50 : 9.50. From this, it seemed that the torques at $\frac{1}{4}$ in. and $\frac{3}{8}$ in. tallied well with their area ratios but, strangely though, the torques with $\frac{3}{16}$ in. and $\frac{5}{16}$ in. axial holes were very much different. the way. The reasons for this behaviour with $\frac{3}{16}$ in. and $\frac{5}{16}$ in. axial entries are not known but perhaps a likely cause might be that the interaction of air streams entering through the tangential inlets and axial entry produced




COTTON YARN - 245 tex.

Tangential Inlet of Nozzle Constant - 1 in. x 1/16 in.

| Yarn Exit Hole | | Hydraulic Mean Length |
|---|---|---|
| + ——— 1/4 in. dia | - | 0.088 cm. |
| ☐ ——— 3/16 in. dia. | - | 0.102 cm. |
| o ——— 3/8 in. dia. | - | 0.110 cm. |

- - - - - Transition in torque direction

(Numbers in brackets indicate yarn lengths in the tube cm.)

Fig. 12.27

TORQUE BEHAVIOUR DUE TO CHANGES IN YARN EXIT HOLE

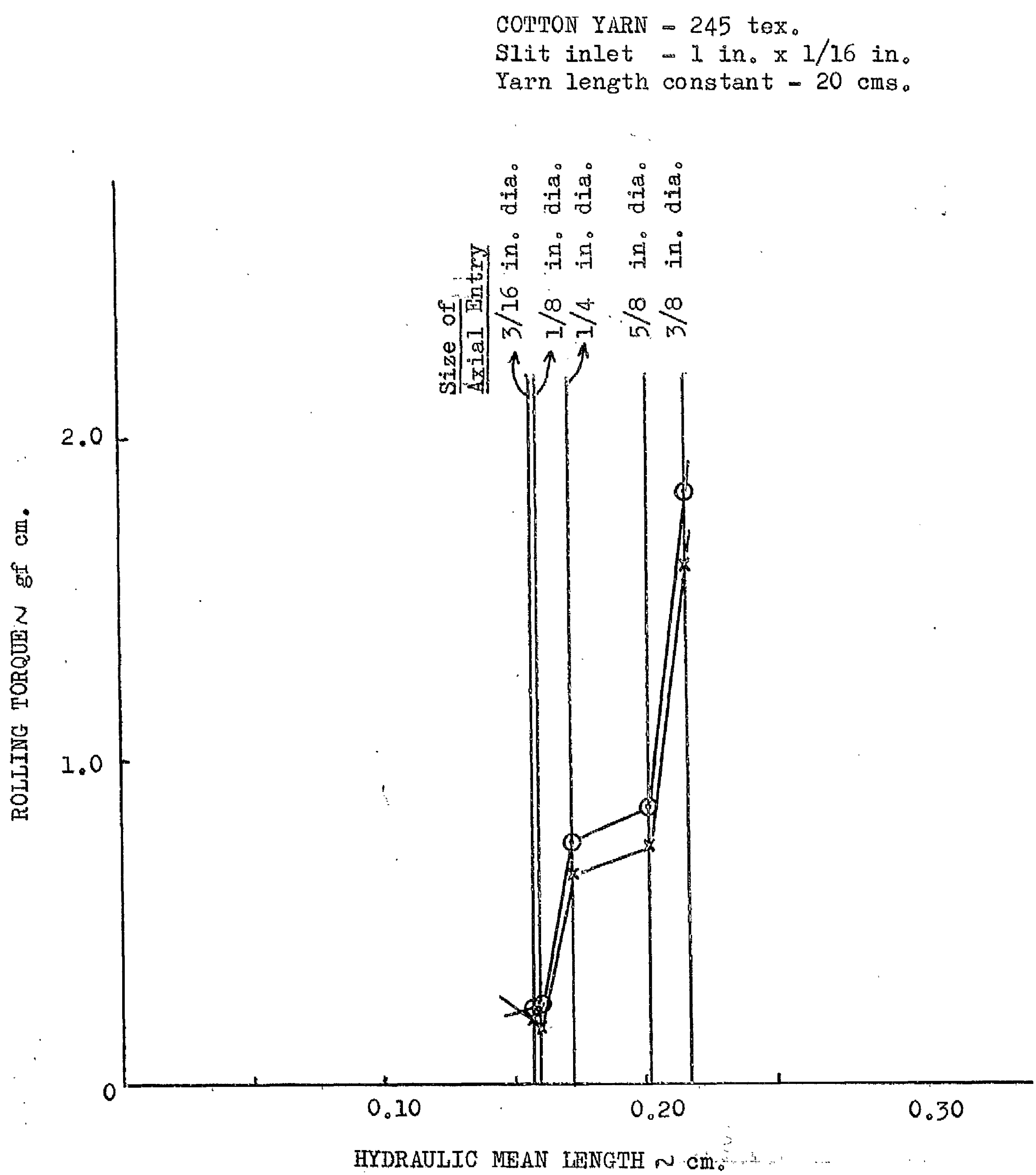



Fig. 12.28

RELATIONSHIP BETWEEN HYDRAULIC MEAN LENGTH AND ROLLING TORQUE WITH DIFFERENT SIZES OF AXIAL ENTRIES.

unfavourable effects. However it should be stressed that this type of behaviour could not be described as generally applicable at all yarn lengths and pressures.

It thus appears that in addition to the geometry of the tangential inlet, the size of the yarn exit hole also exercises a great influence on the amount of torque applied to the yarn.

12.12.5. Effect of spinning tube size on torque

The torque tests conducted so far were confined to spinning tubes of $\frac{3}{4}$ in. internal diameter only. Since tubes of 1 in. bore were also used in spinning experiments, it was felt that a few tests should be performed with a 1 in. tube bore. In these tests, the nozzle dimensions of 1 in. X $\frac{1}{8}$ in. for the tangential inlets and $\frac{1}{8}$ in. for the axial hole were kept as standard. The air pressure was varied from -16 in. to -30 in. of water at each of the yarn length of 10, 20, 30, 40, 50 and 60 cm.

From Fig. 12.29., it might be noticed that the 1 in. tube always gave maximum torque values at a yarn length of 20 cm. This behaviour was true at the different pressures used and the value of torque increased with pressure. The patterns of torque behaviour with yarn lengths were almost similar to each other at the different air pressures. For the sake of comparison, the torque values obtained with a $\frac{3}{4}$ in. tube at a pressure of -25 in. of water were also plotted on the same figure. It might be observed that the torque behaviour with yarn length in a $\frac{3}{4}$ in. tube differed considerably from that found with a 1 in. tube.

Approximate values of the ratios of torque values obtained with 1 in. and $\frac{3}{4}$ in. tubes were worked out for the

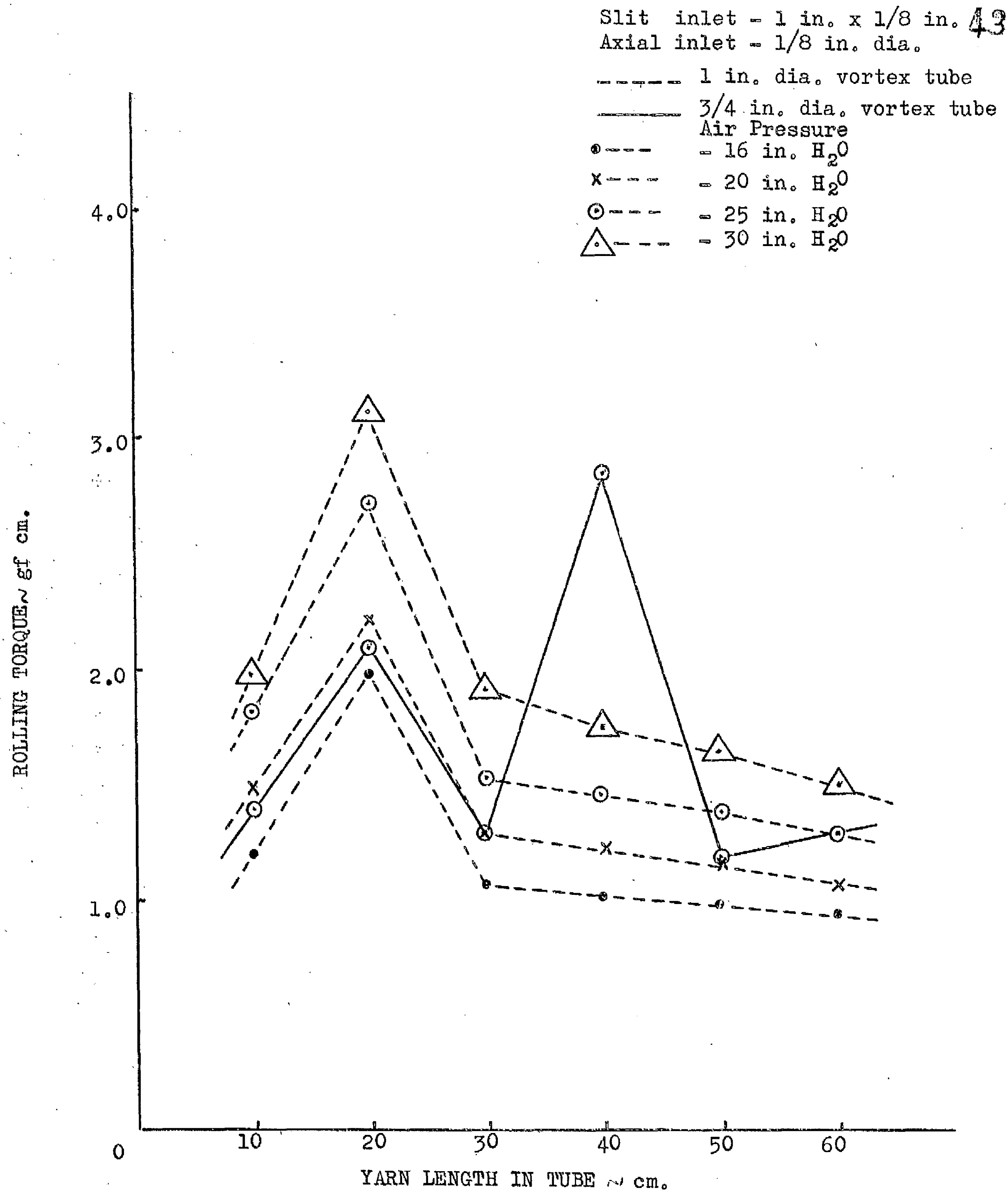



Fig. 12.29

RELATIONSHIP BETWEEN YARN LENGTH AND ROLLING TORQUE WITH TUBE BOX SIZES various yarn lengths. This is shown in Table 12.2. It might be noted that an increase in yarn length tended to decrease the torque ratio.

The ratio of the diameter of the two tubes was 1.33. Thus, for a given linear density of yarn and for the same rotational speed of yarn, one would expect that the torque applied on yarn in a 1 in. tube should be about 1.33 times that obtained with a $\frac{3}{4}$ in. tube, provided that the efficiency of torque insertion in both the tubes remained the same.

In these tests, the linear density of yarn as well as the yarn material used were the same. However the measured rotational speeds of yarn, at any given yarn length and air pressure, varied with the tube sizes. Under similar working conditions, the measured rotational speeds of yarn with the 1 in. tube were much lower than that obtained with $\frac{3}{4}$ in. tube. The ratio of

$$\frac{\text{yarn speed with 1 in. dia. tube}}{\text{yarn speed with } \frac{3}{4} \text{ in. dia. tube}}$$

was termed as the "yarn speed ratio". The average values of this ratio for the different air pressures, at any given yarn length, were calculated and these are given in Table 12.2. The relative torque efficiency and yarn speed ratio are plotted against the yarn length in the tube in Fig. 12.30. From this figure, it appeared that, in general, the relative torque efficiency with the 1 in. tube was slightly higher than that obtained with a $\frac{3}{4}$ in. tube, even though the yarn speeds with the 1 in. tube tended to be low. Moreover the relative torque efficiency was found to be once again at an optimum value at 20 cm. yarn length.

All the above observations seemed to point that, as far as rolling torques were concerned, the larger the

TABLE 12.2.

| (1) Yarn length in the tube (cm) | (2) Yarn Speed Ratio $\left(= \frac{\text{speed with 1in. tube}}{\text{speed with } \frac{3}{4}\text{in. tube}}\right)$ | (3) Actual Torque Ratio $\left(= \frac{\text{torque with 1in. tube}}{\text{torque with } \frac{3}{4}\text{in. tube}}\right)$ | (4) Calculated Torque Ratio (yarn speed ratio X 1.33) *assuming constant power input to yarn.* | (5) Relative Torque Efficiency of 1in. tube w.r.t. $\frac{3}{4}$in. tube $\left(= \frac{\text{column 3}}{\text{column 4}} \times 100\right)$ (%) |
|---|---|---|---|---|
| 10 | 0.93 | 1.30 | 1.24 | 105 |
| 20 | 0.87 | 1.30 | 1.16 | 112 |
| 30 | 0.84 | 1.20 | 1.12 | 107 |
| 40 | 0.82 | 0.50 | 1.09 | 46 |
| 50 | 0.81 | 1.15 | 1.08 | 107 |
| 60 | 0.80 | 1.00 | 1.06 | 94 |

COTTON YARN - 245 tex.
Nozzle - 3/4 in. x 3/16 in.
Air Pressure - -25 in. $H_2O$

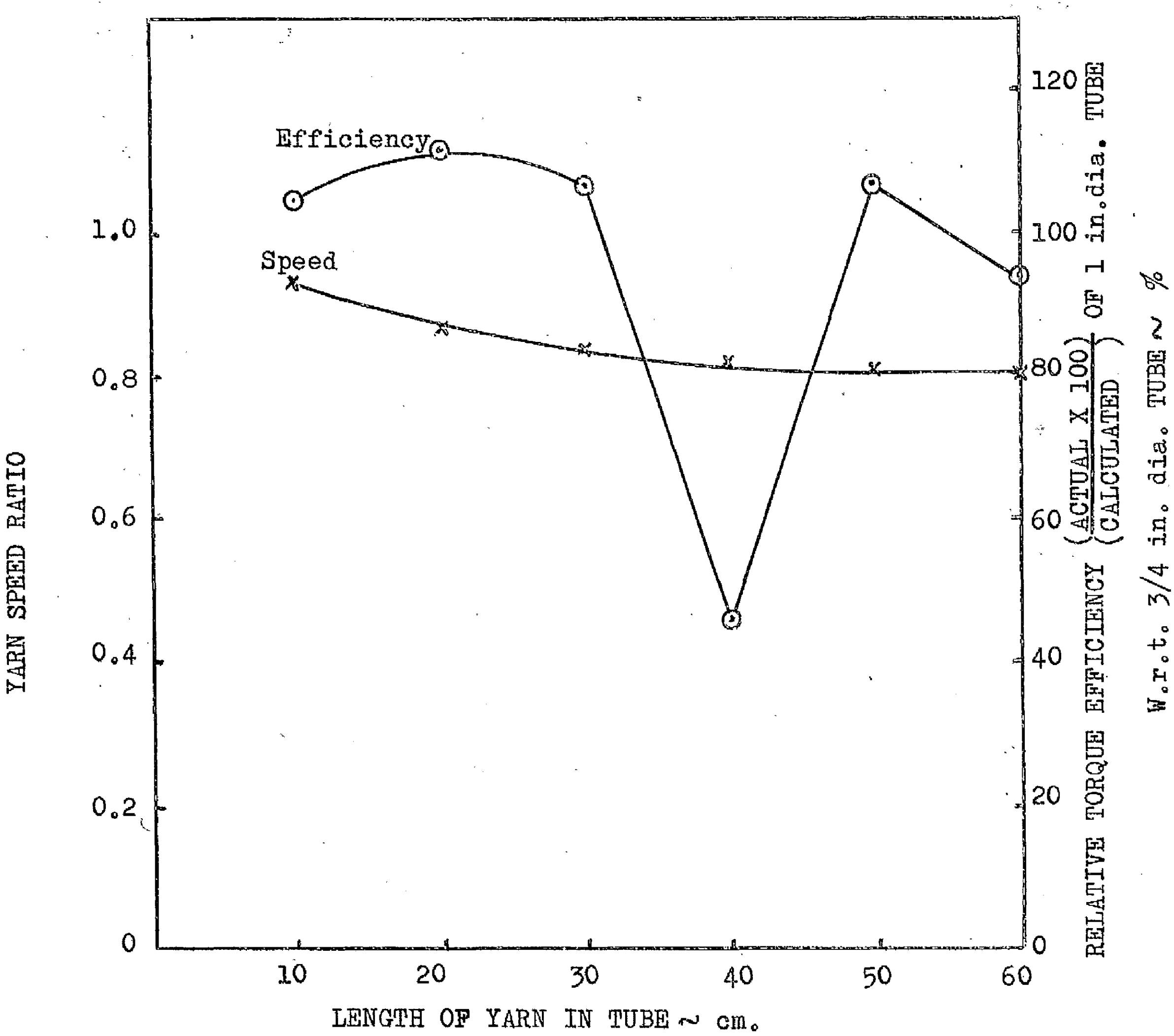



Fig. 12.30

RELATIONSHIP BETWEEN YARN LENGTH AND (a) YARN SPEED RATIO AND (b) TORQUE EFFICIENCY tube bore, the greater was the amount of torque applied and the greater was the efficiency. The limitation in tube bore to give the optimum torque value could not be established because of the limited number of tube bore sizes that were used in this experiment.

12.12.6. A brief comparison of sliding and rolling torques

Generally, the amount of torque obtained from sliding tended to be much less than that from rolling. This is shown clearly in Fig. 12.31. It was not possible to arrive at an optimum value of hydraulic mean length from amongst the limited number of nozzles which produced sliding torques. However the optimum yarn length which yielded maximum torque at any hydraulic mean length appeared to be about 30 cm. Under actual spinning conditions, the length of forming yarn usually ranged between 20 cm. and 30 cm. and this perhaps gave almost optimum torque conditions.

With rolling torque, there was a tendency for the torques to reach their optimum values at a hydraulic mean length of about 0.20 cm. This applied to all the different yarn lengths tested. An increase in air pressure tended to increase the torque values. Moreover it was noted that, in general, the shorter the yarn length, the higher was the value of torque applied per unit length of yarn. During spinning with nozzles which produced rolling torque, the length of forming yarn was usually about 10 cm. to 20 cm. This yarn length tended to produce high torques per unit length of yarn.

However the important conclusions that were drawn from the comparison of these two torques were

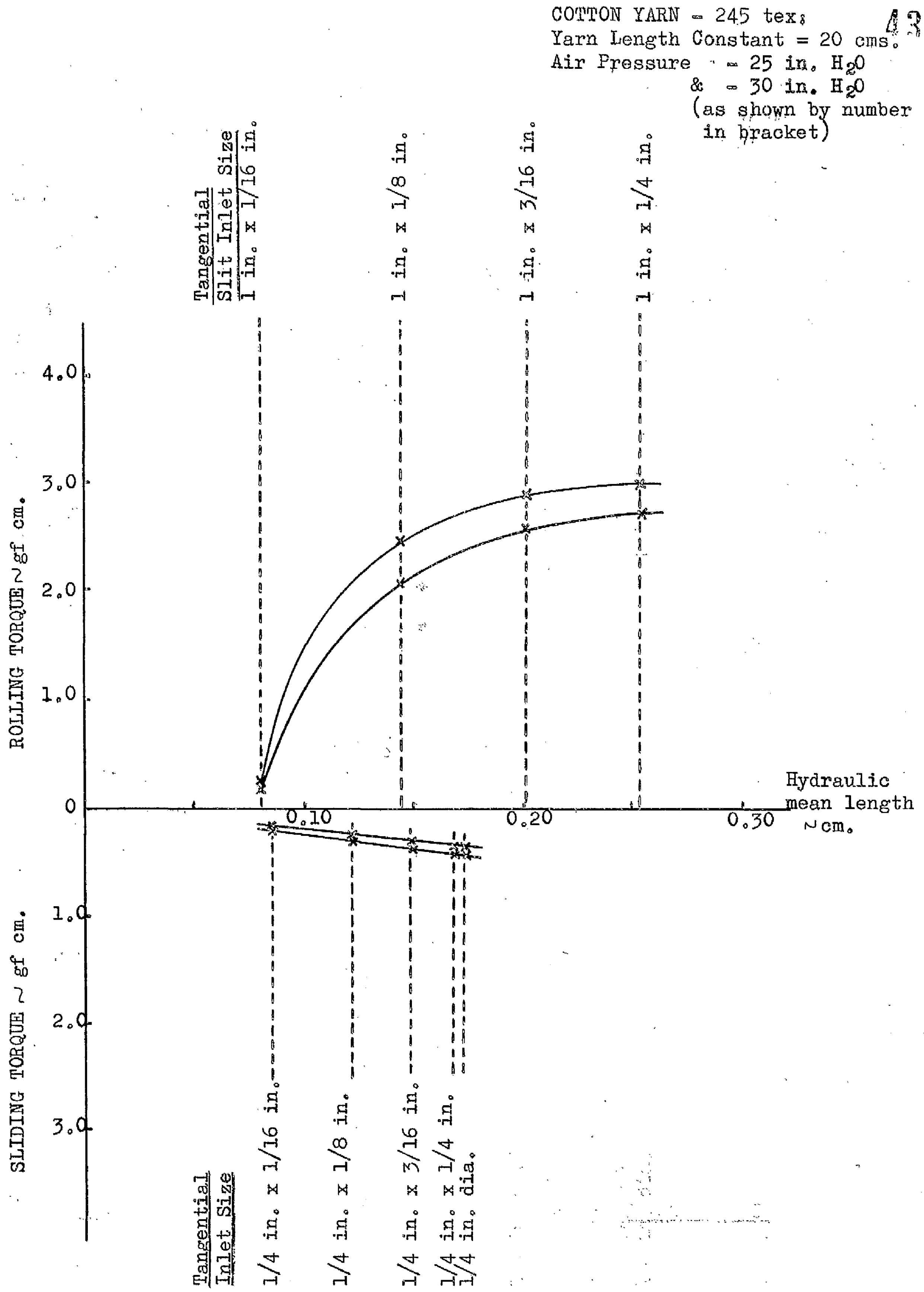



Fig. 12.31

RELATIONSHIP BETWEEN HYDRAULIC MEAN LENGTH AND TORQUE(SLIDING AND ROLLING) those which were concerned with the nature of torque generation and the amount of torque applied. They were as follows:-

(a) The slit length seemed to be one of the main factors for deciding the nature of torque applied to yarn.

(b) The slit width influenced the total amount of torque applied to the yarn. Generally, the larger the width, the greater was the torque input. Perhaps this was due to the increase in air flow with the width of the nozzle.

As already mentioned earlier, slit lengths up to $\frac{1}{4}$ in. tended to produce sliding torque and those of 1 in. tended to give rolling torques. The possible explanation to this behaviour is given below:-

Air entering into the tube acts upon a short length of forming yarn(or seed yarn, as the case may be) lying in the path of air entry. The distribution of air over a longer length of this yarn part(as in the case with 1 in. slit length when compared with $\frac{1}{4}$ in. slit length) will tend to assist the yarn to roll effectively on the tube wall. Thus the transition from one type of torque to another seemed to be governed, to a large extent, by the dimension of the slit length.

However when once the conditions of rolling torque have been established, then the net rolling torque applied to yarn depends upon

(a) the size of the yarn exit hole(axial entry)

and (b) the size of the tube bore.

# PART II

## MEASUREMENT OF TENSION OF YARN IN SPINNING TUBES

### 12.13. INTRODUCTION

The object of tension measurements was to obtain an understanding of the relationships which exist between yarn tension and different parameters, such as, yarn tail length, air pressure in tube, rotational speed of yarn, linear density of yarn and yarn withdrawal rate as well as geometrical parameters. Also the relationship between torque on yarn tension was studied.

Yarn tension was measured by means of a Rothschild electronic tensiometer. This tensiometer was chosen because of its accuracy in measurement and the facility to obtain tension recordings. In most of the following tests, the tension values were not read directly from the scale on the meter because of the frequent, though small, fluctuations in readings. Instead the average tension over a period of three minutes during each test was determined from the recorded graph by means of a planimeter.

The measurement of yarn tension during torque tests was found to greatly upset the torque readings because the passage of yarn through the tension measuring head tended to exert a restraining influence on the twist flow to the suspension medium. Therefore it was necessary to perform the tension tests separately. However these tests were carried out under conditions identical to those maintained during torque tests. Most of the tension tests were conducted with (a) no fibre feed to the spinning tube and (b) a seed yarn of the required length anchored at about two feet from the nozzle end of the tube. Nevertheless, in addition to the above, a few tests were also carried out during the spinning process.

Stroboscopic measurement of the yarn helix gave the rotational speed of yarn. It was difficult to determine the exact yarn speed during the actual spinning conditions. This was because of the frequent fluctuations in speed due to the influence of one or more of the following factors:-

(a) irregularities in rate and uniformity of fibre feed,

(b) irregular rate of fibre attachment to the forming yarn,

(c) frequent variations in length and linear density of forming yarn

and (d) variations in air pressure in the tube.

When a seed yarn of a given length and uniform linear density was allowed to rotate in a spinning tube, without the yarn being withdrawn, it was found that the yarn speed remained at a fairly constant value. Very minor fluctuations in speed existed but these were considered negligible from the practical point of view. The causes of these speed fluctuations might be due to

(a) continuous wear on yarn because of its abrasion against tube wall,

(b) changes in torque balance in yarn and hence the possibility of changes in effective yarn length in tube due to yarn contraction or extension

and (c) slight alterations in static charge level in the spinning tube.

The factors that tend to cause tension in yarn are as follows:-

(a) the axial component of the air drag force acting on yarn,

(b) the centrifugal force of the ballooning portion of yarn in the tube

and (c) frictional drag.

These factors are, in turn, related to the following parameters:-

(a) yarn length in the tube,

(b) the air pressure difference maintained in the tube,

(c) the design geometry of the spinning tube

and (d) the linear density of the yarn.

## 12.14. RELATIONSHIP BETWEEN YARN LENGTH IN THE TUBE AND THE YARN TENSION

As in the case of torque tests, it was thought desirable to obtain an idea of the effects of static charging on yarn tension. Accordingly the first test was done under conditions of static accumulation. It was obvious from Fig. 12.32. that the presence of static in the tube tended to reduce yarn tension. Evidently, this reduction in tension was due to the reduced yarn speed in a charged tube, as already shown in Fig. 12.4. The differences in tensions with and without static accumulation seemed to be more pronounced with short yarn lengths than with long lengths. If the charge level remained constant during the tests with the different yarn lengths, then there seemed no reason for this tension behaviour. Perhaps the procedure adopted in tension tests might be blamed for this. Since the tests were performed beginning with the maximum yarn length(60 cm.) and ending with the minimum length(10 cm.), there was the possibility of a gradual build up of charge with time during the test period. The charge level might have been considerably increased when testing short yarn lengths. This, in turn,

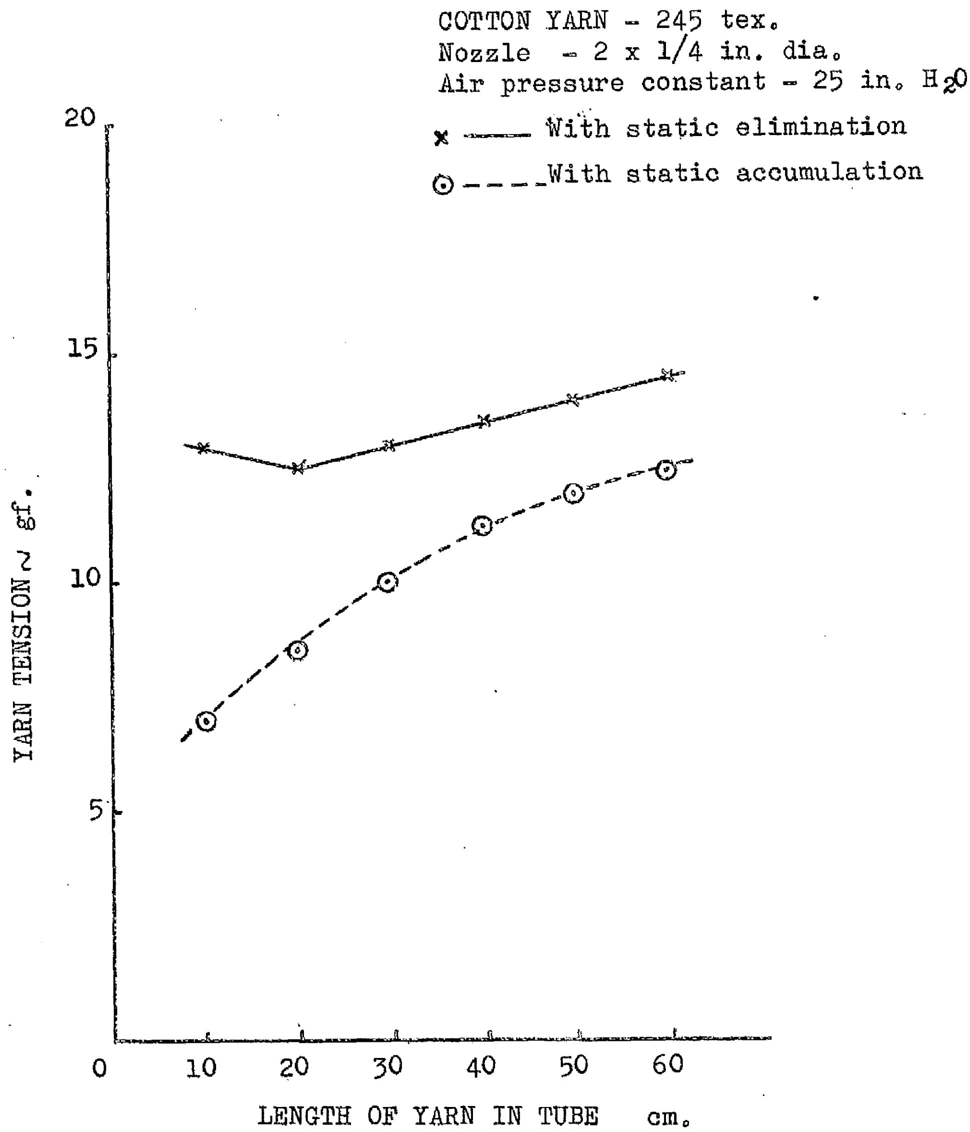



Fig. 12.32

RELATIONSHIP BETWEEN YARN LENGTH AND YARN TENSION WITH AND WITHOUT STATIC CONTROL might have adversely affected the rotational speed of yarn so as to cause the disproportionate reductions in yarn tensions.

The above tests seemed to point that means to eliminate static should be positively included in all the subsequent tests in order to standardise the test conditions.

Referring to Fig. 12.33., it might be observed that, in general, the yarn tension appeared to be a linear function of yarn length. However an exception to this relationship was noted at yarn lengths of 10 cm. It seemed that there was a tendency for the yarn to reach a minimum tension value at 20 cm. yarn length. This particular behaviour occurred only in nozzles which produced net sliding torques. With nozzles of the rolling torque type, the tension reduced with decrease in yarn length, as represented by the tension slope in Fig. 12.45.

The relationship between yarn length and the tension per unit length of yarn, shown in Fig. 12.34., tended to be roughly hyperbolic.

## 12.15. RELATIONSHIP BETWEEN AIR PRESSURE AND YARN TENSION

The relationship between air pressure and yarn tension is shown in Fig. 12.35. In this figure, the slope of the curves indicated that tension might be a linear function of (air pressure)$^{\frac{1}{2}}$. Figs. 12.36. and 12.37. confirmed the predicted relationship. From these figures, it might be noted that, at any given yarn length, the yarn tension was a linear function of (air pressure)$^{\frac{1}{2}}$. The slopes of the curves varied with the yarn lengths. Reference to Fig. 12.38. showed that a similar pattern of behaviour existed for the different materials of yarns tested.

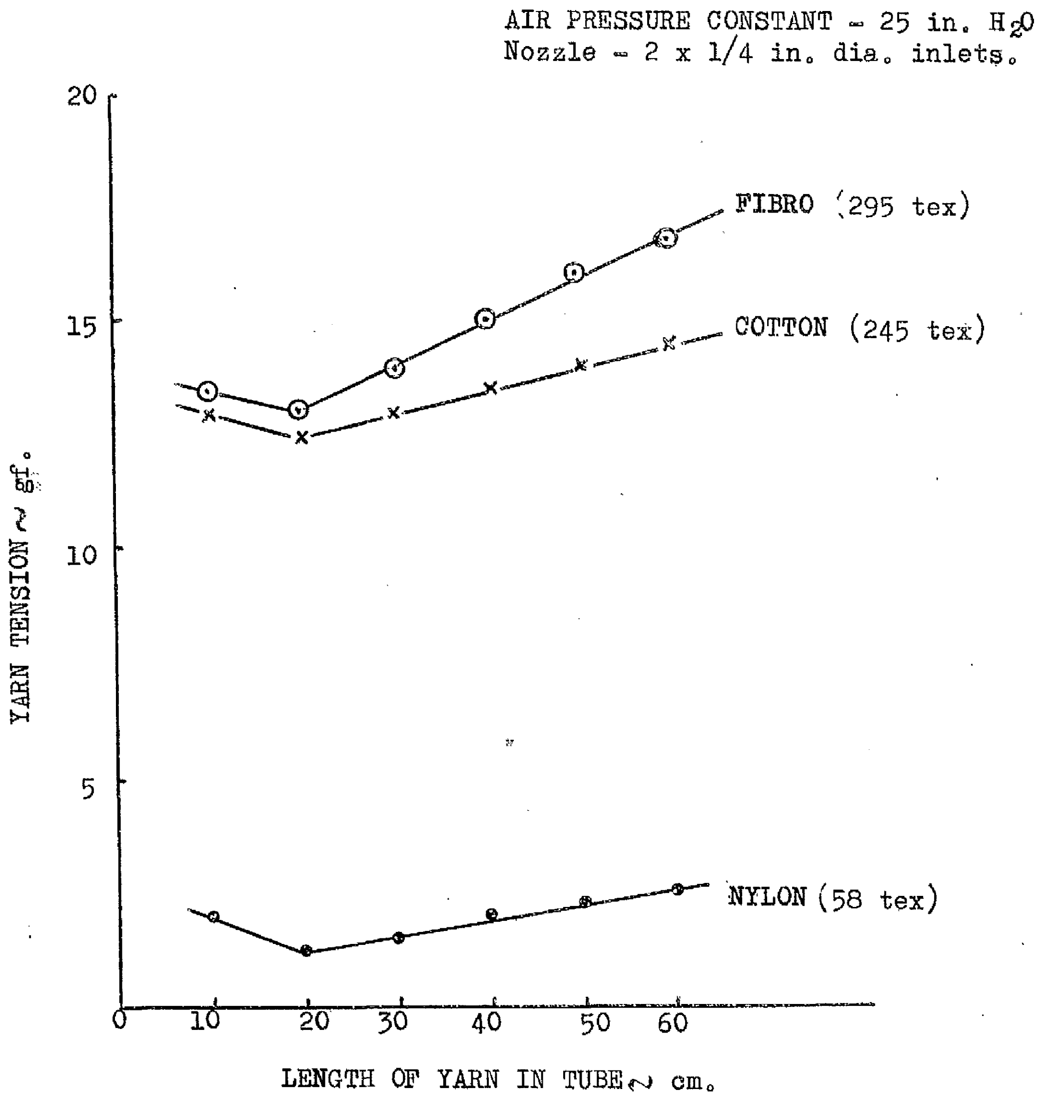



Fig. 12.33

RELATIONSHIP BETWEEN YARN LENGTH AND YARN TENSION WITH DIFFERENT YARNS

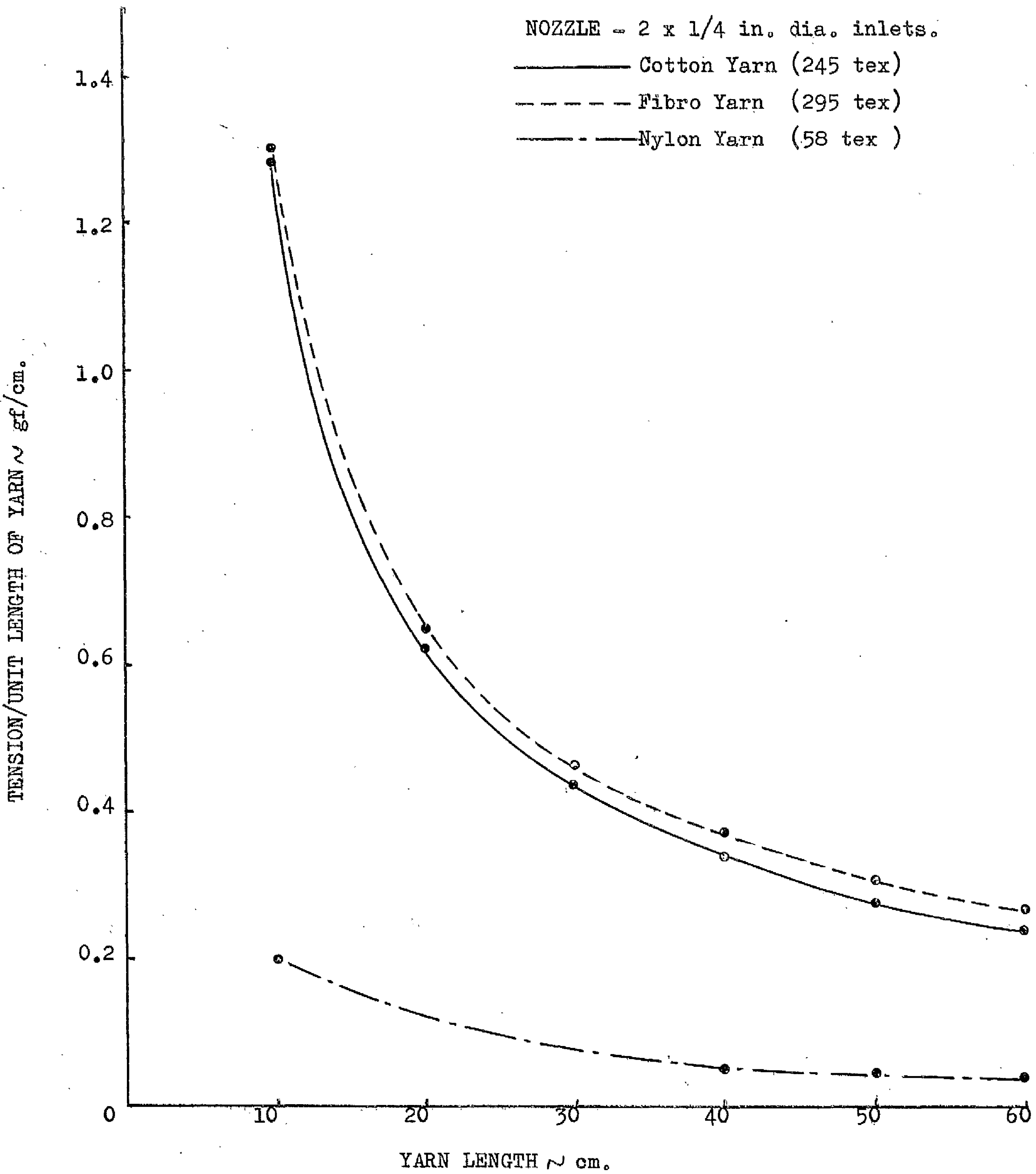



Fig. 12.34.

RELATIONSHIP BETWEEN YARN LENGTH AND TENSION PER UNIT LENGTH WITH DIFFERENT YARNS

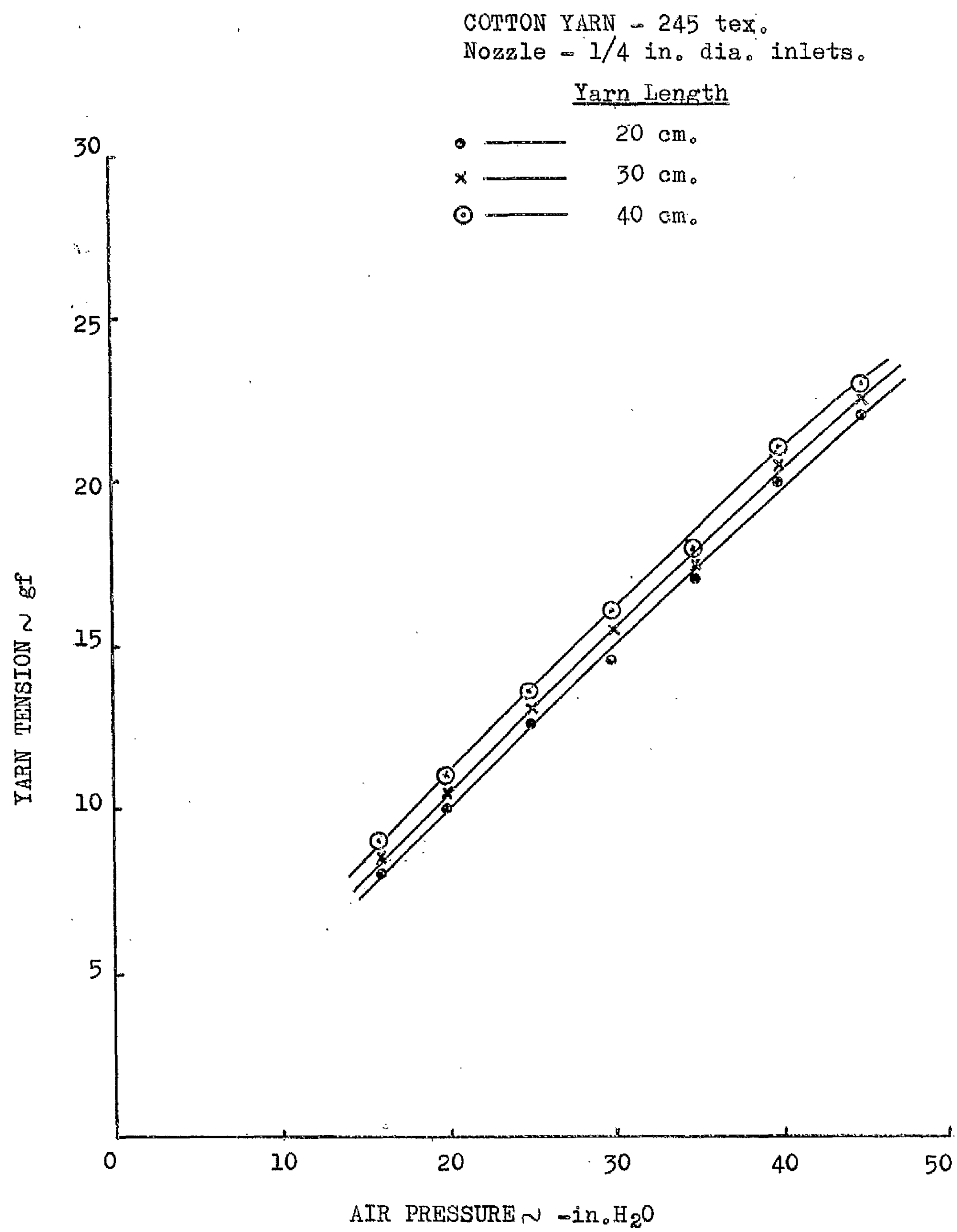



Fig. 12.35

RELATIONSHIP BETWEEN AIR PRESSURE AND YARN TENSION WITH DIFFERENT YARN LENGTHS

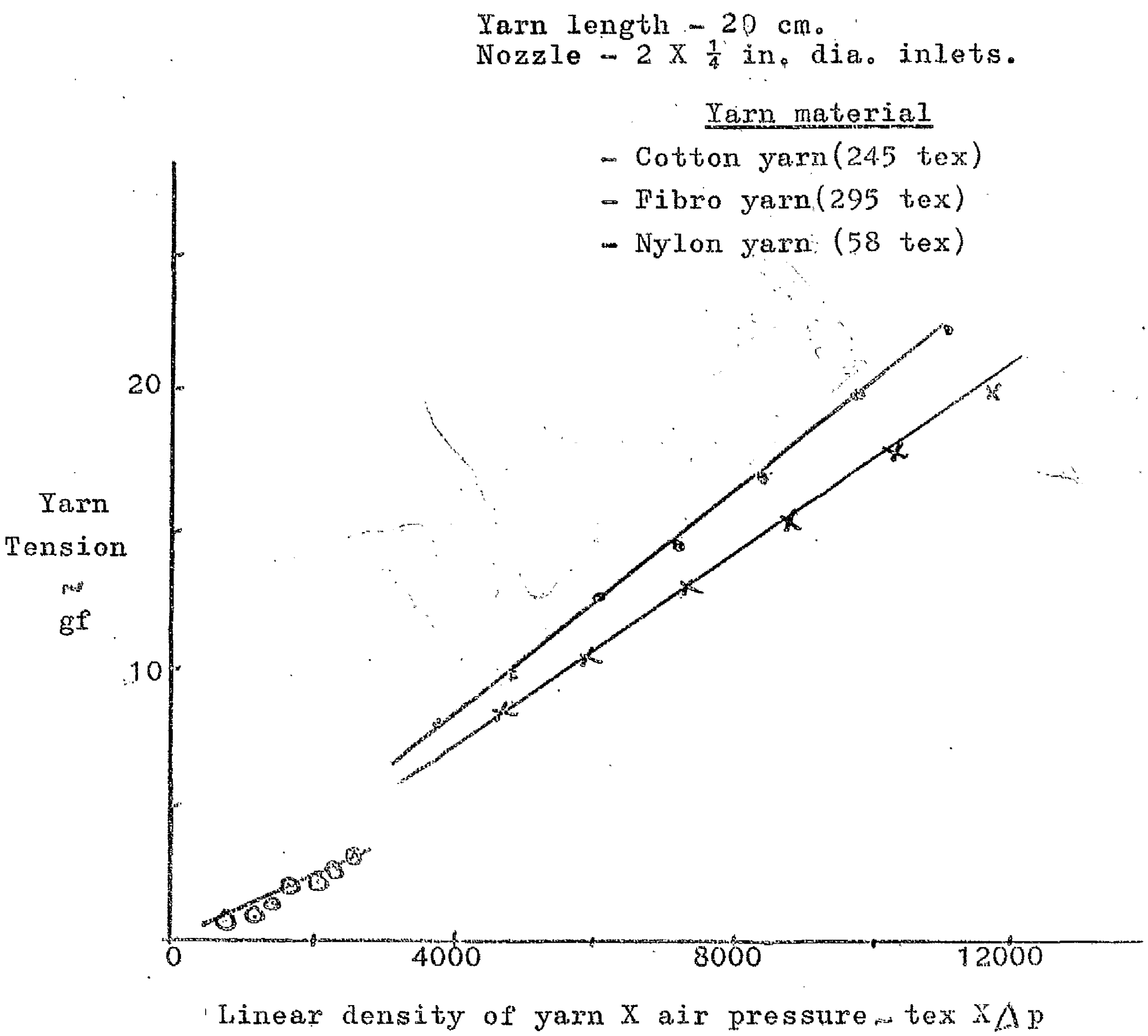



Fig. 12.36.

RELATIONSHIP BETWEEN (AIR PRESSURE)(LINEAR DENSITY OF YARN) AND YARN TENSION WITH DIFFERENT YARN MATERIALS

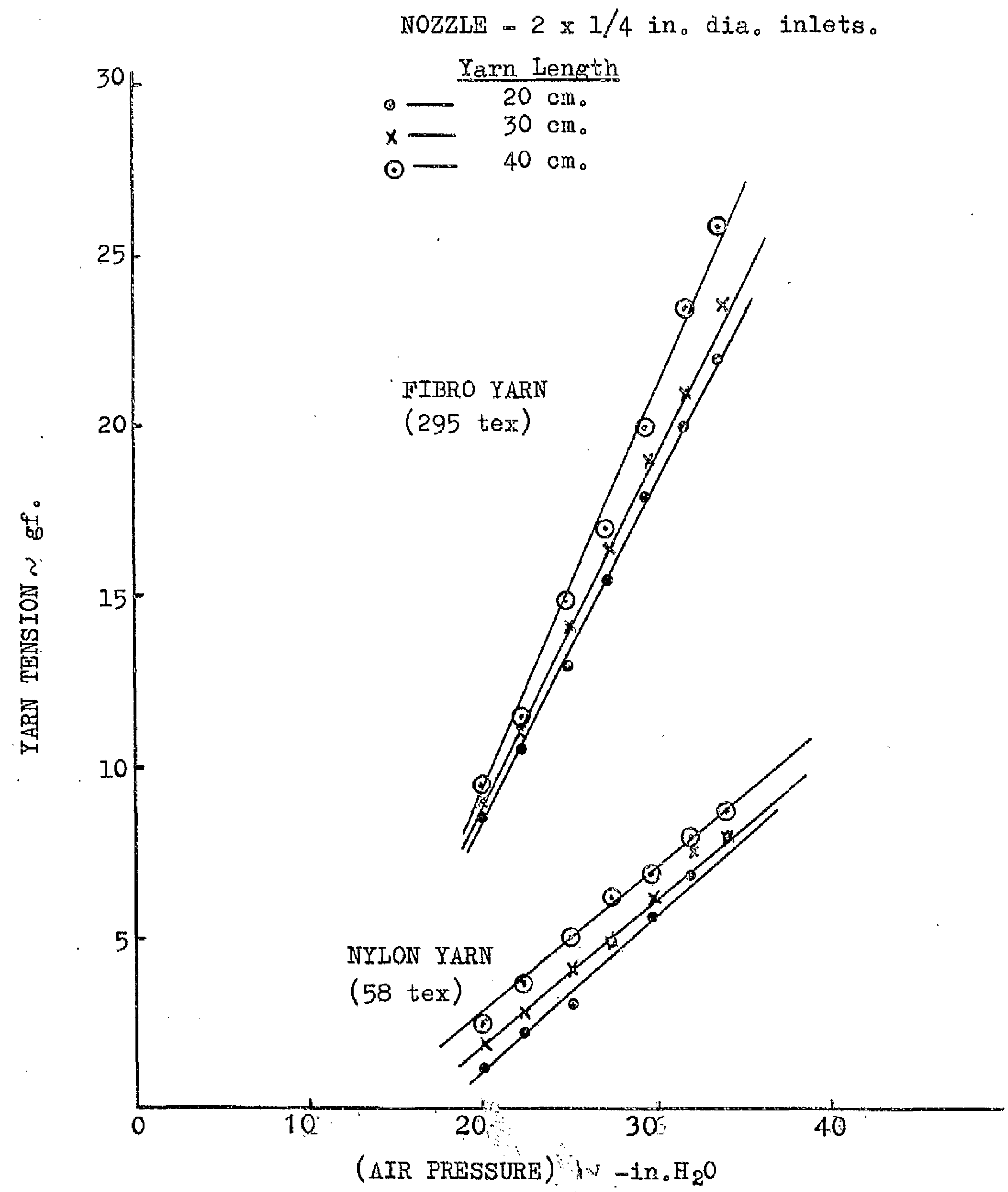



Fig. 12.37

RELATIONSHIP BETWEEN (AIR PRESSURE)½ AND YARN TENSION WITH FIBRO AND NYLON YARNS OF DIFFERENT LENGTHS

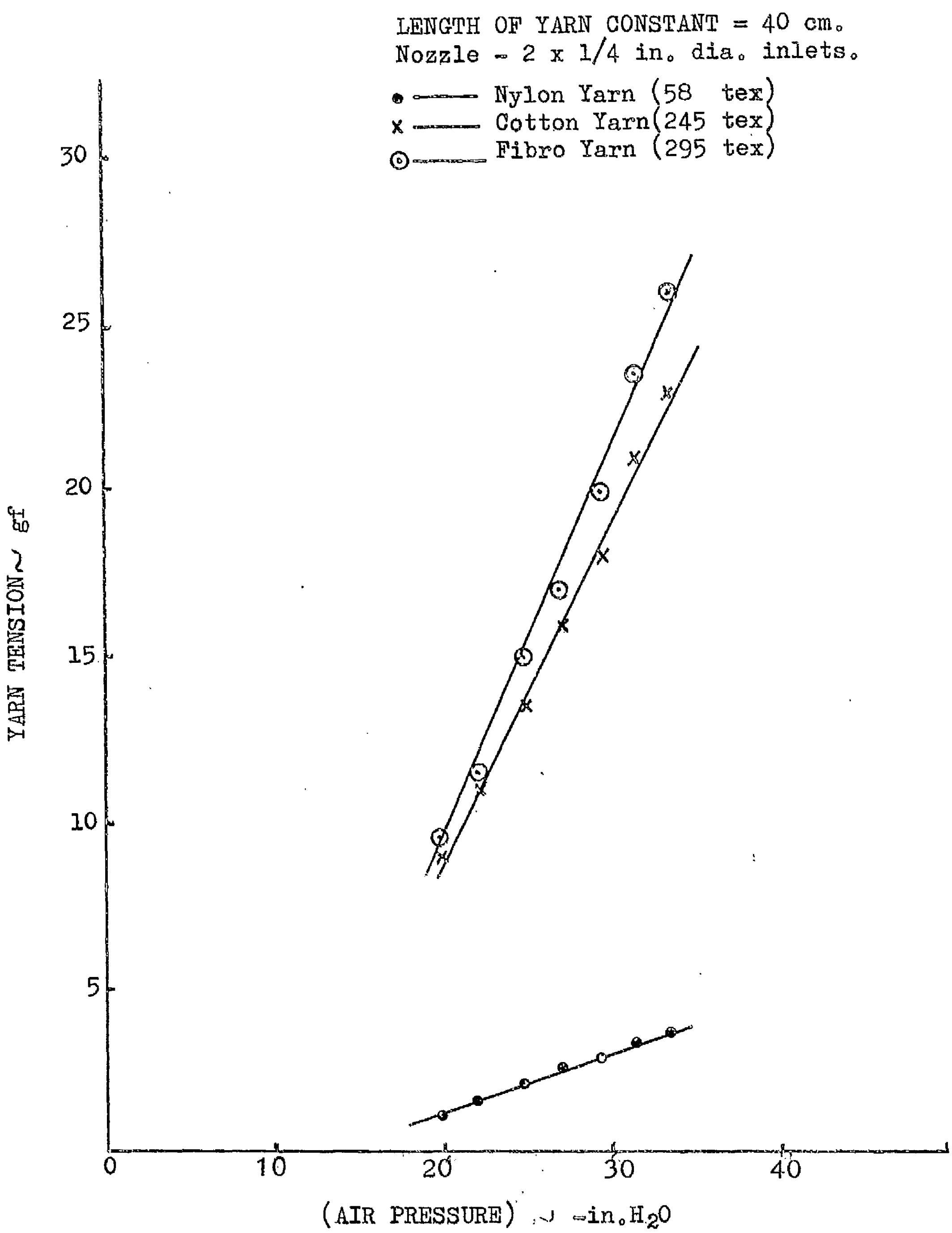



Fig. 12.38

RELATIONSHIP BETWEEN (AIR PRESSURE) AND YARN TENSION WITH DIFFERENT YARNS

It might be seen from Fig. 12.39. that the tension per unit length of yarn tended to increase proportionately with air pressure. The shorter yarn lengths exhibited higher values of tension per unit length and this behaviour was in conformity with the relationship shown in Fig. 12.34.

12.16. RELATIONSHIP BETWEEN YARN SPEED AND YARN TENSION

From Fig. 12.40., it was found that yarn tension was proportional to (yarn speed)$^2$. This relationship is consistent with the expected behaviour because the tension is proportional to the centrifugal force on the yarn and this force, in turn, is proportional to the square of the yarn speed. The different gradient of the lines even when corrected to account for count variations suggested that the tension was influenced by other factors, such as, the nature of the yarn material, charging effects etc.

The relationship between linear density of yarn and (yarn speed)$^2$ is shown in Fig. 12.41. Under steady conditions of air flow and for a given nozzle design, yarn length and linear density, the magnitude of the aerodynamic force acting on yarn would tend to remain constant and this would tend to maintain a constant yarn speed. Any alterations to the yarn mass (either by changing the linear density of yarn or the yarn length in tube) would increase the frictional drag on yarn and this would affect the yarn speed. The higher the linear density of yarn, the lower will be its rotational speed. The graph in Fig. 12.41. seems to fairly well with the theoretical deductions worked out in section 9.6. and the divergency may be explained by the above considerations. Any deviation from the expected behaviour could only be attributed to the retarding forces acting on yarn and these forces would tend to vary with the frictional forces (solid

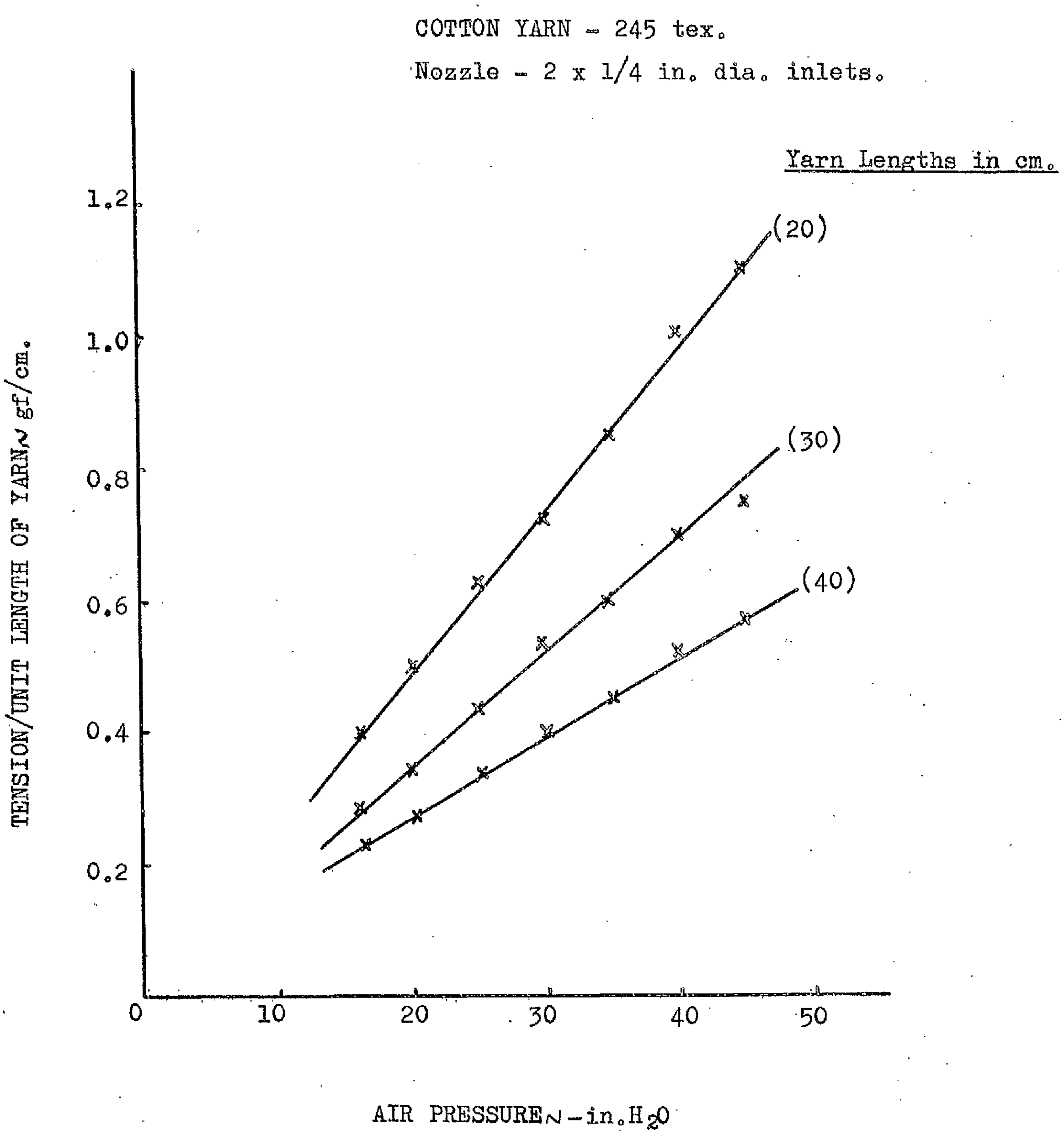



Fig. 12.39

RELATIONSHIP BETWEEN AIR PRESSURE IN THE TUBE AND TENSION PER UNIT LENGTH OF YARN

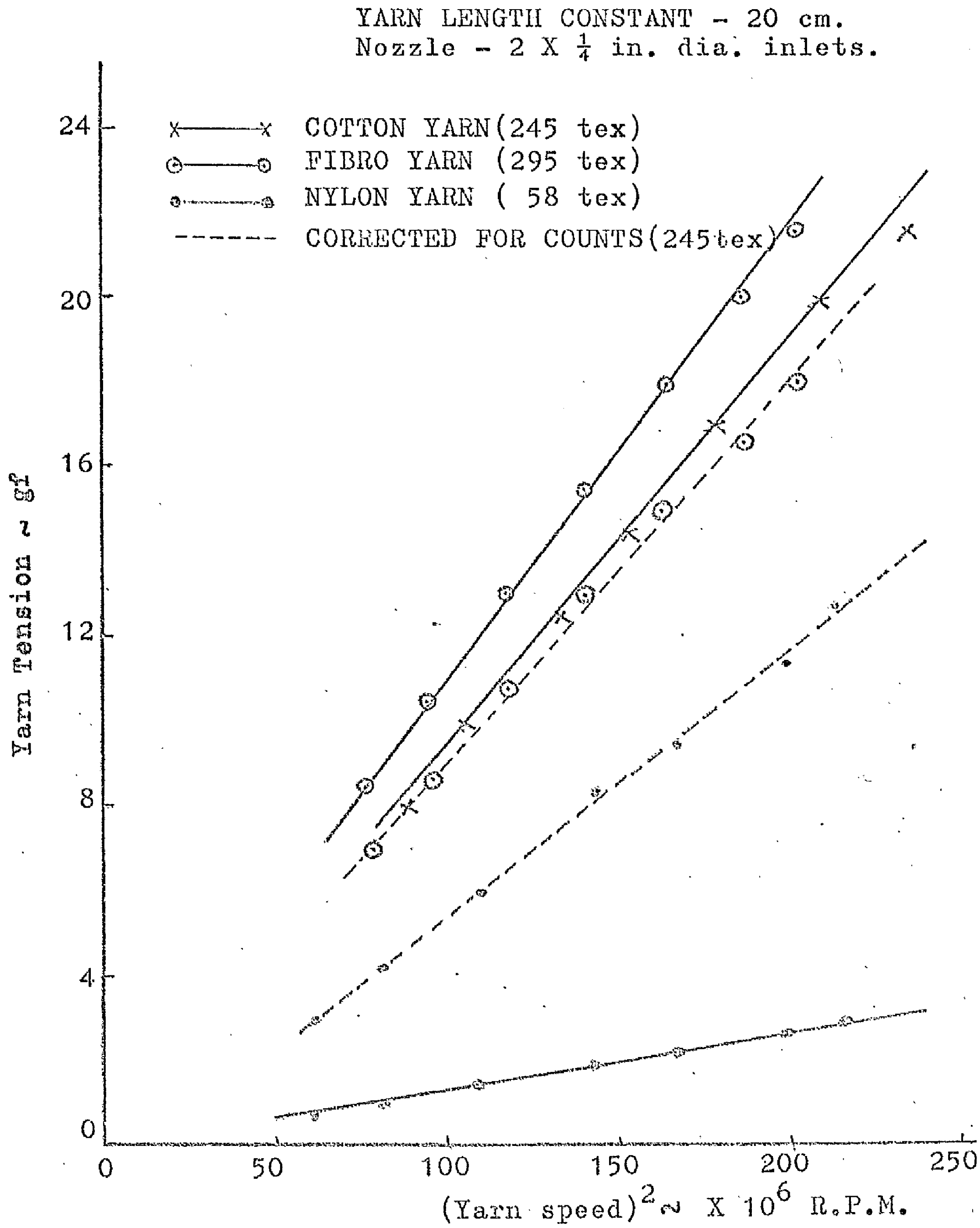



Fig. 12.40.

RELATIONSHIP BETWEEN (YARN SPEED)$^2$ AND YARN TENSION WITH DIFFERENT YARNS

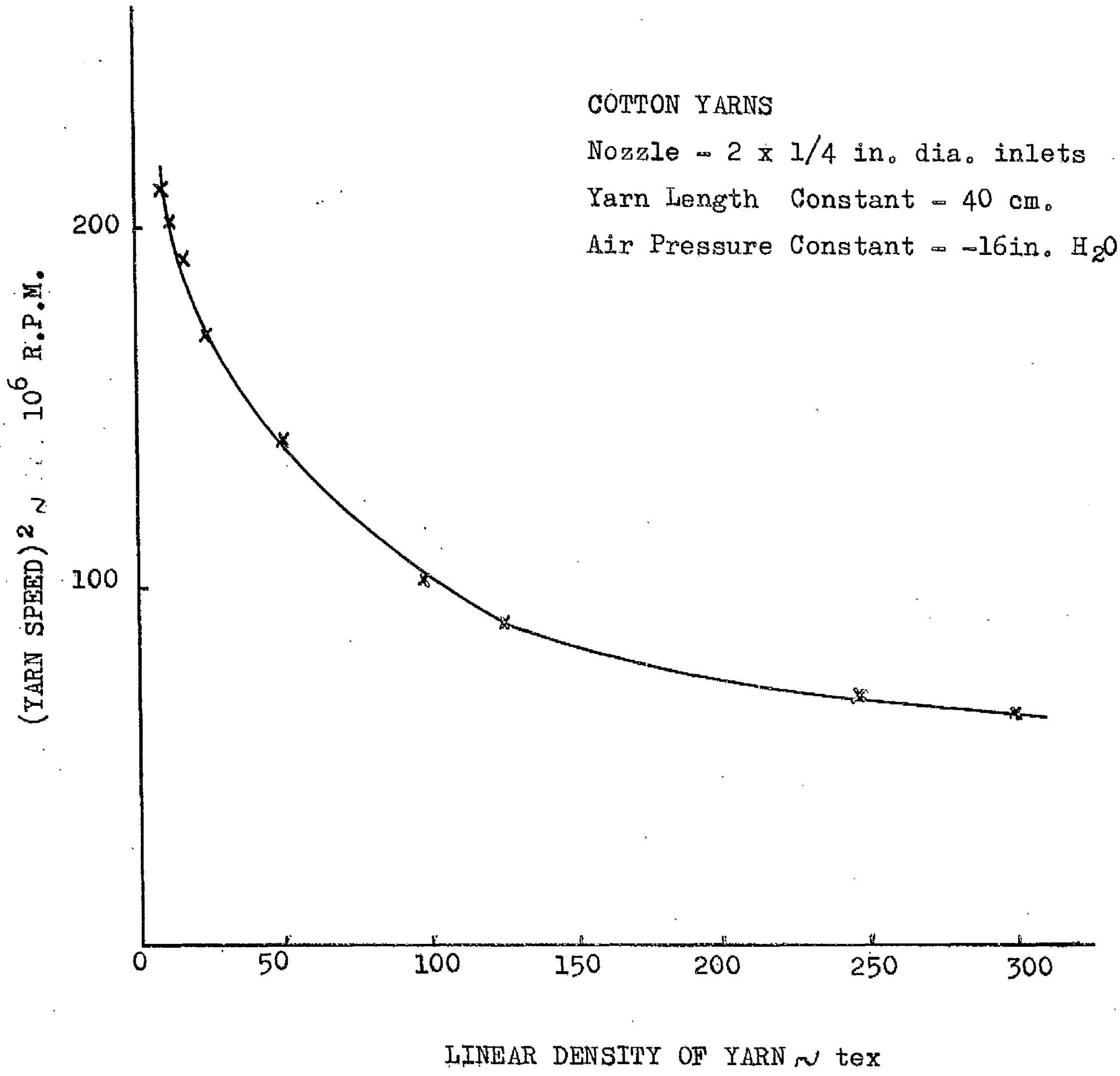



Fig. 12.41

RELATIONSHIP BETWEEN LINEAR DENSITY OF YARN AND (YARN SPEED)$^2$

friction and retarding forces due to static charges) which, in turn, would depend upon several factors, such as, yarn and tube materials, charge level in tube etc.

The relationship between air pressure and (yarn speed)$^2$, at a constant yarn length, was found to be linear. This relationship shown in Figs. 12.42. and 12.43. seemed to be consistent with the following two relationships.

volume rate of air flow $\propto$ (air pressure)$^{\frac{1}{2}}$ - Fig. 12.55.

and

yarn speed $\propto$ volume rate of air flow - Fig. 12.44.

Referring back to Figs. 12.42. and 12.43., it might be noted that the gradient of the lines varied with the yarn length and also with the linear density of yarn.

## 12.17. EFFECT OF SPINNING TUBE GEOMETRY ON YARN TENSION

Two spinning tube designs, one with two $\frac{1}{4}$ in. diameter tangential inlets which produced predominantly sliding torque and the other with two 1 in. X $\frac{1}{8}$ in. slit inlets which gave rolling torque were selected for this experiment. Figs. 12.45. to 12.48., both inclusive, show yarn tension, yarn speed, tension per cm. and torque per cm. plotted against (a) yarn tail length and (b) air pressure, for both the spinning tube designs. From a comparison of these graphs, it might be observed that the increase in tension with yarn tail length is smaller in the case of sliding torque than with the rolling torque. It was observed that the helix angle of the yarns obtained with these two nozzles differed considerably. The yarn helix when using the slit inlet nozzle was more extended than that obtained with the circular inlet nozzle. The variation in helix angles might have been responsible for the observed variation in yarn tensions.

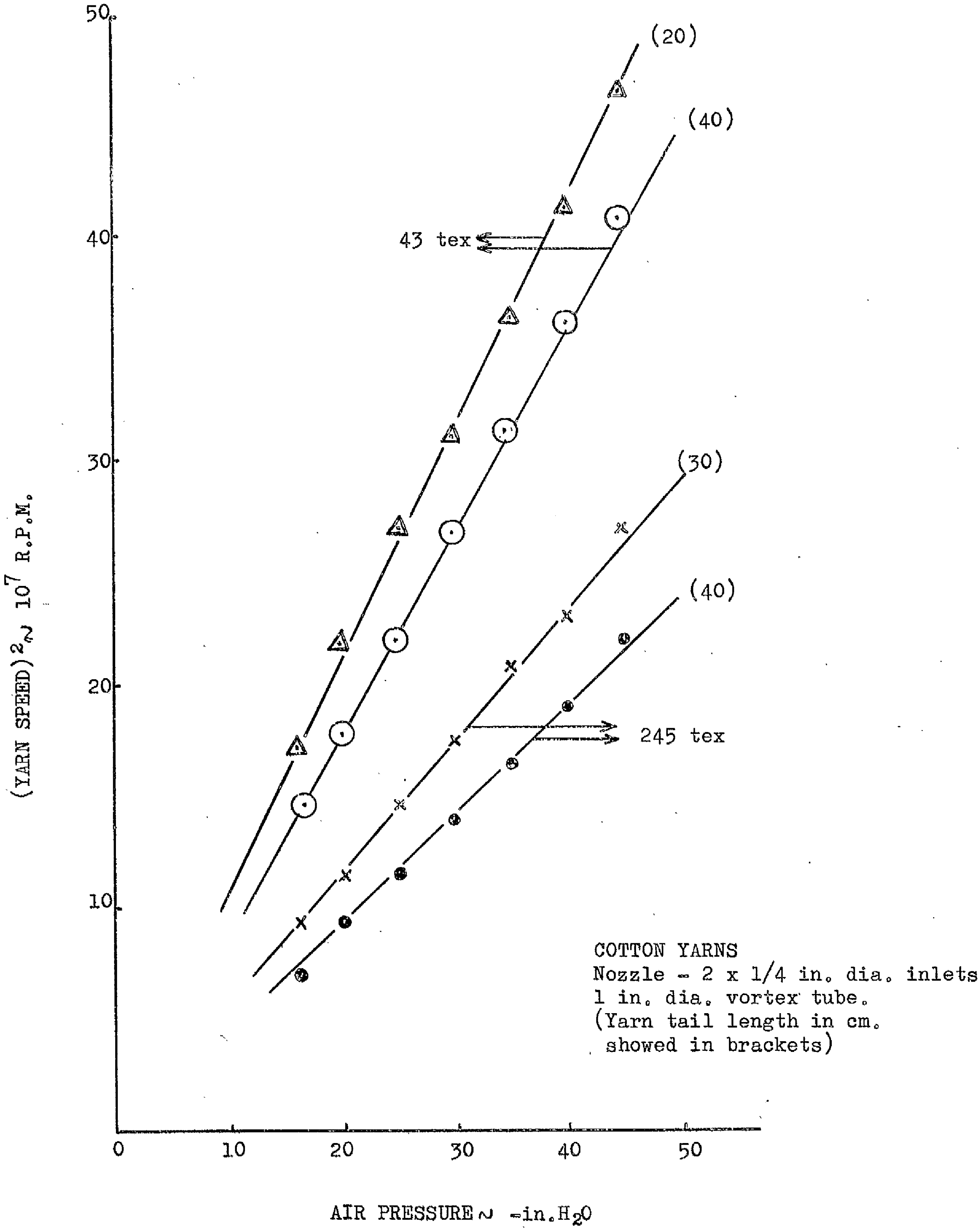



Fig. 12.42

RELATIONSHIP BETWEEN AIR PRESSURE IN THE TUBE AND (YARN SPEED)$^2$

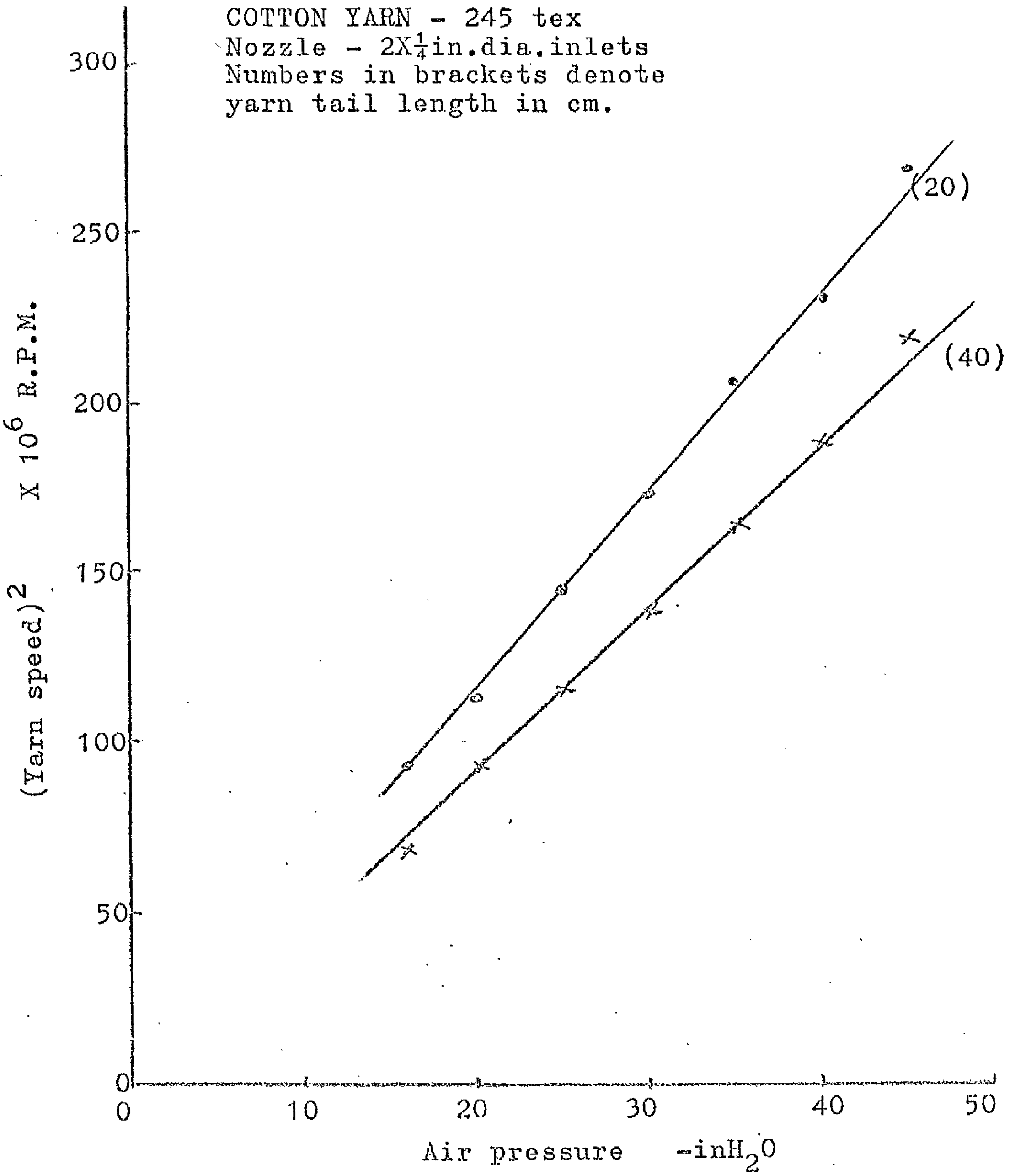



Fig. 12.43.

RELATIONSHIP BETWEEN AIR PRESSURE IN THE TUBE AND (YARN SPEED)$^2$

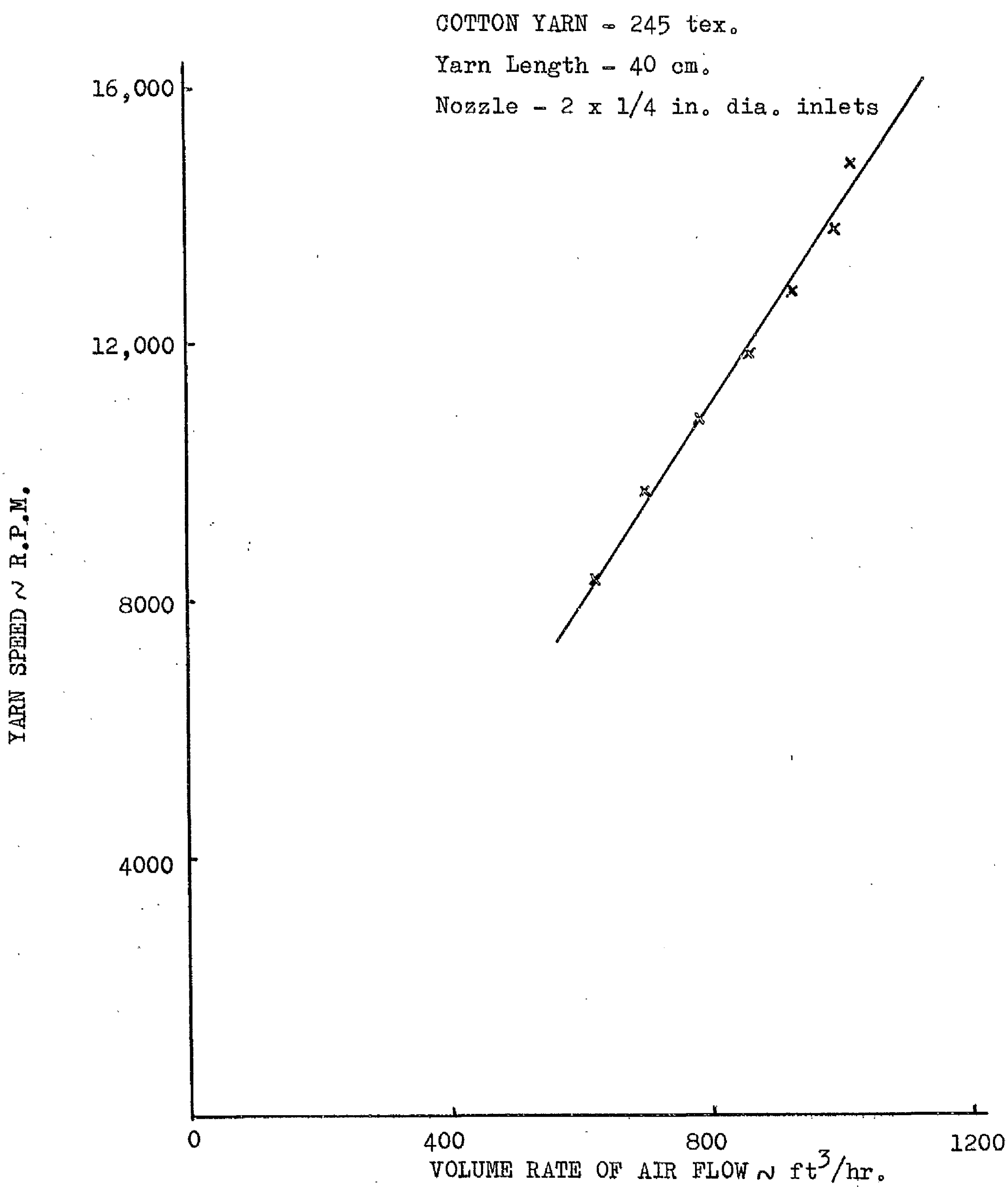



Fig. 12.44

RELATIONSHIP BETWEEN VOLUME RATE OF AIRFLOW AND YARN SPEED

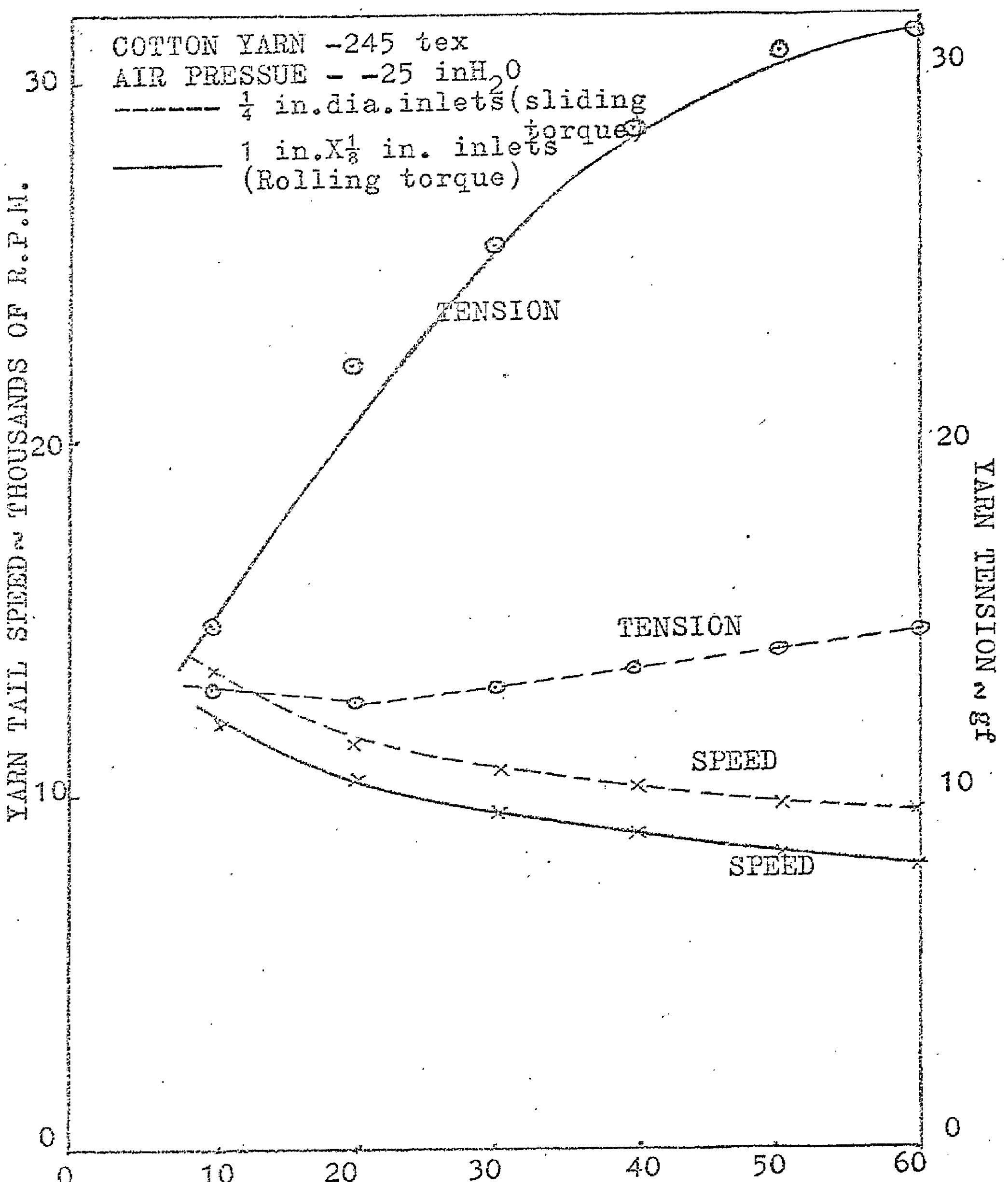



Fig. 12.45.

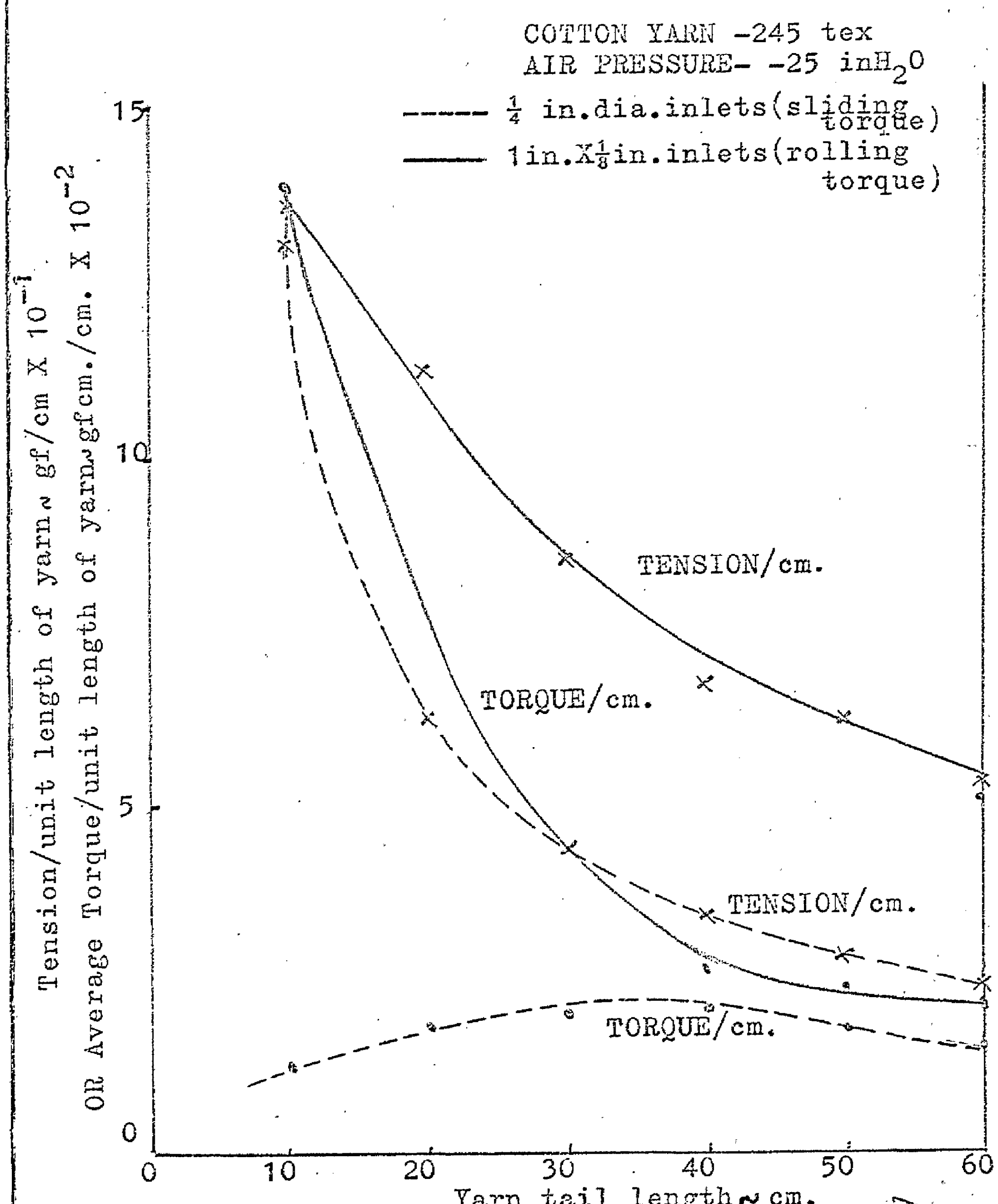



Fig. 12.46.

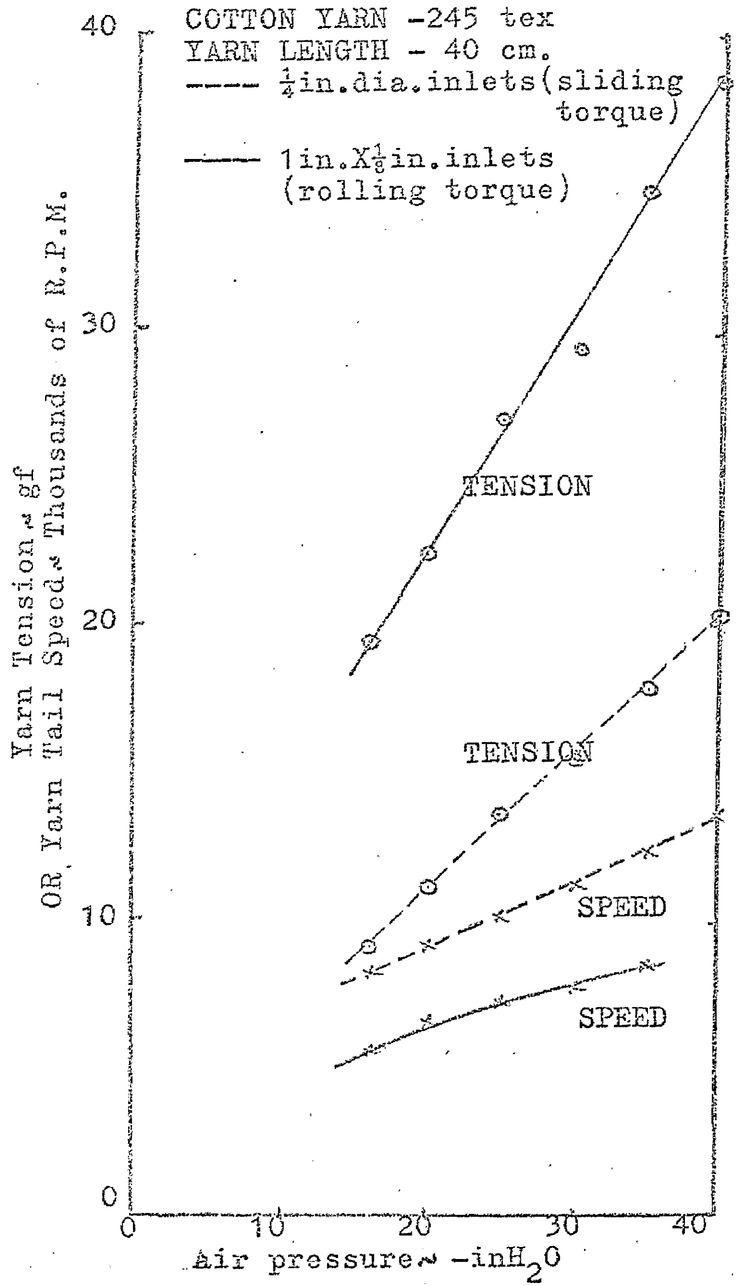



Fig. 12.47.

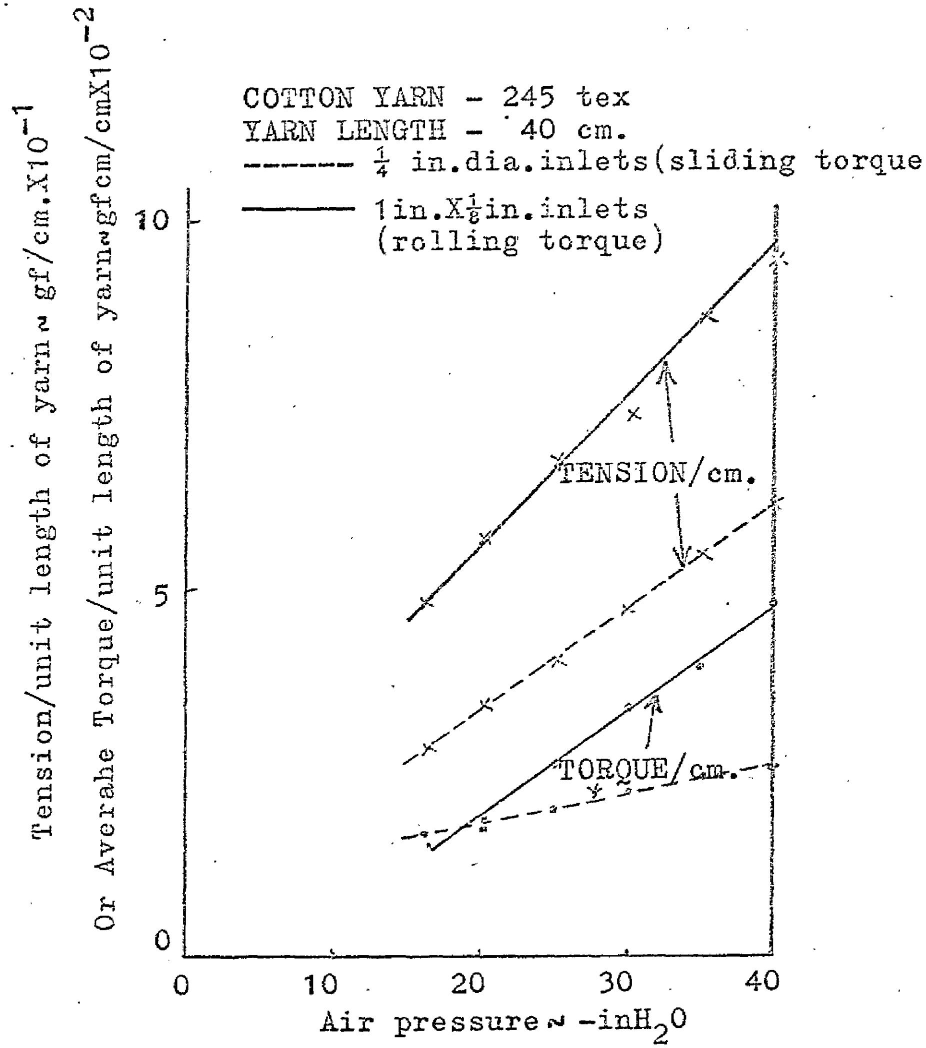



Fig. 12.48.

## 12.18. TENSION MEASUREMENTS DURING SPINNING

Tension measurements were made during the spinning process. The relationships between the yarn tension and

(a) the linear density of yarn

(b) the yarn withdrawal rate

and (c) the air pressure

are given in Figs. 12.49, 12.50. and 12.51. respectively.

It will be observed that tension is directly proportional to the linear density of yarn. Thus a measure of the tension values during the spinning process, at any given air pressure, indicates the value of linear density of yarn issuing from the spinning tube. A control of the yarn linear density may be exercised by the tension variations if they are related to yarn take-off rate. This principle formed the basis of Chandarana's[10] auto-levelling device.

It should be noted that the tension values obtained during spinning are quite low.

Since there were small variations in the linear density of yarn with the yarn take-up rate, it was thought best to use the product of these two parameters as the y-ordinate. It appeared that this product remained at a fairly constant level.

The relationship between the product of yarn tension and linear density of yarn tended to be a linear function of (air pressure)$^{\frac{1}{2}}$.

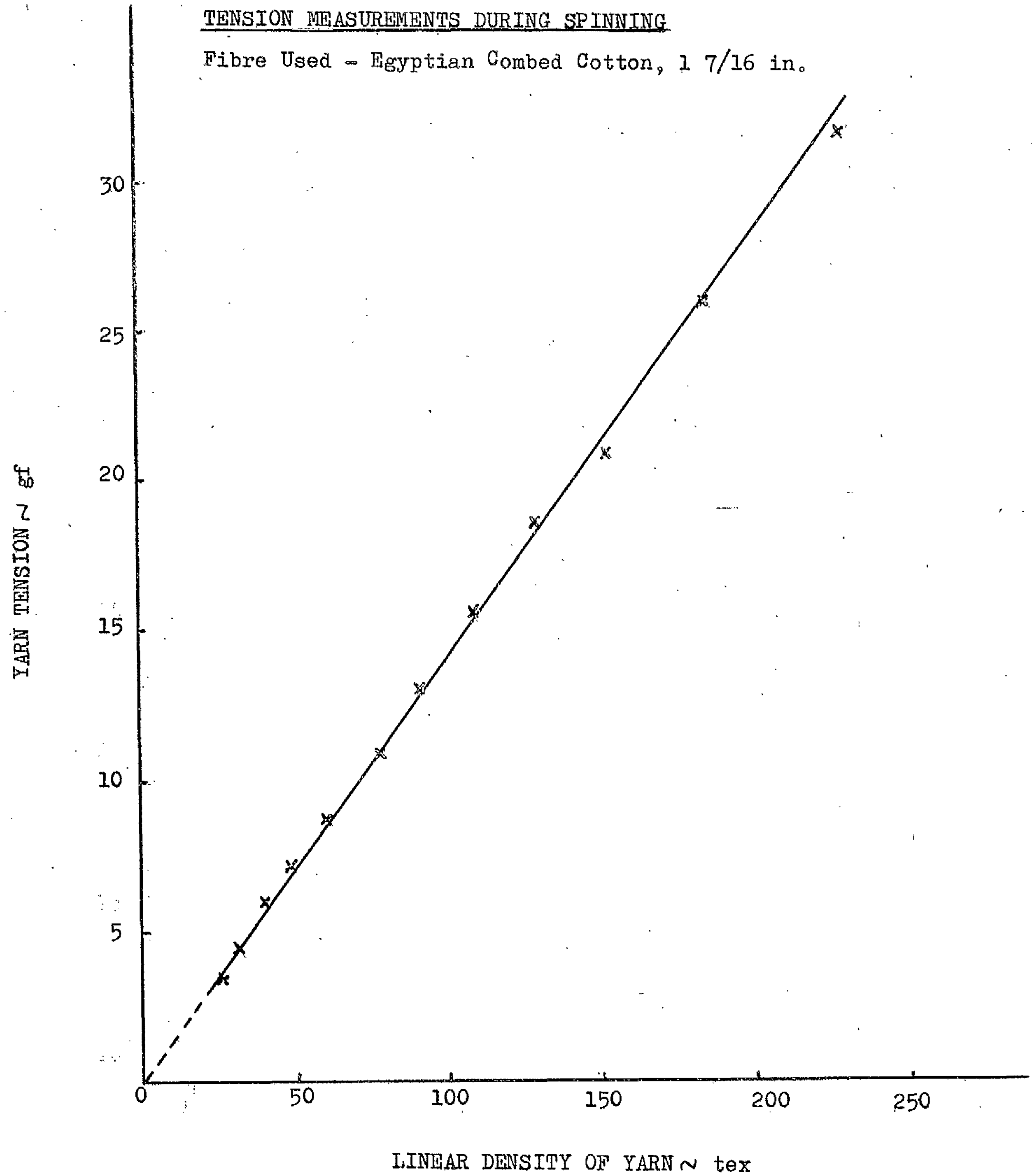



Fig. 12.49

RELATIONSHIP BETWEEN LINEAR DENSITY OF YARN AND YARN TENSION DURING SPINNING

TENSION MEASUREMENTS DURING SPINNING

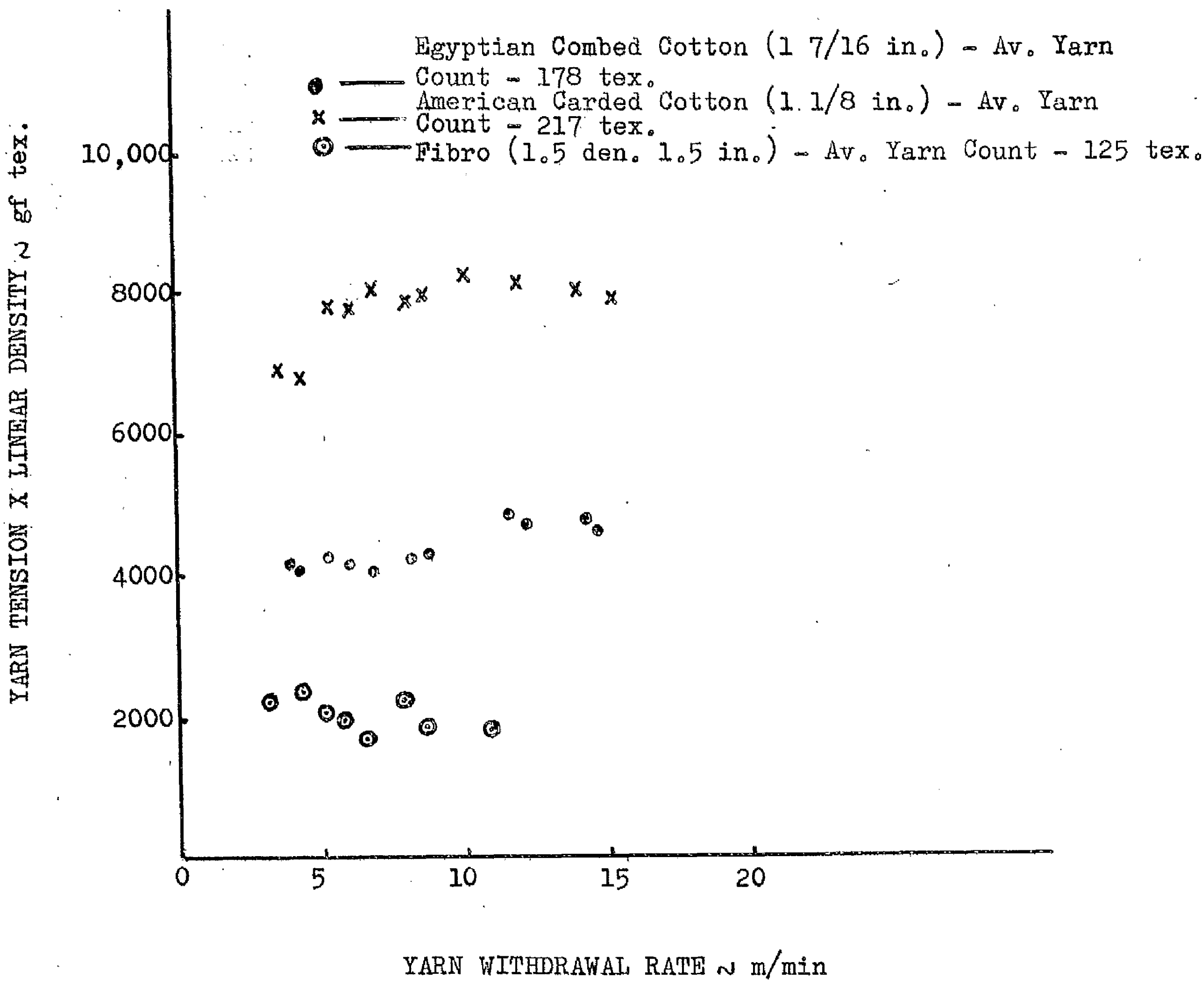



Fig. 12.50

EFFECT OF YARN WITHDRAWAL RATE ON YARN TENSION

TENSION MEASUREMENTS DURING SPINNING

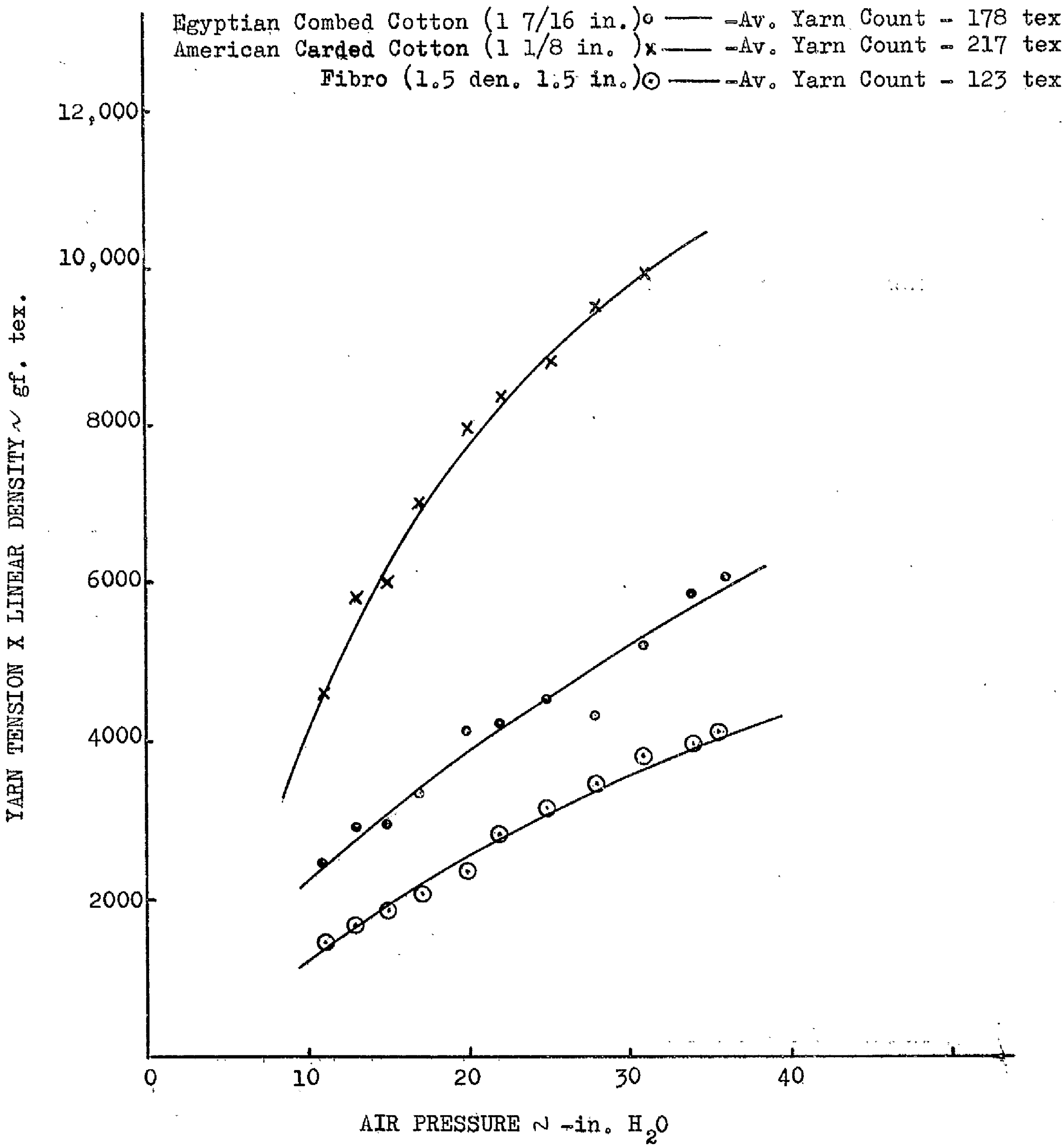



Fig. 12.51

RELATIONSHIP BETWEEN AIR PRESSURE AND THE PRODUCT YARN TENSION AND LINEAR DENSITY

# PART III

## MEASUREMENT OF AIR FLOW IN SPINNING TUBES

### 12.19. INTRODUCTION

The measurement of air flow was carried out with a view to obtain an idea of the power consumed by the spinning tubes of various designs and dimension, when worked at different air pressures.

The method employed in this research work for measuring the rate of air flow in the spinning tubes was chosen from the British Standard 1042, Parts I and III, 1964.

This method has certain limitations. It is not applicable to fluids exhibiting non-steady or pulsating flow, to flow in partially filled pipes or to suspension of solids in liquids or gases. The last condition precludes the use of this method for measurment of air flow when fibres are fed into the system for spinning yarn. The small percentage of fibres that do not attach themselves to the forming yarn will find their way into the air stream whose flow rate is measured and this fibre suspension in air will debar the application of this method. Moreover there is a possibility of the fibres in the air stream accumulating at the pressure tapping regions and this will affect the accuracy of the pressure readings. Furthermore it is presumed that the air flow rates with and without fibre feed will not differ much especially when only small quantities of fibres are fed into the inlet slot during the spinning of a yarn of medium counts. Considering all the above points, it was thought that the air flow measurements should be carried out without feeding fibres into the system, i.e, when not actually spinning yarn. The results obtained by these measurments were, however, considered to be reasonably close to those values of air flow rates which would have been obtained with fibres fed into the system. Hence these results were applied to represent the values for spinning conditions when yarn was spun under similar pressure differences.

There are three main classes of device suggested for fluid flow measurement. They are:

(a) Orifice plates,

(b) Nozzles

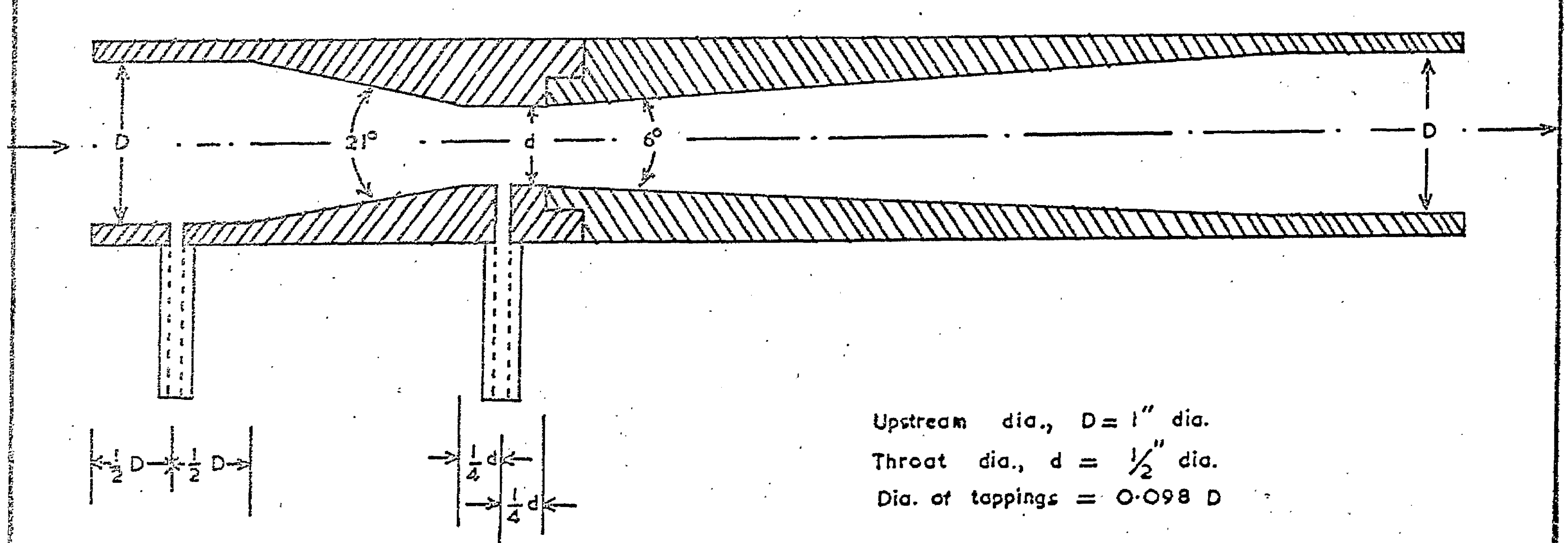
and (c) Venturi tubes.

The selection of the type of device most suitable for the present work depended upon certain considerations. Since the most important consideration was the accuracy of the final results it was thought that a venturi tube would be the ideal one in this case. The main advantage of the venturi tube is that this device has an appreciably lower net pressure loss than orifice plate or nozzle. The net pressure loss is expressed as a percentage of the pressure difference.

A venturi tube consists of a conical convergent entry leading to a cylindrical throat followed by a conical divergent outlet. The cross-sectional view of the venturi tube is shown in Fig.12.52. Deviations in the sizes of the upstream and throat diameters from the Standard specification were made in order to meet the requirement of the present work. It was felt that these modifications would affect the

Fig. 12.52

SECTIONAL VIEW OF VENTURI METER



accuracy of the measurements only slightly and, therefore, the results obtained from this venturi tube would still be adequate for the present work.

The venturi tube was connected to and placed between the spinning tube and the suction pump. The pressure difference was measured by a water manometer.

In these calculations, it was assumed that air was an incompressible fluid and that the compressibility factor was unity. Friction effects and density changes due to temperature increase in the venturi tube were ignored. It was felt unnecessary to go into the details by which the equation for the rate of air flow was deviced. The rate of air flow was calculated from the following expression, (ref. BS. 1042)*

$Q = 359.2kEd^2 \frac{h}{\rho}$ , where

Q=volume rate of air flow ($ft^3/hr$)

k= gas discharge coefficient (found from the calibration curve shown in Fig. 12.53. ); the venturi tube was calibrated with an ordinary gas meter to obtain the discharge coefficient,

E= velocity of approch factor

$= \frac{1}{\sqrt{(1-m^2)}}$ , where m= area ratio $(\frac{d^2}{D^2})$,

d= throat diameter ($\frac{1}{2}$in.)

D= internal diameter of upstream pipe (1 in.)

= 1.033 (approximately),

h= venturi pressure difference measured from a water manometer (in$H_2O$) and

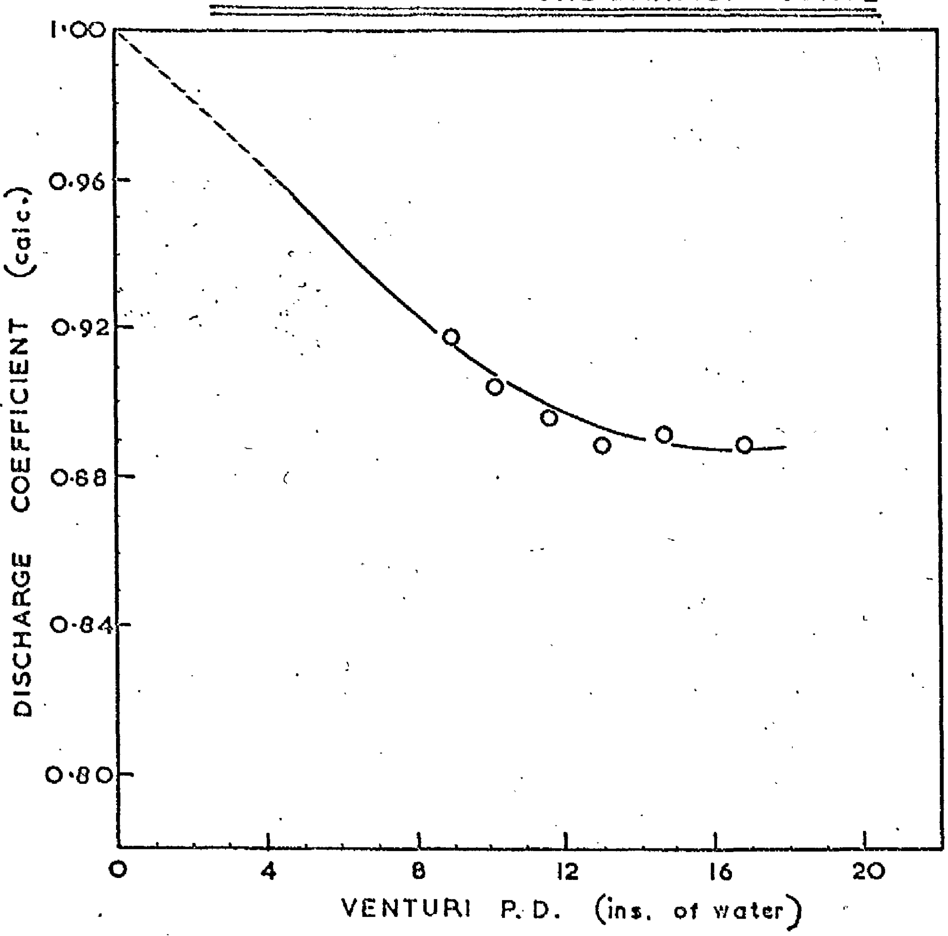
$\rho$= density of air,

= 0.07150 lb /$ft^3$ at 78° F and a barometric pressure of 746 mm. of mercury.

* See p. 463.

Fig.12.53

VENTURI METER CALIBRATION CURVE



Therefore, $Q = 347 \times k \times \sqrt{h}\ ft^3/hr$

and $q = \frac{Q}{3600}\ ft^3/sec.$

The Reynolds number was calculated from the following relation:-

$$\text{Reynolds number} = \frac{\text{velocity of air in tube(ft/sec)} \times \text{tube diameter(ft)}}{\text{kinematic viscosity of air } (ft^2/sec)}$$

The kinematic viscosity of air (84) at 78° F is $1.66 \times 10^{-4}\ ft^2/sec$

This value was assumed to remain constant at the different air flow rates.

## 12.20. SOME RESULTS WITH AIR FLOW MEASUREMENTS

The relationship between the total area of opening in the spinning tube was plotted against the volume rate of air flow. This is shown in Fig. 12.54.

The relationship between the volume rate of air flow and $(\text{air pressure})^{\frac{1}{2}}$ with a number of spinning tube designs is shown in Fig. 12.55. It was observed from these graphs that the volume rate of air flow was directly proportional to $(\text{air pressure})^{\frac{1}{2}}$.

## 12.21. POWER CONSUMED BY THE VORTEX SPINNER

The power required to pump the air through the spinning tube was calculated from the expression

$$p \times q \times \frac{746}{550} \text{ (watts)}, \text{ where}$$

$p$ = upstream pressure(i.e., the air pressure difference across the tube) in $lb\ ft^{-2}$

and $q$ = quantity of air flow through the tube in $ft^3 sec^{-1}$.

The relationship between the air pressure difference across the tube and the power consumption is shown in the logarithmic graph in Fig. 12.56. From this graph it was found that power consumption was proportional to $(\text{air pressure})^{1.5}$.

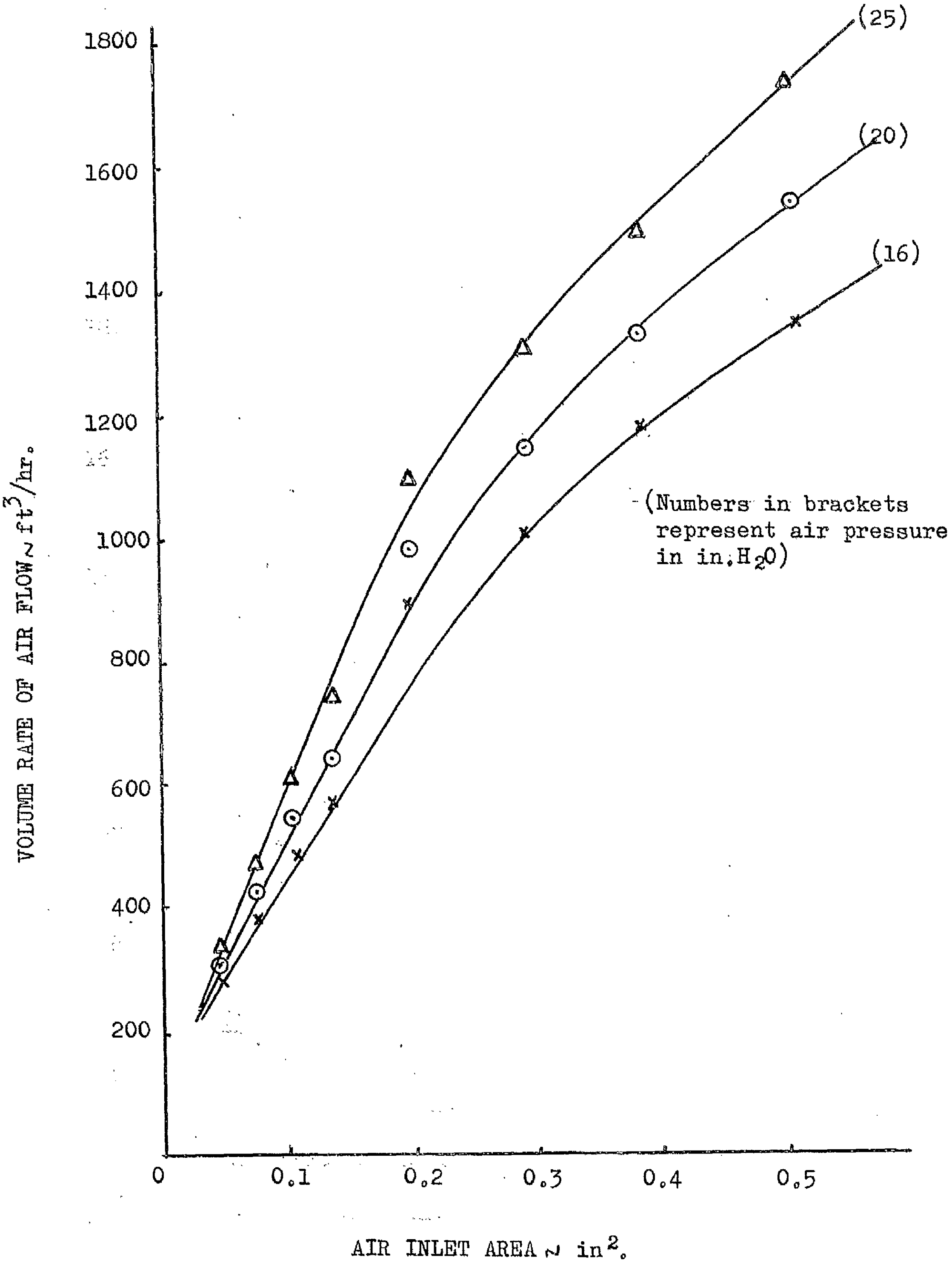



Fig. 12.54

RELATIONSHIP BETWEEN AREA OF OPENING IN THE SPINNING TUBE AND THE VOLUME RATE OF AIR FLOW

LEGEND TO NUMBERS IN BRACKETS
NOZZLE DIMENSIONS

| No. | Size of Tangential Inlet (in) x (in) | Size of Axial Hole (in) | Tube Bore (in) |
|---|---|---|---|
| 1 | 1/4 dia. | 1/8 | 1 |
| 2 | 1/4 x 1/16 | 1/8 | 3/4 |
| 3 | 1/4 x 1/8 | 1/8 | 3/4 |
| 4 | 1/4 x 3/16 | 1/8 | 3/4 |
| 5 | 1/4 x 1/4 | 1/8 | 3/4 |
| 6 | 1/2 x 3/16 | 1/8 | 1 |
| 7 | 1/2 x 1/16 | 1/8 | 3/4 |
| 8 | 1/2 x 3/16 | 1/8 | 3/4 |
| 9 | 3/4 x 3/16 | 1/8 | 3/4 |
| 10 | 1 x 3/16 | 1/8 | 3/4 |
| 11 | 3/4 x 7/32 | 1/4 | 1 |
| 12 | 1 x 1/16 | 1/8 | 3/4 |
| 13 | 1 x 1/16 | 3/16 | 3/4 |
| 14 | 1 x 1/16 | 1/4 | 3/4 |
| 15 | 1 x 1/16 | 5/16 | 3/4 |
| 16 | 1 x 1/16 | 3/8 | 3/4 |

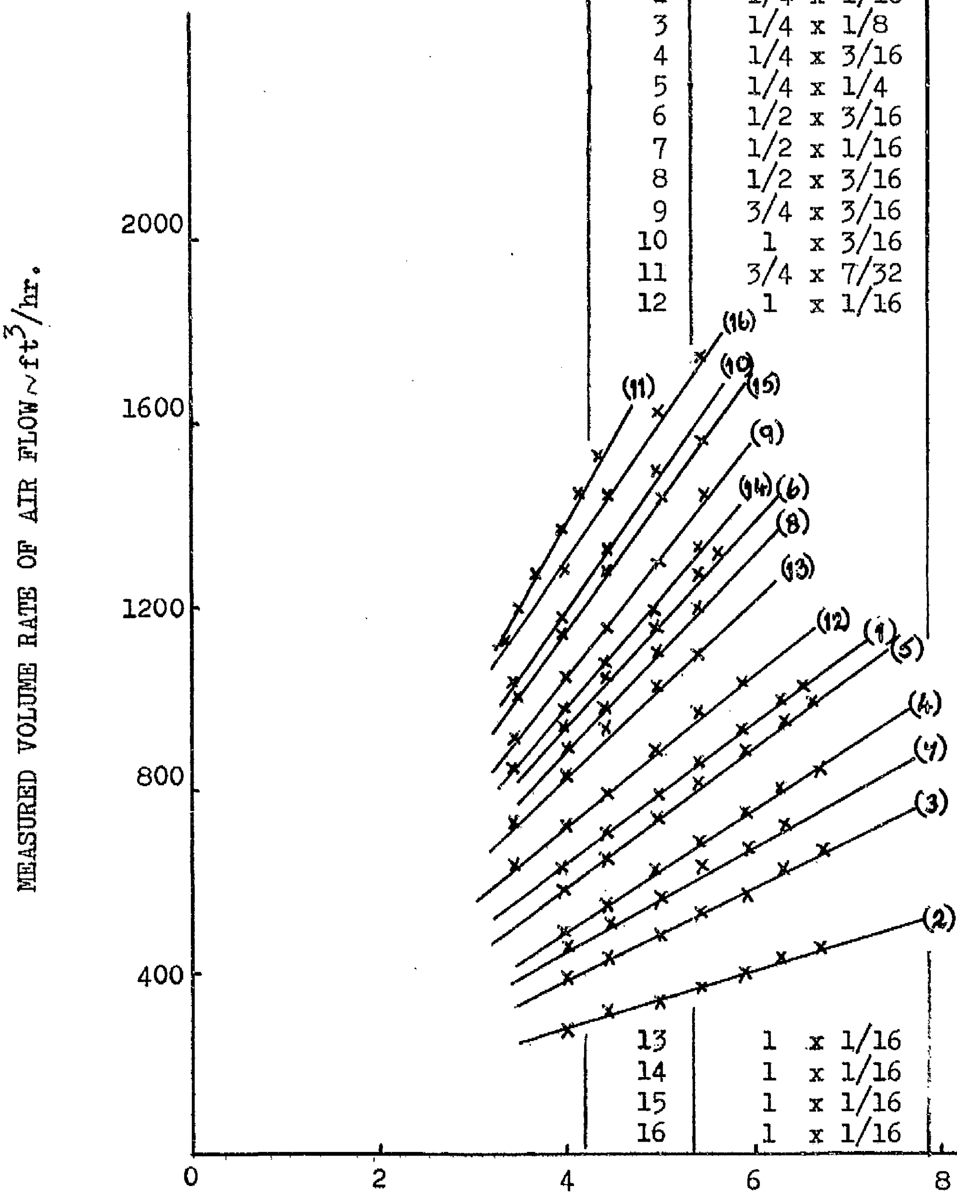



Fig. 12.55

RELATIONSHIP BETWEEN $(\text{AIR PRESSURE})^{\frac{1}{2}}$ AND VOLUME RATE OF AIR FLOW

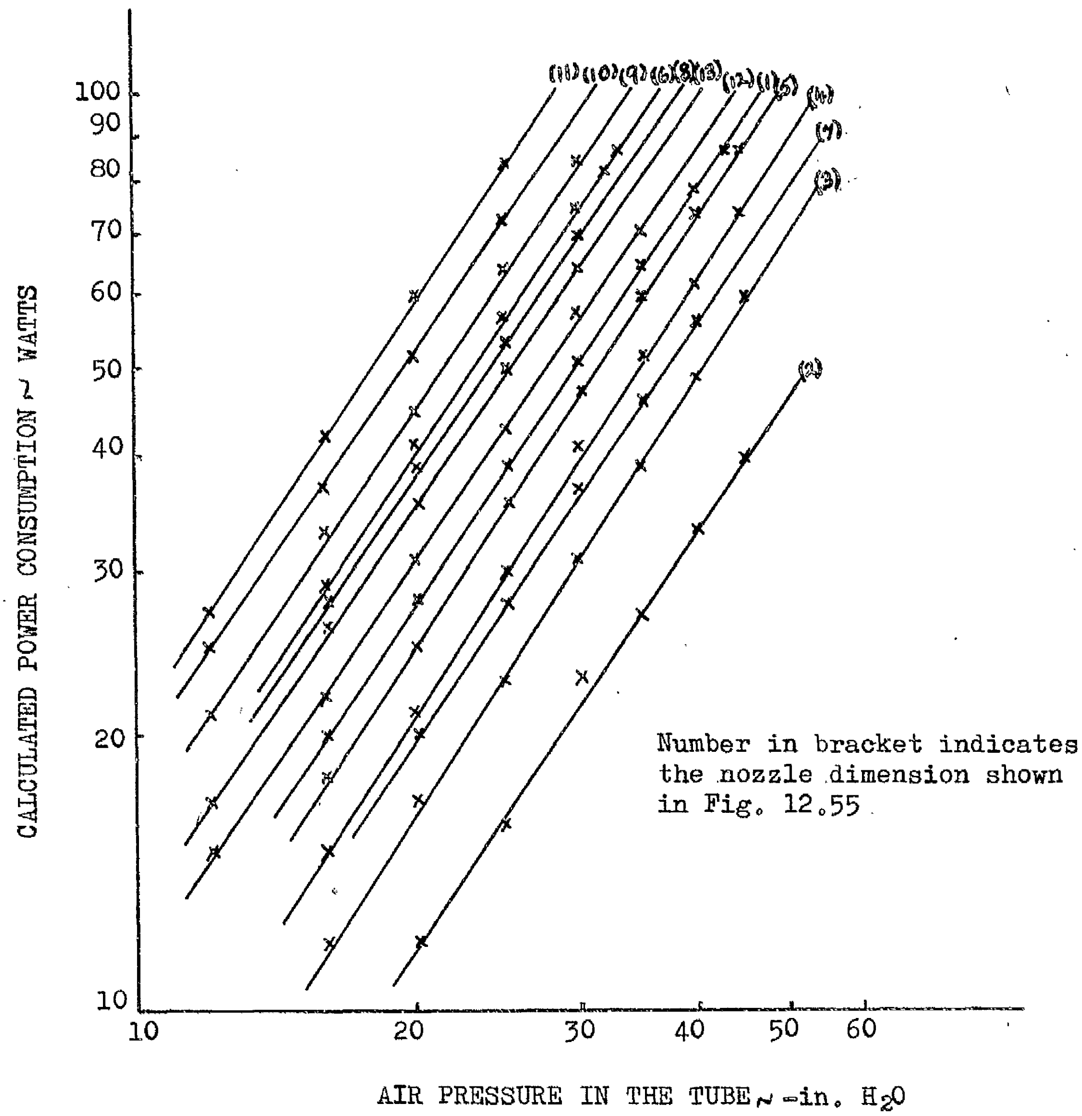



Fig. 12.56

RELATIONSHIP BETWEEN AIR PRESSURE AND THE CALCULATED POWER CONSUMPTION OF SPINNING TUBES WITH DIFFERENT DESIGNS

In the above figure, the values of power consumption were found for one spinning tube used with a variety of nozzles. However, in practice, when a number of vortex spinners are worked from a central suction unit, the power requirement per spinner will be higher than the above calculated values. This is because of the friction losses that will occur due to branches etc. and the generally low efficiency of the suction unit.

The calculated power requirement of the spinning tube with $\frac{3}{4}$ in. X $\frac{3}{16}$ in. tangential inlets with an $\frac{1}{8}$ in. axial entry and a tube bore of $\frac{3}{4}$ in. when working with an air pressure of -25 in$H_2O$ was about 64 watts. (This spinning tube gave the best spinning performance when using fibres of 1 7/16 in. staple length). Assuming that the vortex spinner inserts 12,000 twists per minute, the power consumed by the spinner can be expressed as equivalent to 5.33 mwatts/twist. According to De Barr and Catling[2], in a ring frame spinning 37 tex(16s c.c.) yarn at a speed of 11,000 r.p.m. with a 8 in. lift and a 2 in. ring diameter, the power consumption of a spindle is about 30 watts. This is equivalent to 2.73 mwatts/twist. Thus the power requirement of the vortex spinner is almost twice that of the ring spindle.

On the other hand, the power requirement for a rotor type spinner of about 3 in. in diameter rotating at 30,000 r.p.m. is about 80 watts, or 2.90 mwatts/twist.

Although, at first sight, it appears that the power consumption of the vortex spinner is high, it should be borne in mind that a comparison of the different types of spinners based on their power consumption alone does not give a full and true picture. The economics of a spinning system must be considered by taking into account the other two main factors, viz., capital cost and labour cost along with the power cost.

The capital cost of the rotor spinner is still too expensive and it may not be economical to spin fine yarns. The ring frame produces the best yarn but the limit of its maximum productivity seems to have been almost attained. The vortex spinner has not yet reached the commercial development stage. However the present production rate of yarn from the vortex spinner is almost equal to that of the ring frame. The yarn quality could still be improved. With an improved yarn quality and even at the present modest production rate, it is conceivable that this system may offer substantial gains in the economics of spinning because of the possibility of low capital cost of the spinner due to its extreme simplicity in manufacture. The indirect savings gained due to the relatively small amount of interest(as compared to large capital investments in the other spinning systems) must be also taken into consideration. Perhaps this savings may offset the increased power consumption of the vortex spinner.
If the process of simplification of the vortex system were to be carried further by linking up the spinner to one of the preparatory spinning processes, such as, carding or drawing, then it is likely that the vortex system may become a viable economic proposition.

# CHAPTER 13

## HIGH SPEED PHOTOGRAPHY IN AIR VORTEX SPINNING

# CHAPTER 13

## HIGH SPEED PHOTOGRAPHY IN AIR VORTEX SPINNING

### 13.1. INTRODUCTION

The main purpose of using high speed photography was to examine the behaviour of fibres and yarn during their movement inside the vortex tube and, if possible, their final assembly into yarn. It was also thought useful to study the movement of a seed yarn under various conditions of air pressure, yarn length in the tube etc., so that an idea of the behaviour of the forming yarn under identical conditions could be obtained.

### 13.2. METHODS OF HIGH SPEED PHOTOGRAPHY USED

Two photographic techniques were used. The first one was the conventional photography in conjunction with very short duration flashes. The flash equipment used gave an effective exposure time of 5 micro second and the intensity of discharge was about 150 joules. In order to determine the picture resolution which could be obtained, it is necessary to know the distance moved by a fibre during the flash duration. A fibre moving with a velocity of, say, 1500 in/sec would travel 1.5 in. during, say, a flash period of 1 msec . This distance is equivalent to 1000 fibre diameters(with fibres of 0.0015 in.dia.) which is too much. Therefore, In order to resolve the individual fibres in the picture, the flash duration should be about 1 μsec.

It should be added that the flash duration obtained with the flash equipment used was sufficient to freeze the yarn movement(say, a 2s c.c. yarn rotating at about 10,000 r.p.m. in a 1 in. diameter tube).

The second technique employed the use of a high speed "Fastax" cine camera designed to take 16 mm. cine film. Film was exposed at a rate of about 6,000 frames per second with an effective exposute time of 80 μsec/frame. After processing, the film was projected at a speed of 16 frames per second. In addition to this projection speed, provisions were also made in the "Specto" projector to view the film at either 2 frames/second or frame by frame. Frame by frame movement of the film permitted a detailed observation of some processes which would have been otherwise not possible due to too rapid movement of the different materials in the process concerned.

## 13.3. LIMITATIONS IN HIGH SPEED CINE PHOTOGRAPHY

It was thought that a study of the fibre movement and their subsequent assembly into yarn(with the help of a seed yarn) might possibly be attempted with the use of high speed cine technique. It might appear, at first sight, that the use of high speed cine photography would be more advantageous than still photography. Unfortunately this was not quite true because of the fact that the exposure time of each frame of the cine film was of a much longer duration than that required to freeze the fibre movement. Single flashes of the order of 1 μsec are required but with the cine camera operating at about 6,000 frames/sec, the exposure time would be about 80 μsec/frame. This is about 80 times longer than the duration required to resolve the individual fibres.

The fibres in and near the assembly zone move at very high speeds. For example, when spinning with a $\frac{3}{4}$ in. X $\frac{3}{16}$ in. nozzle at about -25 in. of water, the fibre speed was estimated to be of the order of 1,500 in/sec. Thus during the exposure time of each frame on the cine camera, each fibre would have moved a distance of about 9 inches. This movement of fibres was considered to be definitely too much even to give a blurred picture of the fibres.

When using sub-micro second flashes, the fibres would have moved only about a fibre diameter and, therefore, it would be possible to obtain relatively clear photograph of the fibres. These photographs would assist in the study of the configuration and attitude of fibres during their movement in the vortex tube, although with the use of high speed cine photography, it might have been possible to obtain information on the direction and rate of movement of fibres.

Another difficulty encountered during photography, both still and cine, was that associated with lighting. Specular reflections from the inner and outer surfaces of the Perspex tube gave intense high lights.

13.4. PHOTOGRAPHIC EVIDENCE OF FIBRE FLOW

As already mentioned earlier, it was not possible to resolve clearly the flow of individual fibres by photographic means. The static build-up in tube was used to obtain a photographic evidence of the fibre flow path. When Fibro fibres were allowed to flow in the tube without static elimination for about 15 minutes, a static charge built up in the tube. This charge made the fibres adhere to the tube wall giving a well defined flow path. A photograph of this is shown in Fig. 13.1.

13.5. PHOTOGRAPHIC EVIDENCE OF YARN SHAPE

With the aid of a short duration flash unit,

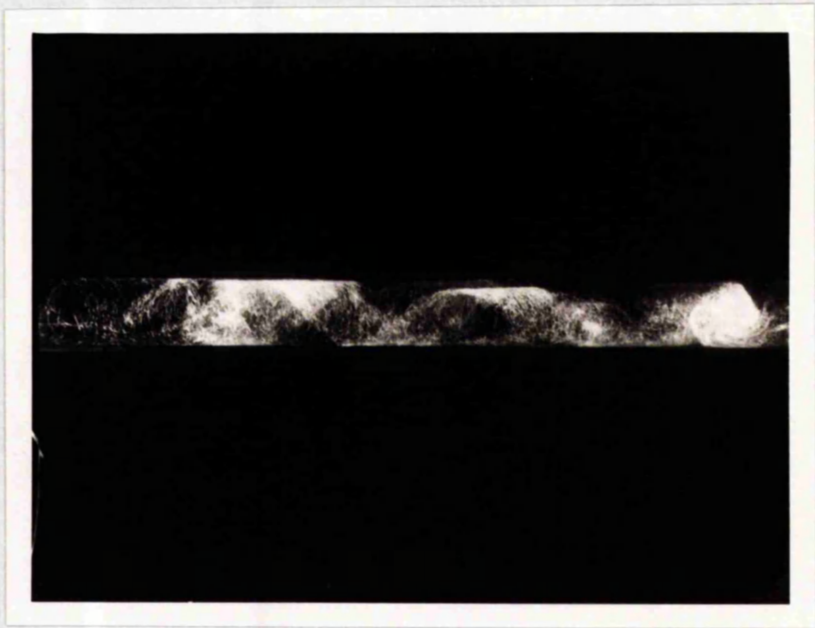


Fig. 13.1.

PHOTOGRAPH OF FIBRE FLOW PATH IN THE VORTEX TUBE photographs of a seed yarn were taken. The shape of the yarn inside the tube was well defined and it was observed to be an approximate helix. It was rather difficult to know whether the observed helix was right-handed or left-handed. This was so because a three dimensional view was reduced to a two dimensional one in the photographs.

Attempts were made to bring to critical focus the yarn lying in the tube wall nearest to the camera so that it would be possible to distinguish the yarn lying in the nearest and farthest walls of the tube. This would have enabledthe exact helical path of the yarn to be determined. Such critical focussing was, however, too difficult to obtain in practice because of the short distance(about 1 in.) involved in separating the nearest and farthest yarn positions in the tube.

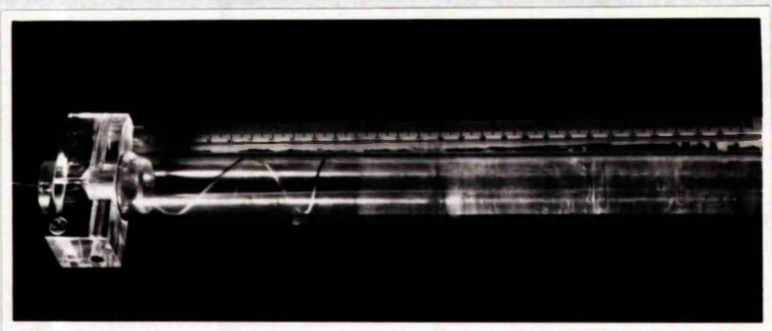
The problem of determining the direction of yarn helix was finally solved by placing a ring tube co-axially with the vortex tube and allowing a seed yarn to move in a narrow annular region between the vortex tube wall and the ring tube surface. Fig. 13.2. shows the photograph of the yarn helix. The helix was found to be left-handed. The position of the tangential inlets in the nozzle used here was such as to produce a vortex flow in the anti-clockwise direction when viewed from the suction end. Thus with this nozzle, the direction of air helix was right-handed and because of this, the fibre path too was right-handed. In fact, the opposition of fibre and yarn helices is an important feature of the air vortex method of spinning yarns.

It was fully realised that the exact shape of the yarn helix could have been affected by the bobbin inside and,

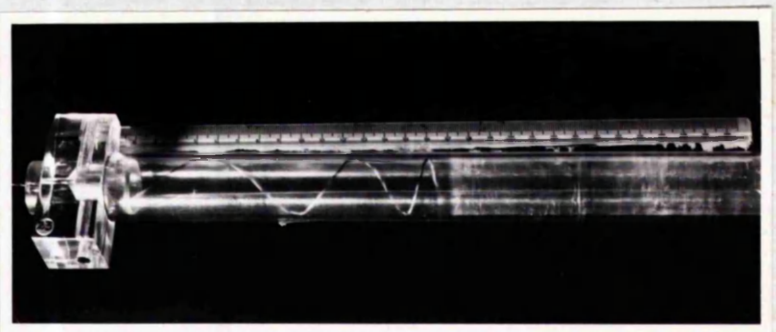
Fig. 13.2.

PHOTOGRAPH OF YARN HELIX WITH A BOBBIN IN THE TUBE

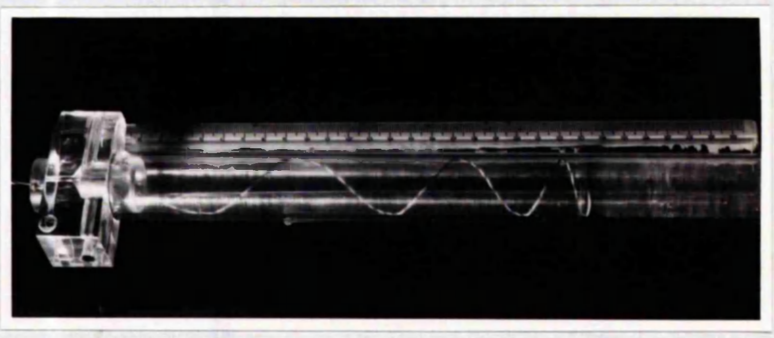
Air pressure - -25 in$H_2O$



Yarn length - 20 cm.



Yarn length - 30 cm.



Yarn length - 40 cm.

Fig. 13.3.

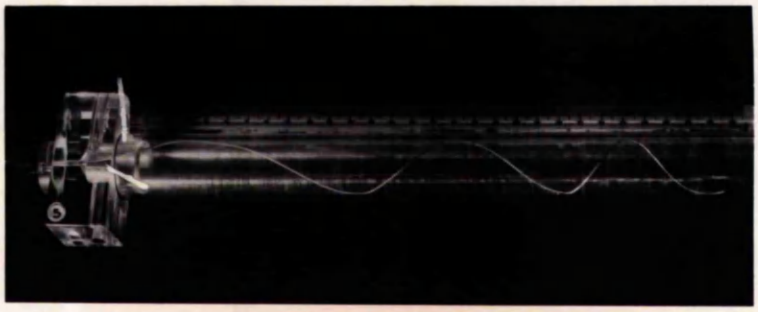
PHOTOGRAPHS OF YARN HELIX WITH DIFFERENT YARN LENGTHS IN THE TUBE therefore, in order to study the exact helical shape photographs of the yarn were taken without any solid body interfering with the air flow.

Fig. 13.3. shows the photographs of the yarn helices with yarn tail lengths of 20, 30 and 40 cm., all at a constant air pressure of -25 in$H_2O$. It may be noted that with the increase in yarn length, the tail end portion of the yarn tends to orient itself in a direction perpendicular to the tube axis. The theoretical reasons for this change in helical angle of the yarn towards its free end is discussed in section 9.3.

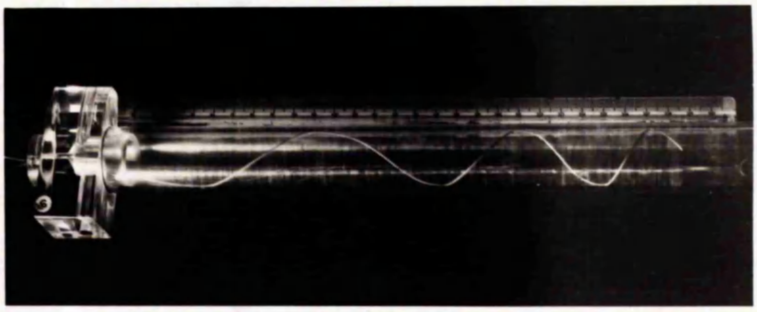
With a seed yarn of constant length in the tube, an increase in the air pressure tightened up the yarn helix. Fig. 13.4. shows the photographs of the yarn helices obtained with a seed yarn (about 295 tex) of constant yarn length (40 cm.) in the tube at the air pressures of -16, -20, -25, -30 and -35 in$H_2O$. The observed tightening up of yarn helix with air velocity supports the theoretical deduction made in section 9.3.

There were occasions when the speed of the seed yarn became unstable especially at high air pressures. This might have been due to the high turbulence in the air flow. The yarn shape too was affected and pulsed with time. During the period of instability, the yarn was seen to come out of contact from the tube wall. This might be due to the formation of snarls in the forming yarn possibly due to overtwisting. Fig. 13.5. shows the photographs of a 36s cotton yarn (16.4 tex) in unstable conditions within the tube. It was observed that finer yarns tended to attain this instability condition at much lower air

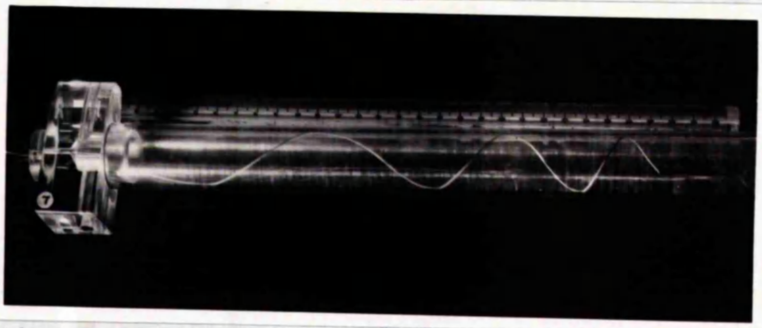
Yarn length - 40 cm.



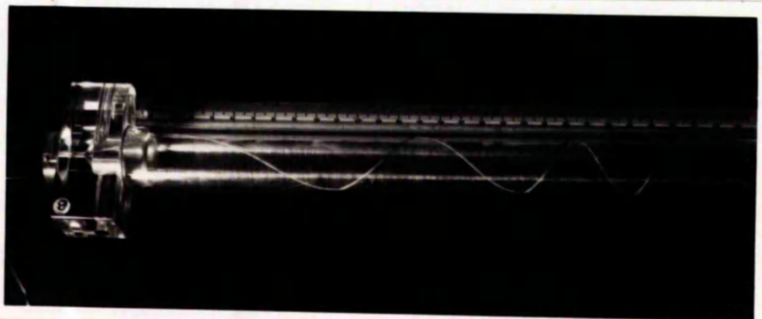
Air pressure - $-16\ inH_2O$



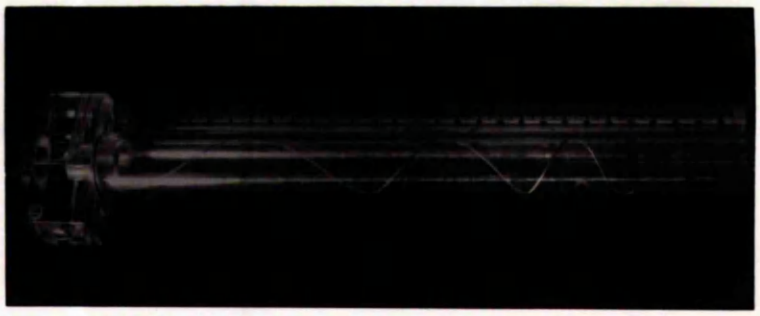
Air pressure - $-20\ inH_2O$



Air pressure - $-25\ inH_2O$



Air pressure - $-30\ inH_2O$



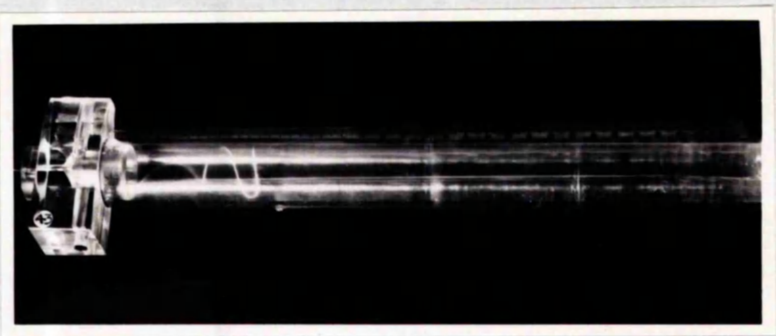
Air pressure - $-35\ inH_2O$

Fig. 13.4.

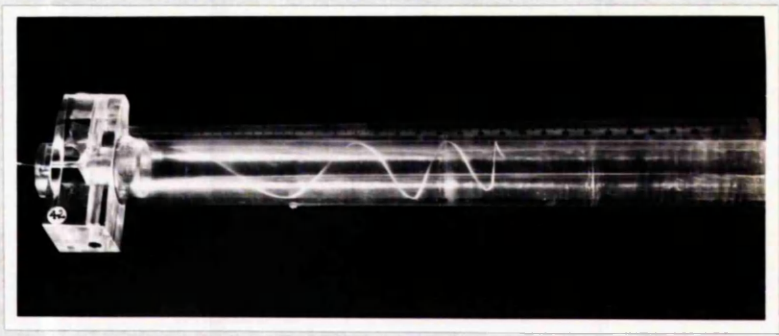
PHOTOGRAPHS OF YARN HELIX WITH DIFFERENT AIR PRESSURES ACROSS THE TUBE

36s cotton count yarn

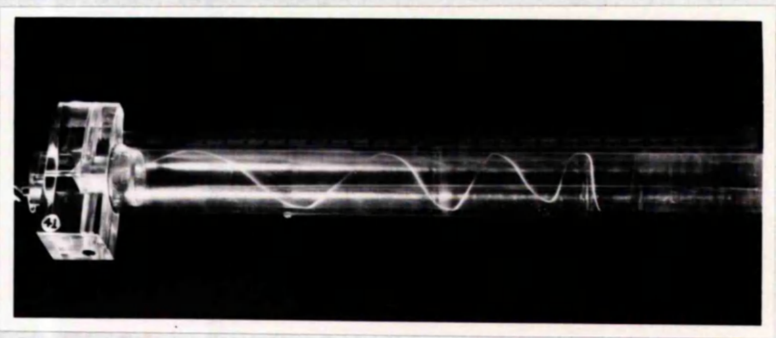
Air pressure - -30 in$H_2O$



Yarn length - 20 cm.



Yarn length - 30 cm.



Yarn length - 40 cm.

Fig. 13.5.

PHOTOGRAPHS OF YARN HELIX IN UNSTABLE CONDITION IN THE TUBE velocities than coarser yarns and this shows that the torsional stiffness of the yarns is a parameter which is consistent with snarl theory mentioned in section 11.5.

## 13.6. STROBOSCOPIC OBSERVATIONS

With the aid of a stroboscope, it was possible to view the forming yarn during the spinning process. However, because of the fluctuations in yarn tail speed, it was difficult to freeze the yarn movement for any long period of time. The cause for these fluctuations in yarn speed were observed visually. Short lengths of yarn tail became detached frequently from the tail end of the forming yarn. This shortened the yarn length in the tube. Perhaps these variations in the yarn length were one of the main causes for the fluctuations in the yarn speed. The yarn speed would also fluctuate if there was any instability in the air flow rate.

## 13.7. SOME OBSERVATIONS FROM HIGH SPEED CINE PHOTOGRAPHY

Generally, fibres seemed to move in tuft forms. Small fibre tufts moved along the tube wall almost in a helical path but occasionally when a large tuft entered the tube, it was seen to move almost in an axial direction (along the tube axis). These tufts were generally not caught by the forming yarn. Even amongst the fibres moving along the tube wall, not all of them became attached to the forming yarn. These fibres contributed to the fibre loss in this spinning method.

When large tufts of fibres did attach to the forming yarn, they formed slubs in the yarn. If these large tufts adhered to the end of the yarn tail, they were frequently observed to break away again later. However the length of the forming yarn was seen to gradually build up, only to suddenly shorten presumably because tufts then broke away. The variation in yarn tail length caused fluctuations in yarn speed. The combined effect of these affected the fibre assembly efficiency, yarn evenness, twist distribution and the breaking tenacity of the yarn.

The fibres in the tufts and the fibres did not seem to be well oriented in the direction of flow, or for that matter, were they oriented in any particular manner. The attachment of a disorganised mass of fibres to the forming yarn is likely to produce a weak and bulky yarn. These fibres contribute to the yarn mass but little to the yarn strength. This is likely to be one of the reasons for the poor breaking tenacity of vortex spun yarns and for the periodic breaks at the end of the forming yarn.

An important observation made from a cine film was the presence of snarls in the forming yarn. The snarled portion portions were found to remain out of contact with the tube wall. This snarling tendency usually occurred at high air velocities only. The effects of the yarn snarls on spinning performance is discussed in section 11.5.

# CHAPTER 14

## STRUCTURE AND PROPERTIES OF AIR VORTEX SPUN YARNS

# CHAPTER 14

## STRUCTURE AND PROPERTIES OF AIR VORTEX SPUN YARNS

### 14.1. INTRODUCTION

The object of this study was to determine the structure of the air vortex spun yarn and relate it to the yarn character.

The structure of the spun yarns is more complex than those of the continuous filament yarns because of the discontinuities at the fibre ends and also because the fibres will partly slip. Even amongst the spun yarns, there exists many differences depending upon the type of spinning system used for the manufacture of yarn. While the woollen or condenser spinning relies mainly on fibre entanglement to give the yarn the necessary cohesion, the more commonly used system such as ring spinning rely on twist to hold the fibres of the yarn together. The yarn structures of break spun yarns, and the air vortex yarn, in particular, seem to be formed by a combination of the build up of twists from layer to layer of yarn and to a certain extent due to the fibre entanglements.

In staple fibre yarns, twist and fibre migration are two factors which are of great importance contributing towards the production of a reasonably strong yarn. Due to twist, frictional forces are created and these are mainly responsible for binding the individual fibres together. The minimum twist needed for a satisfactory cohesion between the fibres depends on the frictional properties of the individual fibres. In addition to the twist, the other fibre properties that determine the yarn character are the staple length, diameter and uniformity. Long staple allows fibre cohesion to be spread over a greater length than short staple. For the same count, finer fibres will accomodate more fibres per diameter than thick fibres. The internal cohesion of the former is better. Uniformity of the fibre diameter permits almost an equal distribution of stress along the length of the yarn.

The frictional forces in the yarn are solely due to the transverse pressures exerted on the yarn when a fibre wrapped in a helical path round other fibres in the yarn is subjected to tension. In addition to friction, fibre migration is considered essential because with migration the variation in radial position of the fibre in the yarn assists the fibres to be gripped at some points along their length, thus giving the yarn certain self-locking characteristics. On the other hand, in the case of no migration, the fibres will be merely wrapped around each other in a series of concentric layers. The fibres on the surface will not be gripped at all and so will not be able to support any tension. Hence they will not exert any inward transverse pressure to grip the fibres in the next layer beneath. This will lead to slippage of fibres when the yarn is put under tension and the yarn will, therefore, be of poor strength. Moreover there is the possibility of the yarn being peeled off in layers when rubbed since the fibres on one layer are not attached firmly to the layer below.

A study of the fibre arrangement in yarn is, therefore, basically necessary to obtain an idea of the yarn structure. Upon the yarn structure depends greatly the yarn character because it is the degree of fibre orientation that determines to a large extent the particular characteristics of a yarn. The yarn character then decides the suitability of that yarn for particular end uses. So with a knowledge of the degree of fibre orientation in the yarn together with the characteristics of the fibre used, it was felt that it should not be too difficult to make a rough prediction of the basic characteristics of that yarn.

The fibre orientation is influenced by many factors such as the amount of twist inserted in the yarn, staple length of fibres used, the nature of the fibre etc, but not the least important factor amongst them is the actual method of spinning adopted. Well drafted ring spun yarns show a high degree of fibre orientation along the major axis of the yarn, i.e., along the yarn length. Such yarns are usually lean, harsh to handle and strong. These can be usefully employed for the production of sewing threads, lingerie fabrics, etc.,. In the case of the condenser spun yarns, the fibres are not so well oriented. This fibre orientation generally accounts for the yarn to appear more 'full' and smoother than ring spun yarns. Such poorly fibre oriented yarns find their end uses where bulk and resilience are needed, such as, in the manufacture of knitted and hosiery goods, fabrics for raising etc.

From the above it appears that the arrangment of fibres in a yarn tends to be controlled by the mechanism of yarn formation involved in any particular spinning method. Furthermore, it is quite evident that the fibre arrangement determines to a large extent the yarn character and consequently its end uses also. Therefore it becomes important to study the fibre orientation in vortex spun yarn not only for the purpose of knowing the yarn character but also, if possible, to gain an understanding of the mechanics of yarn formation inside the tube.

At first sight it appears that the structure of the vortex spun yarn is very much different from that of a conventionally spun yarn. As mentioned earlier, one of the main reasons for this appearance may be found in the nature of spinning employed. In the conventional methods of spinning, say, as in ring spinning, a yarn is formed by twisting a ribbon of fibres emerging from the nip of the front rollers. The twist holds the fibres together forming the yarn. It may be true to say that the fibres issuing from of the roller nip are more or less positively controlled during the time when they are being twisted to form the yarn. The rate as well as the number of twists per unit length in the yarn can be also controlled within reasonable limits.

In the case of the vortex spun yarn, the fibres emerging from the front roller nip are under the direct influence of the air suction from the nozzle. As soon as the fibres are released from the grip of the rollers, they are carried away by the suction into the vortex tube where the yarn is formed. Short fibres get themselves released and then conveyed into the vortex stream a little earlier than the longer ones. Thus the relative positioning of fibres before their release from the rollers tends to be greatly altered during the process of fibre feeding. The random fibre assembly also increases this effect.

The peculiar behaviour of fibres as compared to that in the conventional spinning is caused mainly due to the break in the fibre flow from the feeding system to the spinning system. Moreover the twist in yarn does not appear to be inserted in any positive manner, i.e., the free end of yarn which is twisted is not positively gripped to avoid twist leakage. It has, therefore, not been possible so far to exercise a precise control over the number of twist insertions per unit length of the yarn.

In the air vortex spinner, the collecting surface is composed partly by the stationary tube and partly by the forming yarn. The fibres reaching the stationary tube surface tend to be decelerated due to frictional and pneumatic forces. Such telescopic retardation tends to produce positional disorder. and the fibres tend to become disoriented. Fibre bends and deformation, tangles and tufts will tend to occur. When the fibres on the tube surface come in contact with the forming yarn, the fibres tend to become wrapped onto the yarn surface to form partial layers. Also the fibres caught directly by the yarn will tend to be wrapped on the yarn surface to form additional layers. These two mechanisms of yarn build up proceed on till the required linear density of yarn is obtained. The twisting of the fibre assembly, either by sliding or rolling on the tube wall, will tend to lead to wrap-twist in the yarn.

From the above, it is reasonable to expect that the very different behaviour of fibres during the spinning process and during their assembly into yarn, as distinct from the conventional methods will tend to be reflected in poor fibre orientation and short fibre length contribution in the yarn.

Attempts were made to study the nature of fibre orientation in the vortex spun yarn. Methods adopted for this purpose may be broadly classified as follows:-

(a) longitudinal method

and (b) cross-sectional method.

Both the methods used were "tracer fibre" techniques as given by Morton and Yen[99]. The behaviour of the tracer fibres in the yarn were assumed to be true representative of the whole population of fibres.

## 14.2. TRACER FIBRE TECHNIQUE

A study of the fibre orientation in the vortex spun yarn was attempted by the "tracer fibre" technique. In this method, a small quanity of the raw material (Egyptian cotton) was dyed in as strong a black shade as possible to give a distinctive colour to the dyed fibres. Diffidulty in dyeing was encountered because the fibres were not scoured. It was felt that by scouring the frictional properties of fibres might have changed considerably in which case the tracer fibres would not have behaved in the same way as the bulk of the material. It ought to be mentioned that even dyeing without scouring might have affected the frictional properties of fibres but possibly to a small extent only. However it was not known to what degree the actual spinning was affected by this factor but it was assumed that in every material respect the tracer fibres behaved in the same way as the bulk of the material during the subsequent processes of carding, drawing and air vortex spinning.

The dyed fibre mass was completely dried and then carefully opened by hand to reduce as far as possible the fibre entanglements caused by the wet process of dyeing. A small quantity (about 0.15%) of the dyed fibre was intimately blended with raw Egyptian cotton at the back of a card. Tests carried out on the staple length of the card sliver showed almost a uniform dispersion of the tracer fibres along the width of the Baer Sorter fibre diagram. This indicated that the staple length of the tracer fibres did not suffer any noticeable damage during the carding process. The card sliver was then passed through three passages of drawing for proper blending. The finisher head draw frame sliver of about 1.25 hank (about 0.472 ktex) containing the dyed fibres was fed to the drafting unit of the vortex spinning system. The coloured fibres acted as "tracers" in the body of the yarn spun later on.

After spinning, yarns were examined to show the orientation of the tracer fibres. Attempts were made to observe the longitudinal as well as the cross-sectional views of the tracer fibres in the yarn.

14.2.1. Longitudinal method

A Projection microscope was used for the examination of the tracer fibres present within the yarn, firstly in one plane and secondly in two planes of the yarn. In both these methods, it was essential to use a liquid of a refractive index nearly equal to that of the main body of the yarn so that all the undyed fibres were almost completely optically dissolved but the dyed tracer fibres were clearly visible. For this purpose, the liquid was made by adding about 60% of paraffin liquid and 40% of $\alpha$-Bromo naphthalene, by volume. This liquid mixture was of a refractive index almost equal to that of the yarn body. The refractive index of the mixture was determined with the help by an Abbe's Refractometer. A rectangular glass trunk placed beneath the objective lens of the microscope contained this liquid mixture. With the help of a special attachment, the yarn specimen was mounted inside this liquid at a desired tension.

14.2.1.1. Yarn view in one plane

The tracer was seen clearly against the faint background of the yarn body. The tracer appeared as a wavy line which represented the projection in one plane of a helix, each wave almost always corresponding to one turn or twist.

A clear image of the whole path of the tracer fibre could not, however, be seen due to the thickness of the yarn and also due to the limited depth of field of the microprojector. The whole arrangement of the tracer at any particular focussing was seen only in a hazy manner on the screen of the Projection microscope. Photographs of tracer fibres were taken from the Projector screen.

The loose structure of the yarn tended to allow a displacement of the fibres when the yarn was kept immersed in the liquid for some time.

14.2.1.2. Yarn view in two planes

In addition to the apparatus used in the previous section, it was necessary to use a means by which it would be possible to obtain two images of a yarn on the screen of the Projection microscope. In order to achieve this, a plane mirror was set at an angle of 45° to the vertical inside the trough filled with the liquid mixture. An image of the yarn as viewed from a plane at right angles to the plane of view of the objective was formed in the mirror.

The two images, however, were at different distances from the objective and hence separate focussing was necessary. Therefore it was not possible to obtain, at the same time, both the images of the yarn clearly on the Projection microscope screen due to limited depth of field of the objective. Hence this method was discarded.

14.2.2. Yarn cross-section

The apparatus used in this technique consisted of
(a) a sliding Microtome,
(b) a low power microscope
and (c) a camera mounted on the eye-piece of the microscope.

The procedure adopted to photograph the cross-sections was as follows:-

A specimen of yarn with the tracer was embedded in a suitable mould. This mould was fixed on the platform of a Microtome such that the yarn was in a vertical position. By sliding the platform, a thin slice of the mould was cut off by the sharp stationary knife. Sufficient cuts were made on the mould to bring out the tracer fibre into view. From then onwards, each slice of equal thickness was to be cut off, the cross-section of the yarn brought directly below the objective of the microscope and the image focussed and then photographed.

14.2.2.1. Preparation of specimen

A short length of a specimen yarn kept under a light tension was embedded in a suitable medium. The media that were tried included the following:-

(a) Paraffin wax (Paraplast)
and (b) An epoxy resin (Araldite).

Molten paraffin wax was poured over a short length of the specimen yarn which was kept slightly taut in a rectangular enclosure.

The use of Paraplast as an embedding medium had certain drawbacks. It was not possible to distinguish clearly the exact boundary of the yarn cross-section in the medium. Therefore, as a next step, the wax medium was coloured with black pigments. Although this enabled a distinct view of the cross-section of the yarn and its boundary, it had the disadvantage of penetrating into the inter-fibre spaces of the yarn and staining some of the fibres. This made it difficult to distinguish between the tracer fibre (dyed black) and the stained fibres. Furthermore when the tracer fibres happened to be on the boundary layer, it was practically impossible to identify and distinguish the tracer from the medium.

It was thought that an impregnation of the yarn with an epoxy resin, such as, Araldite, would prevent the penetration of coloured pigments into the inter-fibre spaces of the yarn and the subsequent staining of the fibres. Accordingly, a specimen of the yarn was impregnated with an epoxy resin and it was possible to identify clearly the tracer fibre in the cross-section. However this method had the main drawback that the fibres when sheared were dragged in the direction of cutting. The relative positions of the fibres in the cross-section were, therefore, disturbed.

In the next method, the wax used as an embedding medium was replaced by an epoxy resin, Araldite CY 212, and a hardener, Araldite HY 956, in the ratio of 5:1 and this medium was allowed to set for about 48 hours. This resin mould was much better than all the previous ones tried. Difficulty was experienced in shearing the cross-sections because of the solidity of the mould. It was thought that a diamond grinder would facilitate the cutting of cross-sections without displacing the relative positions of fibres in the cross-section.

A technique of polishing and etching the cross-section, similar to that used in metallurgy, was tried. It was thought that the polishing and etching of the surface of the mould would show the yarn cross-section much more clearly than before.

Fine grinding on the mould was carried out by using a series of emery papers of increasing fineness. Paraffin liquid was used on strips of emery papers to prevent embedding of the emery particles on the grinding surface of the mould. The fine scratches produced by grinding were removed by polishing the ground surface with fine polishing powders, such as, alumina and Jewellers' Rouge on chamois leather. As the polish surface would appear bright without showing any details in the specimen, it was necessary to selectively corrode or etch the polished surface so that the mould or specimen would stand out in relief with respect to each other. Since freshly prepared cuprammonium hydroxide solution dissolves cellulose, this solution was used as an etching agent. The polished specimen was immersed in the etching solution for about 5 minutes. Finally the specimen was rinsed in running water and allowed to dry.

The etching was only partly successful. However it was felt that a fully etched surface might be obtained if the surface of the mould was kept immersed in the etching solution for a longer period.

It is considered relevant to mention the method adopted by Senturk[100] in the preparation of specimens for cross-sections. His method was basically similar to the one described above. He also used the epoxy resin as the embedding medium. The specimen was polished by carbon silicate papers of different grades (200 to 600). Instead of etching, the resin was stained with a dye, Durazol Brilliant Blue. This method was relatively simple and it gave good results. The sample thickness was about $30\mu$ to $60\mu$.

## 14.3. PHOTOGRAPHIC VIEWS OF THE YARN STRUCTURE

### 14.3.1. Longitudinal view

Photographs of the arrangement of the tracer fibres lying longitudinally within the yarn are shown in Fig.14.1. Although not much information on yarn structure could be obtained from a study of these photographs, nevertheless they did throw some light on certain aspects of yarn formation. (A nozzle producing rolling twist was used in spinning).

### 14.3.2. Inferences from the longitudinal views

It could be clearly observed in both the specimens that the fibres are 'S' twisted. This implies that the yarn is also S-twisted. In both the photographs, the tracer fibres are looped at one of their ends. The formation of the loop may be explained as follows:-

Let the 'leading end' of a fibre be defined as the fibre end entering the nozzle first when it is released from the front roller nip. The leading end as soon as it comes in contact with the forming yarn attaches itself onto the yarn body. At the point of attachment, the fibre is quite likely to coil itself around the forming yarn.

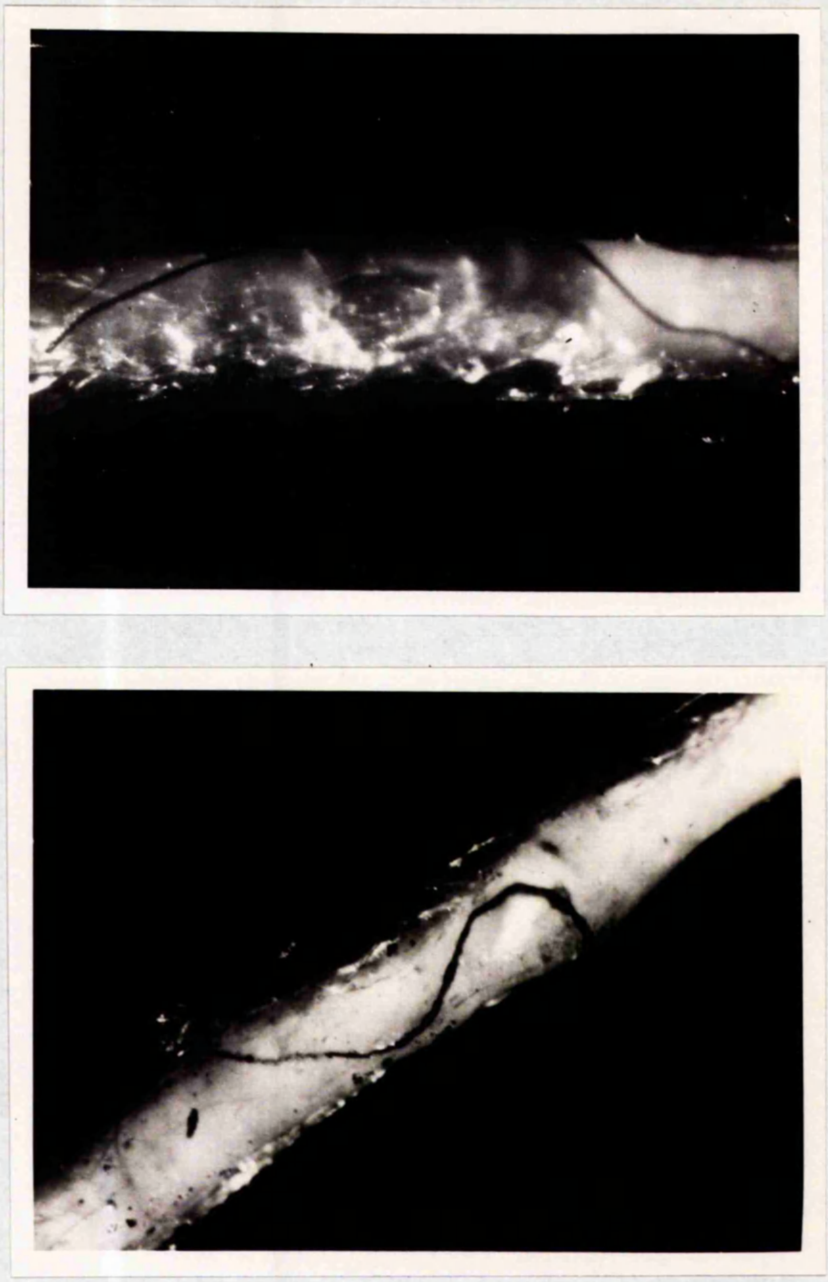


Fig. 14.1.

PHOTOGRAPHS OF A TRACER FIBRE IN THE VORTEX YARN

The rest of the fibre length may then bend over at the place of attachment, thus forming the loop so that the trailing end lies downstream. This trailing end may then twist itself around the forming yarn in fairly coarse pitched helix.

The different fibre configurations that might occur due to the attachment of fibres to the yarn are discussed in section 10.3.

It was felt that a short length of a coloured yarn introduced along with the fibres into the vortex stream might indicate the path followed by assembling particles in the vortex spun yarn. The behaviour of a yarn in the vortex stream would not be the same as that of a fibre because of the greater mass of the yarn and different drag coefficient. Nevertheless it would assist in obtaining a general idea of the twist structure in the yarn.

Short lengths of coloured yarns were introduced into the vortex stream along with the fibres. The leading ends of these yarn pieces were marked. It was found that these coloured yarns were twisted around the main body of the yarn. Photographs of these twisted yarns are shown in Fig. 14.2. It could be clearly seen from these photographs that the coloured yarns were twisted around the yarn body in Z direction. Incidentally, the nozzle used for spinning this yarn was one producing sliding twist in the yarn - two $\frac{1}{4}$ in. diameter tangential inlets. The twists appeared to decrease progressively towards the free end of the yarn, thus varying the twists per unit length. The leading end of the yarn was looped to about 180° and

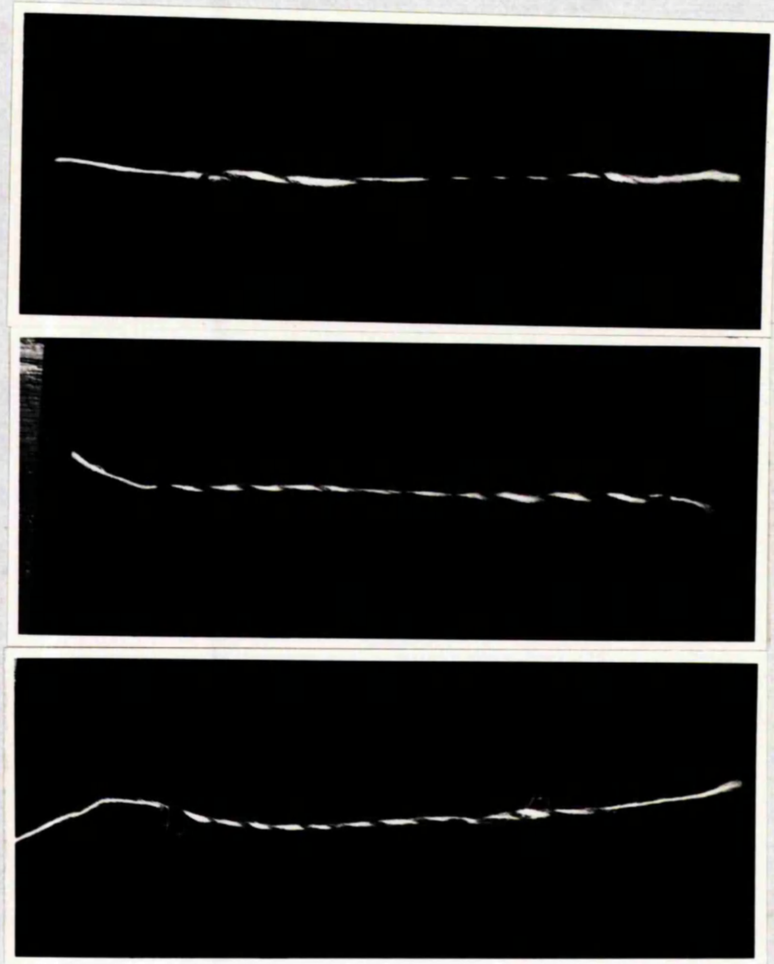


Fig. 14.2.

PHOTOGRAPHS OF SHORT LENGTHS OF COLOURED YARNS TWISTED AROUND THE VORTEX YARN IN THE TUBE it was observed that, at times, the extra length of the loop twisted around the yarn body again. There were also some 360° loop formations at different positions of the yarn.

It could be also noticed that the coloured yarns were usually twisted around the surface of the yarn body. This indicated that the vortex yarns were formed by the building up of different layers of fibres, one over the other, without much inter-twining.

14.3.3. Cross-sectional views

Photographs of the cross-sections of vortex yarns spun directly from a card are shown in Fig. 14.3. The fibre used in spinning was Fibro (viscose rayon) of 1 7/16 in. staple length and 1.5 denier. The cross-sections have been taken at random from yarns of different linear densities. The cross-sectional photographs were obtained from Senturk[100] because these photographs showed the fibre arrangement much more distinctly than those taken by the author.

14.3.4. Inferences from the cross-sectional views

The fibres tend to form local dense regions. This indicates that the fibres travel and assemble in tuft forms. At the outer layer, the fibre packing tends to be rather open. Perhaps these fibres represent the protruding fibres and the extent of this will be reflected on yarn hairiness. It may be that these fibres are not well bound with the inner core. The inner core is densely packed and the photographs suggests that the yarn core is highly twisted. Moreover the variation in the oblique position of the fibres in the cross-section also indicates the variation of twist

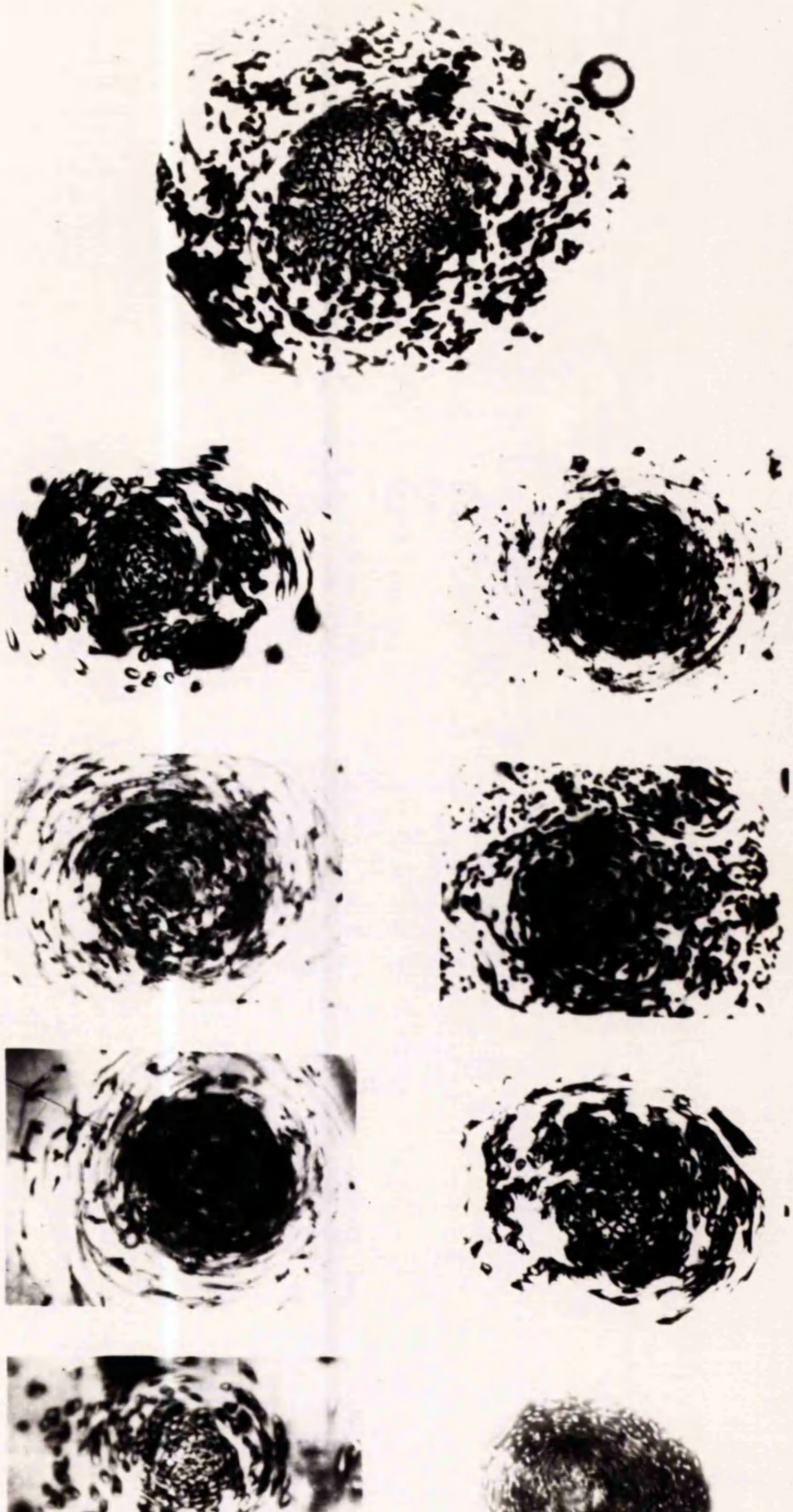


Fig. 14.3.

PHOTOGRAPHS OF CROSS-SECTIONS OF

VORTEX YARNS

distribution from the inside to the outside of the yarn. In this case, it appears that the central region of the yarn is more highly twisted than the outer layer. The explanation for the variation in twist distribution may be seen in the mechanism of yarn formation.

As the forming yarn is twisted by the vortex, the fibres conveyed into the air stream tend to wrap themselves around the forming yarn in layers. The addition of each fibre layer imparts an extra element of twist to the yarn beneath. Thus the twist per unit length seem to be greater inside than outside of the yarn. This is precisely the reason for experiencing difficulty in determining twists by the conventional methods. In fact, even after the twists in the outer layers are removed, it is observed that there was still some amount of twist in the next layers.

## 14.4. CONCLUSIONS

The strength of the conventionally spun yarn depends not only on the number of twists per unit length but also on the fibre arrangement within the yarn. Inter-twining of the fibres of the different layers helps to bind the layers firmly and this produces a strong yarn. In the case of the vortex spun yarns, such intertwinings seem to be less common with the result that the strength of these yarns is low and the yarn is much softer than normal. It also explains the greater liability of vortex spun yarns to fibre slippage when under tension.

It seems likely that fibre slippage and disorganised fibre orientation will contribute to breaking elongation of vortex yarns when under tension. It is likely that these yarns would have a higher percentage breaking elongation than that of conventionally spun yarns. It was found experimentally that the percentage breaking elongation for the vortex yarns usually ranged between 8 and 11% as compared to 4 and 6% in the conventionally spun yarns of the same twist factor as the vortex yarns. The higher percentage breaking elongation may not necessarily mean higher elastic recovery. It may well be that these vortex yarns would be less elastic once they have been subjected to tension because the fibres may become permanently displaced from their original positions.

A detailed work on the structure and properties of break spun yarns including that of air vortex yarns was taken up by Senturk[100]. Hence it was felt that some of his observations might be included here.

It was observed by Senturk that at low extension limits, the vortex yarn possessed twice as much elastic recovery as an equivalent ring spun yarn. Up to 6% extension, the elastic recovery of vortex yarn was higher than ring spun yarn. The figures for vortex and ring spun yarns were 42% and 38% respectively. As the limit was increased, the elastic recovery tended to fall sharply indicating permanent deformation of fibres in the yarn structure.

In the case of vortex spun yarn, the percentage of fibre length contribution was very low. The following figures, given by Senturk, may be of interest:-

| Type of yarn | Fibre length contribution |
|---|---|
| Ring spun yarn | 87.2% |
| Drum spun yarn | 74.7% |
| Air vortex spun yarn | 65.5% |

The lower fibre length contribution results in a weak yarn. These yarns are about 30% weaker than ring spun yarns.

The orientation of the fibres in the vortex and ring yarn is also given below:-

| | Vortex yarn | Ring yarn |
|---|---|---|
| Straight fibres | - 11.4% | - 49.9% |
| Folded fibres | - 58.8% | - 41.7% |
| Entangled fibres | - 29.8% | - 8.4% |

Entangled fibres constituted about one-third of the total fibre population. The interlocking of fibres due to entanglements will tend to contribute, to some extent, to yarn strength. However extreme cases of fibre entanglement will tend to provide improved interlocking of fibres. This might enhance the strength of the yarn still further. This possibly explains the relatively high breaking tenacity of yarns with poor evenness mentioned in section 5.5.2.3. On the other hand, the low breaking tenacity of extremely even yarns might have been due to a lack of fibre migration.

From the foregoing, it appears that the combination of poor fibre length contribution, a poor fibre migration and to a less extent the fibre entanglement might be responsible for the generally low strength of the vortex yarns. The high elongation of vortex yarn might be attributed partly to the low twist factor that are normally obtained in this spinner and partly due to the folded and entangled fibres which might act as an extensible components of the system.

The fibre arrangement in the vortex yarn is not well oriented. Consequently, this yarn is bulkier than a ring spun yarn. It is estimated[100] that the air vortex yarn is from 15% to 20% more bulky than the ring spun yarn. This greater bulk may be considered as an advantage because, for a given linear density of yarn, the fabric made from air vortex yarn is likely to possess a better handle and cover than those produced from ring spun yarn. However these fabrics will be weaker because of the lower yarn strength. In this context, it might be relevant to include the findings of Chandarana[10]. The fabric woven with vortex spun weft gave lower values of tensile strength (weft way), tearing strength (both warp way and weft way) and bursting strength. However the fabric was smooth and soft to handle and looked more resilient.

Mishra[98] observed, during an investigation of the cross-section of blended yarns spun in air vortex spinner, that the component fibres forming the blend were intimately mixed with each other. He further observed that a blend composed of natural and man-made fibres gave a more compact yarn structure than a blend composed of man-made fibres only. Perhaps this suggested that cotton fibres tend to improve the fibre density in the yarn. A highly crimped fibre, such as Courtelle, showed a very open structure and this might be due to the crimpy nature of the fibres. A comparison of two yarns, one made from 3 denier nylon and the other from 1.5 denier nylon, showed that there was no noticeable difference in the packing density of the inner layers although the outer layers of 3 denier nylon yarn were less densely packed than those of 1.5 denier nylon yarn. This difference might be attributed to the difference in fibre fineness.

# SECTION V

# CHAPTER 15

# SUMMARY AND CONCLUSIONS

# CHAPTER 15

## SUMMARY AND CONCLUSIONS

### 15.1. THE RING SPINNING SYSTEM

The ring frame of today has almost reached its pinnacle of achievement both in terms of quantity and quality of production. The economic and technical limitations of the ring spinning system are now fully understood. It is inconceivable from where any major break through in the ring spinning will come.

### 15.2. BREAK SPINNING

Break spinning which is still in the stages of development offers scope of producing reasonably good yarns at high production rates. The yarn produced can be directly wound on to as large a package as desired. Of the different types of break spinners, the rotor spinner has already reached the stage of commercial application. Its production rate is about 3 times higher than that of the ring frame. It produces a good regular yarn but the yarn strength is about 20% less than that of the ring spun yarn. The rotor spinner is a high capital cost unit. In another form of break spinning, viz., in air vortex spinning, the spinning tube is extremely simple in construction and also in operation because of the absence of any mechanically moving parts. Again, because of this, this spinner is likely to be a low capital cost unit. From the capital cost point of view, the air vortex system is really attractive. This system, therefore, seems to have some potential in the process of yarn manufacture.

## 15.3. THE PRESENT RESEARCH

The present research is a continuation of the work carried out by Hirway on the air vortex spinner. A preliminary study was concerned with a critical assessment of the spinner. This led to modifications in the spinning tube design parameters.

## 15.4. THE PRELIMINARY STUDY

The modifications made to the spinning tube included alterations in the nozzle and tube bore sizes, changes in the positioning of the tangential inlets, the use of fibre guides and in smoothing of the flow transition from the nozzle to the tube. However the most important modification was concerned with the change in the spinning draft ratio. The control of static charges also played an important role in the improvement of the spinning performance. With the modified spinning tube worked under conditions of static control, the best performance of the tube was obtained at the spinning draft ratio of 0.9. A comparison of the spinning performances obtained before and after these modifications showed that

(a) the yarn take-up rate increased by about a factor of five,

(b) the fibre assembly efficiency was increased by about 200%,

(c) the yarn regularity was improved by about 50%

and (d) the breaking tenacity of the yarn improved about six folds.

## 15.5. EXPERIMENTS TO OPTIMISE THE SPINNING TUBE DESIGN

Experiments were performed to optimise the spinning tube design geometry to obtain a still further improvement in the spinning performance. It was found to be essential that the tube material should be prone to static electrification, because the presence of static under controlled conditions improved the working on the tube. Metallic tubes which did not produce static failed to produce a good yarn. The use of the tube materials which have a high coefficient of kinetic friction with the yarn material also produced poor yarns. Rough surfaces in the tube wall caused bad fibre assembly and this led to greater yarn irregularity in the yarn. For the purpose of research, the tube material should enable viewing(as well as taking photographs) of the yarn movement. At the same time, the material should not be as fragile as glass and it should have good machinability. Clear Perspex satisfied all these requirements and so, it was chosen as the spinning tube material.

A tube of $\frac{3}{4}$ inch bore gave the best spinning performance when spinning fibres of 1 7/16 in. staple length. The intervention of abrupt transition in the material flow in the spinning tube greatly affected the flow behaviour and this resulted in poor spinning.

The effects of tube transition due to

(a) changes in the cross-section of the tubes,

(b) bends in tubes

and (c) branches in tubes have been considered in detail. In addition to pressure losses which occur in all these sorts of tube transitions, the air and fibre flows as well as the yarn rotation were found to be greatly affected to the detriment of spinning. Sudden enlargement or contraction and sharp bends in the working section of the spinning tube should be avoided as far as possible. Where step transitions are found necessary, a gradual taper must be used as an alternative. A smooth bend at a sufficiently long distance from the nozzle end may not interfere the spinning process. The least branching of tubes should be used but where tube branching occurs it would be preferable to maintain a smooth streamline flow. A short length of the tubing reduces the friction losses in the air flow and this would reduce the power consumed by the spinner. Step transitions can be avoided by designing the nozzle as an integral part of the spinning tube.

A convergent taper tube was found to give slightly better spinning performance than a divergent tube. However the cylindrical tube still yielded the best results.

Of the different cylindrical inlet sizes experimented upon, those of $\frac{1}{4}$ in. proved superior to the others. Efforts made to increase the tangential and axial components of vortex flow by various designs of the inlets in order to improve the spinning performance proved to be futile.

The performance of the spinning tube seemed to depend on a proper distribution of air flow across the inlets. A reasonably wide spread of the air and fibre flow was obtained with the use of slit inlets. Amongst these designs, the $\frac{3}{4}$ in. X $\frac{3}{16}$ in. inlet gave the best spinning performance. The fibre assembly efficiency reached 95% and the yarn quality had also improved. The even distribution of fibres over a wide fibre helical path facilitated the fibre attachment. An important outcome of the use of the slit inlets was the reversed twist found in the yarn. This reversed twisting mechanism offers a vast potential for obtaining a high rate of twist insertion and thus the discovery of this mechanism was considered to be a step forward in the design of the vortex spinner.

The amount of reversed twisting depended mainly on

(a) the design geometry of the spinning tube

and (b) the friction between of the yarn and the tube wall.

A paradox seems to exist in the vortex spinning. For an efficient reversed twisting of the yarn, the frictional coefficient between the yarn and the tube wall must be high but for an efficient fibre assembly the frictional coefficient must be low. Torque tests have proved that for a given hydraulic mean length of the inlets, the rolling torque obtained was much higher than the sliding torque. The design of the yarn exit hole(shape and diameter) also influenced the torque introduced into the yarn. Up to the medium range of counts, say, up to 20s c.c., a $\frac{1}{4}$ in. axial entry was the best. Above this count range, a $\frac{1}{8}$ in. dimension was preferred.

## 15.6. TORQUE TESTS

In order to obtain the maximum torque in the yarn,

(a) a control over the static charges was essential,

(b) air pressures of the order of -25 in$H_2O$ to -35 in$H_2O$ were necessary,

(c) an optimum length of forming yarn was required

and (d) the optimum geometry of the spinning tube was also required.

However there was a limit to the maximum torque input. The unrestrained open end of the yarn allowed the leakage of any additional torque inserted above a certain limit. This limit seemed to depend on the torsional stiffness of the yarn, the nature of the yarn material etc. During spinning, the twist constants of yarns with a given fibre remained fairly constant for different linear density of yarns. However the maximum twist constants varied with the type of fibres used. Fibres with high coefficient of friction tended to give high twist constants. The nature of the fibre surface might have also contributed to this behaviour.

The net torque in the yarn is the resultant of the sliding and rolling torques. The predominant of the two usually determines the nature of the torque. A short length of the forming yarn consistent with good fibre assembly efficiency would be the ideal condition for obtaining maximum rolling torque inputs to the yarn. A large tube bore and a large axial entry also increased the torque insertion rate.

Under almost identical working conditions, the torque due to rolling was more efficient than that due to sliding. The design and geometry of the nozzle part of the spinning tube controlled the nature of torque in the yarn. The slit length determined the type of torque (sliding or rolling) and the slit width the amount of torque. For the spinning tube of $\frac{3}{4}$ in. bore, the transitional stage from one type of torque to another was reached between $\frac{1}{2}$ in. and $\frac{3}{4}$ in. slit lengths. The change in the torque direction was affected by the change in the yarn length. Shorter yarn lengths produced high rolling torques and longer yarns gave sliding torques. Thus it was found experimentally that yarn lengths of about 20 cm. gave the maximum rolling torque. On the other hand, the maximum sliding torque was obtained with yarn lengths in the region of 30 cm. to 40 cm. An open helix with a short yarn length encouraged the yarn to roll and a tight helix with long yarn length produced twist by sliding of the yarn.

15.7. TENSION MEASUREMENTS

Yarn tension was found to be a linear function of the yarn length and also of (air pressure difference across the tube)$^{\frac{1}{2}}$.

Yarn tension was proportional to the linear density of yarn and also to (yarn speed)$^{2}$.

The values of the yarn tension during spinning were quite low even at high yarn take-up rates. Thus the yarn tension did not seem to be a limiting parameter in the vortex spinning as it is normally in the ring spinning.

15.8. AIR FLOW AND POWER CONSUMPTION

The volume rate of air flow was measured with a venturi meter for the different spinning tube designs when working with different air pressures. The power consumed by the spinning tubes under these conditions were calculated. The power requirement of the vortex spinner is high but this should not be considered as a serious drawback because the economics of this system, as in any other system, also, is governed by the eternal triangle of capital, power and labour costs. The air vortex system would seem to score over other conventional systems mainly because of the low capital cost of the spinner. It is also possible to make it still more economical applying the vortex spinner nearer to early stages of preparatory processes.

15.9. THEORY OF AIR FLOW

The air flow in the vortex tube was considered in some detail. The air flow path was approximately helical in the tube. The effects of the maximum air velocities at the annular region near the tube wall are discussed.

The temperature effects due to high rates of air flow were also considered.

15.10. THEORY OF FIBRE FLOW

The effects of different forces acting on the fibres have been analysed. The velocity of a fibre is always less than that of air in the tube. The retarding forces on the fibres due to solid friction and static charges tend to result in a telescopic packing of the fibres on the tube surface and this will tend to lead to the production of an irregular yarn. Once again, there is a paradox in vortex spinning. If, in order to avoid the ill effects due to these retardation forces, the forces were made to move the yarn away from the tube wall then this will result in a poor fibre assembly. Thus from the point of view of the fibre flow, the contact of the fibres with the tube wall is detrimental to good spinning but this contact with the tube wall is essential for a proper fibre assembly.

A convergent tapered tube might reduce telescopic retardation of fibres by causing the leading ends of the fibre to accelerate under the influence of the pneumatic forces in the tube. The conservation of flow would accelerate the air velocity in the tapered section of the tube. However the results obtained with spinning in a convergent tapered tube were not superior to those obtained with a cylindrical tube.

The presence of static charges had some beneficial effect on the yarn formation. Due to these charges, the attitudes of the fibres might be conducive to an efficient fibre capture which leads to good fibre assembly.

## 15.11. THEORY OF YARN MOVEMENT

The yarn shape was found to be approximately helical with the pitch of the helix decreasing towards the suction end. A theoretical explanation of this pheneomenon is included. The helix of the yarn shape is opposed to the air and fibre helices but the direction of yarn rotation is in the same direction as that of the vortex flow. An open helix encourages the yarn to roll on the tube wall and a tight helix favours the production of sliding twist in the yarn.

## 15.12. THEORY OF FIBRE ASSEMBLY

The formation of the yarn is discussed at some length and the various possibilities that might arise from the different fibre configurations at the time of attachment were considered. There are two forms of fibre assembly occurring in the vortex tube. The forming yarn can collect the fibres from the tube surface or the fibres can attach to the forming yarn. The intersecections of the yarn trajectory and the fibre path are the places where the fibre assembly takes place. Due to the decreasing population of the fibres attaching at every subsequent intersection point, the forming yarn is tapered. The end of the taper is formed at the point where the tension in the forming yarn exceeds the cohesive forces binding the yarn together.

Fibres usually tend to follow the curvilinear path along the tube wall but large tufts are more likely to proceed axially in the tube. Attachment of these tufts will form slubs in the yarn. They are also likely to cause breaks when they become attached to a weak portion of the yarn tail. The fluctuations in the yarn speed are due to the length variations in the forming yarn.

## 15.13. FURTHER TESTS TO OPTIMISE THE SPINNING TUBE

An air pressure difference across the tube of -25 in$H_2O$ was found to give a good compromise between the fibre assembly efficiency and the yarn properties. Up to a certain yarn take-up rate, the fibre assembly efficiency remained fairly constant. Above this limit which varied with the nature of the fibre used, the fibre assembly efficiency deteriorated sharply.

No rigid relationship could be established between the staple length of the fibres used and the bore of the spinning tube. A tube of $\frac{3}{4}$ in. bore accomodated the fine and medium-stapled cottons and other fibres but with short-staple fibres the tube bore had to be reduced to $\frac{1}{2}$ in. Wool and jute fibres which were about 4 in. to 6 in. long could not be spun well in either the $\frac{3}{4}$ in. or 1 in. tube. The lap length of the fibre seemed to decide the minimum tube bore that can be used.

## 15.14. PHOTOGRAPHY IN VORTEX SPINNING

It was difficult to resolve the fibres as individuals in the photographs taken with short duration flashes of about 5 msec. During the flash duration of, say, 1 msec, a fibre moving with a velocity of, say, 1500 in/sec would have travelled a distance of 1.5 in. This is equivalent to about 1000 fibre diameters. For a 1 $\mu$sec flash the fibre would travel 0.0015 in. which is about one fibre diameter. Thus to obtain reasonably clear pictures it is necessary to use sub-microsecond flashes. With the flash equipment used, it was not possible to take clear photographs of the fibres in the tube.

A simple way of photographing the fibre flow path was to allow the spinning tube to become highly charged. The fibres then adhered to the tube wall along the fibre flow path. Photographic evidence of the fibre path is included.

It was relatively easy to obtain photographs of the yarn helix in the tube. It was observed from these photographs that the helix tightened towards the free end of the yarn.

Stroboscopic viewing of the yarn helix during spinning showed that the yarn speed fluctuated greatly. High speed cine photography revealed the causes of these fluctuations. Short lenghs were observed to break away from the forming yarn tail at infrequent intervals. The snarling of the forming yarn during spinning was also observed from the cine film. This snarling tendency made the yarn at that portion to leave the tube wall and, in that zone, there could be little or no capture of fibres by the yarn.

15.15. STRUCTURE AND PROPERTIES OF THE VORTEX SPUN YARN

The structure of the vortex yarn was found to be entirely different from that of the ring yarn. About a third of the fibres in the vortex yarn were entangled and more than half were folded. Such fibre configurations reduced the effective staple length of the fibres. This shortening of the effective staple length is one of the main causes for the poor strength of these yarns. Again, due to the disorganised fibre arrangement the yarn was more bulky than ring yarn. The folds in the yarn structure acted as extensible components and, therefore, this yarn was more extensible than the ring yarn. Due to the poor fibre migration, the fibres were permenently displaced in relation to each other at high extensions. The elastic recovery of this yarn at up to 6% extension compared well with that of the ring spun yarn but above these limit, permanent deformation in the yarn structure occurred.

The poor strength of these yarns is due to a combination of low fibre length contribution, poor fibre migration and low twists per unit length.

Longitudinal views of tracer fibres in the yarn showed that hooks were usually formed at one end of the fibres. Cross-sectional views showed that the fibre packing density was higher at the inner core than at the outside. These photographs suggested that the inner core was more highly twisted than the outer layers.

The 'full' and resilient nature of the vortex yarn gives an improved cover to fabrics made from it. Fabrics and makes these also smooth to handle. The vortex yarns appear to be best suited for those specific end uses where the handle of the fabric is more important than its strength.

## 15.16. GENERAL CONCLUSIONS

Spinning yarns by means of air vortex is mechanically simple. Good yarns have been produced at yarn take-up rates of up to 25 m/min. A perfected system of air vortex spinning should be capable of operation without highly trained personnel. The low capital cost of the spinners should incur small interest charges on the lower capital investment. This system might become practical for the manufacture of yarns where the strength is not of primary importance. As it stands today, the air vortex system is felt to be complementary and not directly competitive with other systems of break spinning.

## 15.17. SUGGESTIONS FOR FUTURE WORK

It is felt that the present research has made an attempt to investigate certain aspects of air vortex spinning. Much work still remains to be done in order to obtain a complete picture of this system as a whole. The following are some suggestions for future work in this field of research.

(a) Particular attention should be paid to the fibre feed arrangement to the vortex spinner so that the fibres are presented as individuals rather than as tufts. It is also necessary that the fibres should be in a well-oriented manner at the time of fibre attachment to the forming yarn. A combination of a miniature taker-in type opening device with a roller/apron drafting apparatus should be attempted. The fibres should be fed into the vortex spinner from the roller nip of the drafting apparatus.

(b) It would be interesting to know if the feeding of fibres simultaneously through both the tangential inlets of the spinning tube would have any effect on the yarn structure.

(c) It would be desirable to obtain additional knowledge on the mechanism of fibre assembly in the tube. It might be possible to obtain photographic evidence of fibre assembly mechanism when spinning long fibres because the use of large tubes and long, coarser fibres might facilitate a clear resolution of photographs, especially when the air flow rate is maintained at the minimum consistent with good yarn formation.

(d) Spinning of long fibres (over 4 in. long) may be tried with vortex tube bores of 2 in. or larger sizes, taking care to avoid any step transitions in the tube.

(e) Since the crazing of the spinning tube gave increased twist insertion rate, it would be desirable to investigate the optimum degree of tube crazing to produce the maximum twist insertion rate consistent with good fibre assembly.

(f) The fibre loss in the vortex spinning was considerably reduced to about 10% to 15% at yarn take-up rates of up to 20 m/min. It is essential that the waste should be still further reduced. Since this fibre loss is recoverable, a process of recirculating the waste fibres into the spinning system may also be adopted. For instance, if the vortex spinner is applied to the finisher card of a tandem carding arrangement, then the waste fibres may be arranged to join the feed to either the breaker or the finisher card.

(g) One of the causes for the low strength of the vortex yarn is attributed to the poor fibre migration. It would be worthwhile to investigate if the desired migration of fibres could be brought about by the processes, such as, needle-punching the yarn or by subjecting the yarn to a low drafting. The drafting and needle punching may introduce a certain degree of interlocking of the fibres.

(h) Spinning of thermoplastic fibres with the use of pre-heated air may be attempted to find if the fibres can be ... heat set during spinning.

# APPENDIX A

## TABLE A.5.1.

Spinning Draft Ratio - 0.83

Nozzle - 2 x 1/4 in. dia. inlets    Vortex Tube - 1 in. dia.

| Yarn Take-up Rate (m/min) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 0.5 | 73.2 | 47.4 | 12.2 | 6.7 | 9.1 | 45 |
| 0.8 | 81.6 | 42.8 | 10.2 | 7.3 | 9.0 | 67 |
| 1.2 | 87.8 | 36.5 | 10.1 | 7.3 | 9.6 | 72 |
| 2.8 | 92.6 | 34.8 | 11.6 | 6.7 | 9.9 | 47 |
| 4.4 | 91.8 | 33.6 | 12.8 | 6.3 | 9.8 | 47 |
| 5.6 | 95.1 | 33.5 | 12.9 | 6.2 | 10.1 | 37 |
| 7.1 | 93.2 | 34.3 | 12.5 | 6.2 | 9.4 | 35 |
| 8.1 | 90.1 | 36.7 | 12.6 | 5.5 | 9.6 | 24 |
| 9.0 | 86.8 | 38.8 | 13.0 | 6.5 | 8.9 | 17 |
| 10.0 | 84.3 | 40.4 | 14.6 | 5.3 | 9.1 | 28 |
| 12.0 | 83.0 | 40.5 | 16.1 | 5.7 | 9.2 | - |

## TABLE A.5.2.

Spinning Draft Ratio - 0.83

Nozzle - 2 x 1/4 in. dia. inlets    Vortex Tube - 1 in. dia.

| Yarn Take-up Rate (m/min.) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) |
|---|---|---|---|
| 2 | 34.8 | 10.8 | 6.8 |
| 4 | 33.5 | 12.8 | 6.3 |
| 6 | 33.5 | 12.8 | 6.2 |
| 8 | 36.5 | 13.5 | 5.6 |
| 10 | 40.5 | 14.5 | 5.3 |
| 12 | 40.5 | 16.0 | - |

TABLE A.5.3.

Spinning Draft Ratio - 0.91

Nozzle - 2 x 1/4 in. dia. inlets   Vortex Tube - 1 in. dia.

| Yarn Take-up Rate (m/min.) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 0.5 | 75.9 | 39.9 | 12.1 | 8.6 | 9.6 | 75 |
| 0.8 | 84.2 | 34.8 | 12.1 | 6.8 | 9.4 | 88 |
| 1.9 | 84.1 | 35.6 | 12.9 | 7.5 | 9.6 | 57 |
| 2.8 | 83.9 | 35.3 | 12.2 | 7.1 | 9.2 | 49 |
| 4.4 | 82.0 | 35.9 | 12.8 | 6.3 | 9.4 | 42 |
| 5.5 | 85.2 | 32.6 | 13.1 | 5.4 | 9.3 | 36 |
| 6.3 | 87.8 | 32.3 | 13.1 | 6.1 | 9.4 | 34 |
| 8.0 | 88.5 | 33.4 | 13.4 | 6.0 | 9.7 | 31 |
| 9.0 | 85.6 | 34.1 | 13.2 | 5.9 | 9.8 | 24 |
| 10.1 | 91.4 | 31.8 | 13.2 | 5.0 | 9.5 | 15 |
| 11.2 | 91.4 | 31.3 | 14.7 | 4.8 | 9.6 | 26 |
| 12.4 | 82.3 | 36.3 | 14.1 | 5.0 | 9.3 | 22 |

TABLE A.5.4.

Spinning Draft Ratio - 0.91

Nozzle - 2 x 1/4 in. dia. inlets   Vortex Tube - 1 in. dia.

| Yarn Take-up Rate (m/min.) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) |
|---|---|---|---|
| 2 | 35.5 | 13.0 | 7.4 |
| 4 | 33.5 | 13.0 | 6.5 |
| 6 | 32.5 | 13.3 | 6.0 |
| 8 | 33.5 | 13.5 | 6.0 |
| 10 | 34.8 | 13.5 | 5.6 |
| 12 | 36.0 | 14.3 | - |

TABLE A.5.5.

Spinning Draft Ratio - 1.00

Nozzle - 2 x 1/4 in. dia. inlets    Vortex Tube - 1 in. dia.

| Yarn Take-up Rate (m/min.) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 0.7 | 79.8 | 34.7 | 14.2 | 6.0 | 8.4 | - |
| 0.8 | 79.2 | 31.6 | 11.3 | 6.2 | 8.1 | - |
| 1.0 | 80.1 | 31.3 | 14.0 | 6.2 | 7.9 | - |
| 2.3 | 77.3 | 28.6 | 14.1 | 6.0 | 8.8 | - |
| 3.5 | 79.3 | 26.7 | 13.8 | 5.2 | 8.4 | - |
| 4.4 | 80.7 | 25.5 | 14.1 | 3.9 | 7.7 | - |
| 5.5 | 82.4 | 30.3 | 11.3 | 5.2 | 9.1 | - |
| 6.2 | 81.7 | 32.8 | 11.8 | 5.9 | 9.5 | - |
| 7.0 | 76.6 | 36.3 | 12.3 | 5.3 | 10.2 | - |
| 8.0 | 75.6 | 35.5 | 12.3 | 5.2 | 9.3 | - |
| 9.0 | 77.2 | 34.6 | 12.7 | 5.2 | 9.5 | 23 |
| 10.0 | 72.8 | 37.2 | 14.5 | 4.9 | 8.6 | 17 |
| 11.1 | 72.2 | 38.7 | 14.9 | 4.9 | 8.9 | 31 |
| 12.3 | 73.5 | 36.7 | 16.3 | 4.1 | 8.7 | 18 |

TABLE A.5.6.

Spinning Draft Ratio - 1.00

Nozzle - 2 x 1/4 in. dia. inlets    Vortex Tube - 1 in. dia.

| Yarn Take-up Rate (m/min.) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) |
|---|---|---|---|
| 2 | 27.3 | 13.0 | 6.0 |
| 4 | 25.5 | 14.0 | 5.2 |
| 6 | 32.8 | 11.5 | 5.2 |
| 8 | 36.3 | 12.3 | 5.2 |
| 10 | 37.3 | 14.5 | 4.8 |
| 12 | 37.8 | 15.6 | - |

TABLE A.5.7.

Spinning Draft Ratio - 1.12

Nozzle - 2 x 1/4 in. dia. inlets  Vortex Tube - 1 in. dia.

| Yarn Take-up Rate (m/min.) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 0.7 | 65.5 | 36.0 | 13.7 | 6.8 | 7.9 | - |
| 0.9 | 69.8 | 33.3 | 13.1 | 6.5 | 8.2 | - |
| 1.0 | 72.1 | 28.6 | 13.3 | 6.5 | 7.7 | - |
| 1.6 | 72.3 | 28.9 | 14.8 | 6.2 | 8.1 | - |
| 1.9 | 70.9 | 30.6 | 14.7 | 5.8 | 7.7 | - |
| 2.2 | 70.0 | 32.5 | 14.5 | 5.7 | 7.9 | - |
| 3.5 | 68.1 | 37.0 | 14.0 | 6.0 | 7.9 | - |
| 4.4 | 65.3 | 38.3 | 14.3 | 5.4 | 7.5 | - |
| 7.1 | 57.1 | 45.5 | 16.3 | 4.9 | 8.4 | - |
| 8.0 | 54.1 | 46.1 | 18.5 | 5.8 | 8.1 | - |
| 9.0 | 54.2 | 46.3 | 17.5 | 4.7 | 7.6 | - |
| 10.0 | 53.0 | 47.8 | 17.4 | 4.3 | 7.2 | - |
| 11.0 | 50.0 | 48.5 | 19.2 | 3.9 | 7.8 | - |
| 12.2 | 51.9 | 48.8 | 18.5 | 4.0 | 7.3 | - |

TABLE A.5.8.

Spinning Draft Ratio - 1.12

Nozzle - 2 x 1/4 in. dia. inlets  Vortex Tube - 1 in. dia.

| Yarn Take-up Rate (m/min.) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) |
|---|---|---|---|
| 2 | 31.0 | 14.8 | 5.8 |
| 4 | 38.8 | 14.3 | 5.7 |
| 6 | 43.8 | 15.3 | 5.0 |
| 8 | 46.0 | 17.0 | 4.9 |
| 10 | 47.8 | 17.5 | 4.3 |
| 12 | 48.8 | 18.5 | - |

TABLE A.5.9

RUNNING AVERAGES OF YARN

TAKE-UP RATE AND BREAKING TENACITY

Spinning Draft Ratio - 0.83

Nozzle - 2 x 1/4 in. dia. inlets Vortex Tube - 1 in. dia.

(from Table A.5.1)

| Yarn Take-up Rate (m/min.) | Yarn Breaking Tenacity (gf/tex) |
|---|---|
| 0.8 | 7.1 |
| 1.3 | 7.1 |
| 1.9 | 6.9 |
| 3.0 | 6.6 |
| 4.3 | 6.4 |
| 5.4 | 6.0 |
| 6.3 | 6.0 |
| 7.1 | 5.7 |
| 8.1 | 6.1 |
| 9.0 | 5.8 |
| 10.1 | 5.6 |
| 11.1 | 5.4 |

TABLE A.5.10

RUNNING AVERAGES OF YARN

TAKE-UP RATE AND BREAKING TENACITY

Spinning Draft Ratio - 0.91

Nozzle - 2 x 1/4 in. dia. inlets Vortex Tube - 1 in. dia.

(from Table A.5.2)

| Yarn Take-up Rate (m/min.) | Yarn Breaking Tenacity (gf/tex) |
|---|---|
| 0.9 | 7.4 |
| 1.3 | 7.1 |
| 2.0 | 7.2 |

Continued on next page.

| | |
|---|---|
| 3.0 | 6.9 |
| 4.2 | 6.3 |
| 5.4 | 5.9 |
| 6.3 | 6.1 |
| 7.1 | 6.2 |
| 8.0 | 6.2 |
| 9.0 | 5.6 |
| 10.1 | 5.3 |
| 11.2 | 4.9 |

TABLE A.5.11

RUNNING AVERAGES OF YARN

TAKE-UP RATE AND BREAKING TENACITY

Spinning Draft Ratio = 1.00

Nozzle - 2 x 1/4 in. dia. inlets    Vortex Tube - 1 in. dia.

(from Table A.5.3)

| Yarn Take-up Rate (m/min.) | Yarn Breaking Tenacity (gf/tex) |
|---|---|
| 0.7 | 6.4 |
| 0.8 | 6.1 |
| 1.0 | 6.2 |
| 1.3 | 6.2 |
| 1.6 | 5.9 |
| 1.9 | 5.7 |
| 2.6 | 5.4 |
| 3.4 | 4.9 |
| 4.5 | 4.8 |
| 5.4 | 5.0 |
| 6.2 | 5.4 |
| 7.1 | 5.4 |
| 8.0 | 5.2 |
| 9.0 | 5.1 |
| 10.0 | 5.0 |
| 11.1 | 4.6 |

TABLE A.5.12

RUNNING AVERAGES OF YARN

TAKE-UP RATE AND BREAKING TENACITY

Spinning Draft Ratio = 1.12

Nozzle = 2 x 1/4 in. dia. inlets    Vortex Tube = 1 in. dia.

(from Table A.5.4)

| Yarn Take-up Rate (m/min.) | Yarn Breaking Tenacity (gf/tex) |
|---|---|
| 0.7 | 6.3 |
| 0.9 | 6.6 |
| 1.0 | 6.8 |
| 1.3 | 6.8 |
| 1.6 | 6.4 |
| 1.9 | 5.8 |
| 2.3 | 5.8 |
| 2.8 | 6.0 |
| 3.6 | 5.9 |
| 4.5 | 6.1 |
| 5.3 | 5.4 |
| 6.2 | 5.6 |
| 7.0 | 5.2 |
| 8.0 | 5.1 |
| 9.0 | 4.9 |
| 10.0 | 4.3 |
| 11.1 | 4.1 |

TABLE A.5.13

Spinning Draft Ratio - 0.91

Nozzle - 2 x 1/4 in. dia. inlets   Vortex Tube - 1 in. dia.

"Shirley" Static Eliminator Switched Off.

| Yarn Take-up Rate (m/min.) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 1.9 | 90.6 | 29.1 | 12.1 | 8.6 | 10.7 | 51 |
| 2.8 | 91.5 | 30.7 | 13.4 | 7.3 | 9.9 | 51 |
| 4.4 | 88.9 | 31.8 | 12.7 | 7.2 | 10.1 | 46 |
| 6.2 | 81.2 | 33.2 | 14.6 | 6.8 | 9.7 | 26 |
| 7.9 | 76.4 | 36.2 | 14.6 | 5.9 | 9.0 | 23 |
| 10.0 | 57.6 | 50.8 | 23.6 | 5.9 | 9.2 | 18 |
| 12.3 | 62.6 | 47.2 | 31.7 | 5.4 | 9.1 | 8 |

TABLE A.5.14

Spinning Draft Ratio - 0.91

Nozzle - 2 x 1/4 in. dia. inlets   Vortex Tube - 1 in. dia.

"Shirley" Static Eliminator Electrode At 6 ins. From The Spinning Tube

| Yarn Take-up Rate (m/min.) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 0.8 | 66.8 | 39.3 | 14.1 | 7.0 | 8.0 | 77 |
| 1.3 | 70.6 | 35.1 | 13.1 | 6.6 | 8.6 | 49 |
| 1.9 | 65.3 | 35.6 | 13.5 | 5.3 | 8.0 | 54 |
| 2.8 | 70.0 | 36.0 | 14.6 | 6.0 | 8.4 | 48 |
| 4.5 | 69.6 | 36.8 | 15.6 | 6.1 | 8.3 | 48 |
| 6.2 | 64.9 | 40.6 | 17.1 | 4.9 | 8.0 | 35 |
| 8.1 | 61.1 | 42.7 | 17.1 | 5.1 | 7.4 | 25 |
| 10.1 | 59.9 | 45.2 | 17.1 | 5.3 | 8.5 | 21 |
| 12.5 | 57.5 | 46.8 | 19.3 | 5.2 | 7.3 | 15 |

TABLE A.5.15

Spinning Draft Ratio - 0.91

Nozzle - 2 x 1/4 in. dia. inlets Vortex Tube - 1 in. dia.

"Shirley"Static Eliminator Electrode At 6 ins. From The Spinning Tube

| Yarn Take-up Rate (m/min.) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 1.9 | 96.4 | 24.7 | 12.5 | 6.8 | 10.2 | 70 |
| 2.8 | 93.9 | 27.4 | 12.9 | 7.3 | 9.3 | 47 |
| 4.4 | 90.2 | 30.5 | 13.0 | 6.8 | 9.7 | 42 |
| 6.2 | 94.9 | 26.4 | 11.2 | 4.9 | 9.1 | 30 |
| 7.9 | 87.2 | 33.2 | 12.7 | 6.6 | 9.5 | 19 |
| 12.2 | 91.4 | 29.9 | 14.2 | 6.1 | 9.8 | 20 |

TABLE A.5.16

Spinning Draft Ratio - 0.91

Nozzle - 2 x 1/4 in. dia. inlets Vortex Tube - 1 in. dia.

"Shirley"Static Eliminator Electrode At 12 ins. From The Spinning Tube

| Yarn Take-up Rate (m/min.) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 1.9 | 95.9 | 24.7 | 10.4 | 7.6 | 10.2 | 51 |
| 2.8 | 94.4 | 27.1 | 11.7 | 7.7 | 10.2 | 45 |
| 4.4 | 88.8 | 30.1 | 13.4 | 7.0 | 9.6 | 35 |
| 6.2 | 81.4 | 32.2 | 14.8 | 7.1 | 9.8 | 29 |
| 7.9 | 81.0 | 35.4 | 15.4 | 7.2 | 10.1 | 26 |
| 10.0 | 84.8 | 31.3 | 16.9 | 4.9 | 9.5 | 22 |
| 12.4 | 64.1 | 48.4 | 28.2 | 4.8 | 8.3 | 8 |

TABLE A.5.17

Spinning Draft Ratio - 1.00

Nozzle - 2 x 1/4 in. dia. inlets    Vortex Tube - 1 in. dia.

"Shirley"Static Eliminator Electrode At 6 ins. From The Spinning Tube

Before Chamfering The Nozzle End

| Yarn Take-up Rate (m/min.) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tenacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 1.9 | 65.7 | 34.7 | 14.1 | 7.17 | 9.64 | 45 |
| 2.8 | 67.6 | 34.6 | 15.7 | 8.09 | 10.74 | 30 |
| 4.3 | 71.0 | 30.8 | 15.3 | 5.89 | 9.89 | 22 |
| 6.0 | 68.9 | 32.9 | 19.0 | 6.37 | 10.74 | 19 |
| 7.8 | 61.1 | 39.9 | 24.8 | 5.03 | 11.11 | 19 |

TABLE A.5.18

Spinning Draft Ratio - 1.00

Nozzle - 2 x 1/4 in. dia. inlets    Vortex Tube - 1 in. dia.

"Shirley"Static Eliminator Electrode At 6 ins. From The Spinning Tube

After Chamfering The Nozzle End

| Yarn Take-up Rate (m/min.) | Linear Density Of Yarn (tex) | Fibre Waste (%) | Yarn Irregularity (P.M.D.) | Yarn Breaking Tanacity (gf/tex) | Yarn Breaking Elongation (%) | Length Of Forming Yarn (cm.) |
|---|---|---|---|---|---|---|
| 4.4 | 72.8 | 29.4 | 13.2 | 6.29 | 11.35 | 20 |
| 6.0 | 74.6 | 27.9 | 13.3 | 4.33 | 9.72 | 19 |
| 7.7 | 74.6 | 27.4 | 12.0 | 5.10 | 11.74 | 20 |
| 9.7 | 78.0 | 25.6 | 12.7 | 4.80 | 10.79 | 19 |
| 12.0 | 77.1 | 24.6 | 12.8 | 5.10 | 10.94 | 16 |

## APPENDIX B



### TABLE B.6.1.

Nozzle: 2X$\frac{1}{4}$in.dia. inlets.
Yarn take-up rate: 10 m/min.

| Tube bore (in.) | Fibre assembly efficiency (%) | Yarn irregularity (P.M.D.) | Breaking tenacity (gf/tex) | Twist constant | Yarn speed (r.p.m.) |
|---|---|---|---|---|---|
| $\frac{1}{2}$ | 88 | 14.6 | 8.0 | 38 | 13,000 |
| $\frac{3}{4}$ | 92 | 10.6 | 9.2 | 44 | 11,800 |
| 1 | 90 | 10.8 | 9.4 | 46 | 10,000 |
| $1\frac{1}{2}$ | 82 | 11.6 | 8.2 | 42 | 8,800 |
| 2 | 78 | 13.8 | 7.8 | 38 | 7,400 |

### TABLE B.6.2.

Nozzle: 2 X $\frac{1}{4}$ in. dia. inlets.
Yarn take-up rate: 10 m/min.

| Tube material | Fibre assembly efficiency (%) | Yarn irregularity (P.M.D.) | Breaking tenacity (gf/tex) | Twist constant | Yarn speed (r.p.m.) |
|---|---|---|---|---|---|
| Polythene | 65 | 15.8 | 4.8 | 28 | 7,800 |
| Polystyrene | 62 | 16.4 | 5.0 | 32 | 8,400 |
| PVC | 67 | 15.0 | 4.7 | 25 | 8,600 |
| Perspex | 78 | 12.4 | 9.0 | 42 | 10,000 |
| Glass | 76 | 12.2 | 8.8 | 42 | 9,800 |
| Copper | 74 | 13.8 | 4.4 | 24 | 9,900 |

### TABLE B.6.3.

MEASURED VALUES OF THE COEFFICIENT OF KINETIC FRICTION BETWEEN COTTON YARN AND TUBES OF DIFFERENT MATERIALS.

(As recommended by B.S.Handbook[82])

| Tube material | $\mu$ |
|---|---|
| Polythene | 0.60 |
| Polystyrene | 0.43 |
| PVC | 0.40 |
| Perspex | 0.38 |
| Glass | 0.39 |
| Copper | 0.33 |

TABLE B.6.4.

Yarn take-up rate: 8 m/min.

| Tangential inlets | Fibre assembly efficiency (%) | Yarn irregularity (P.M.D.) | Breaking tenacity (gf/tex) | Twist constant |
|---|---|---|---|---|
| 2 X $\frac{1}{4}$ in.dia. | 78 | 12.4 | 9.0 | 42 |
| 3 X $\frac{13}{64}$ in.dia. | 74 | 13.2 | 7.8 | 34 |
| 4 X $\frac{11}{64}$ in.dia. | 72 | 13.6 | 7.2 | 30 |
| 6 X $\frac{9}{64}$ in.dia. | 68 | 14.4 | 6.6 | 27 |

TABLE B.6.5.

Cotton yarn - 245 tex.

Air pressure - -25in$H_2O$

| Tangential inlets | Yarn speed (R.P.M.) |
|---|---|
| 2 X $\frac{1}{4}$ in. dia. | 9,600 |
| 3 X $\frac{13}{64}$ in. dia. | 9,200 |
| 4 X $\frac{11}{64}$ in. dia. | 8,800 |
| 6 X $\frac{9}{64}$ in. dia. | 8,400 |

APPENDIX B.6.6.

The values of $K_1$ for a sudden contraction[86] in tube transition are given below. The values quoted apply to the region of fully developed turbulence.

| $\frac{A_2}{A_1}$ | $K_1$ |
|---|---|
| 0.1 | 0.362 |
| 0.2 | 0.338 |
| 0.3 | 0.308 |
| 0.4 | 0.267 |
| 0.5 | 0.221 |
| 0.6 | 0.164 |
| 0.7 | 0.105 |
| 0.8 | 0.053 |
| 0.9 | 0.015 |

# APPENDIX C

## APPENDIX C. 8.1.

### PARTICLE FLOW IN A VORTEX TUBE

A study of the particle flow in a vortex tube was thought to be a necessary preliminary step in an analysis of the general problem. The effects of the various forces acting on particles may then be applied, with some modifications, to fibres and later to yarns also.

Aerodynamic forces on particles.

The path followed by particles is governed by the forces exerted by the air stream on these particles. It is reasonable to consider that, at low Reynolds numbers, the drag forces are much larger than the lift forces. Hence it may be assumed for the purpose of simplicity that the lift forces are negligible in which case only the drag forces acting on particles need be taken into consideration.

In the following analysis of aerodynamic forces acting on particles the solid frictional effects between the particles and tube wall are ignored.

Consider a two dimensional flow of a particle moving with a linear velocity $V_f$ and an airstream moving with a velocity $V_a$. Let $V_r$ be the velocity of the airstream relative to the particle. Please refer to Fig. C.8.1.

Let m be the mass of the particle under considertion,

D be the drag force,

$\rho$ be the air density,

$C_D$ be the body drag coefficient,

S be the projected area of the particle ,

$\gamma$ be the angle between a fixed (arbitrary) reference line OA and the path of the particleOB,

$\theta$ be the angle between the reference line OA and the airstream path OC,

$\alpha = \theta - r =$ the angle between the particle path OB and the airstream path OC

and $\phi$ be the angle that $V_r$ makes with the particle path OB.

Velocities of the particle, airstream and air relative to the particle is seen in Fig.

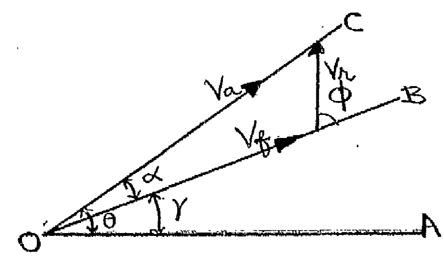



Fig. C.8.1.
VELOCITIES OF THE PARTICLE, AIR STREAM AND AIR RELATIVE TO THE PARTICLE

Now $D = \frac{1}{2}\rho V_r^2 C_D S$ ..................(1)

It may be noted from this equation that

$D \propto V_r^2$ and also $D \propto C_D$

From Fig. C.8.1.

$$\sin\phi = \frac{V_a \sin\alpha}{V_r} \quad ..............(2)$$

and $$\cos 0 = \frac{V_a \cos\alpha - V_f}{V_r} \quad ............(3)$$

The equations of motions of the particle written in the intrinsic (tangential and normal) co-ordinates of the trajectory are given as follows:-(101)

In the following, $\frac{d}{dt}$ is denoted by the dot notation.

That is, $\dot{V} = \frac{dV}{dt}$

$$m\,\dot{V}_f = D\cos\phi \quad ....(4)$$

and $$m\,V_f\,\dot{\gamma} = D\sin\phi \quad ....(5)$$

The magnitude of the relative velocity $V_r$ can be obtained by a geometrical consideration of the Fig.

$$V_r^2 = V_f^2 + V_a^2 - 2V_fV_a\cos\alpha \quad .....(6)$$

The particle trajectory at any time t can be obtained by integrating the following expressions where the subscript "o" denotes the initial conditions.

$$V_f = V_{fo} + \int_0^t \mathring{V}_f \, dt \quad \ldots\ldots\ldots\ldots (7)$$

$$\gamma = \gamma_o + \int_0^t \mathring{\gamma} \, dt \quad \ldots\ldots\ldots\ldots (8)$$

In order to arrive at the particle trajectory, it is essential to know the magnitude and direction of the air stream.

The magnitude of the air stream is given by

$$V_a = V_a(x,y)$$

and it direction by

$$\theta = \alpha + \gamma = \theta(x,y)$$

These values can be calculated. Thus it would be possible to compute numerically the particle speed and direction at a time $t = \Delta t$ provided the following values are determined.

$V_r^2$ from equation (6),

$D$ from equation (1),

$\mathring{V}_f$ from equations (3) and (4)

and $\dot{\gamma}$ from equations (2) and (5).

Therefore $V_f$ is obtained from equation (7) and $\gamma$ from equation (8).

The particle paths are given by

$$x = x_o + \mathring{x}_o t + \int_0^t \mathring{x} \, dt$$

$$\text{and } y = y_o + \mathring{y}_o t + \int_0^t \mathring{y} \, dt$$

where $\mathring{x} = V_f \cos\gamma$

and $\mathring{y} = V_f \sin\gamma$

Nozzle - 2 x 1/4 in. dia. Tangential inlets. Vortex Tube - 1 in. dia.

| Yarn Length In Vortex Tube | Air Pressure In Tube -in $H_2O$ | With Static Elimination | | | | | | With Static Accumulation | | | | | | Loss In Yarn Speed Due To Static Charges |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm) | Torque Per cm (gf.cm/cm) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm) | Torque Per cm (gf.cm/cm) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm) | (% age) |
| 40 | 16 | 335 | 0.651 | 0.0163 | 8350 | 9.0 | 0.225 | 305 | 0.592 | 0.0148 | 7,450 | 8.00 | 0.200 | 10.8 |
| | 20 | 375 | 0.728 | 0.0182 | 9650 | 11.0 | 0.275 | 335 | 0.651 | 0.0163 | 8,450 | 9.50 | 0.238 | 12.4 |
| | 25 | 415 | 0.806 | 0.0201 | 10800 | 13.5 | 0.338 | 370 | 0.719 | 0.0180 | 9,500 | 11.25 | 0.281 | 12.0 |
| | 30 | 460 | 0.893 | 0.0223 | 11,800 | 16.0 | 0.400 | 395 | 0.767 | 0.0192 | 10,700 | 13.75 | 0.344 | 9.3 |
| | 35 | 500 | 0.971 | 0.0243 | 12,800 | 18.0 | 0.450 | 420 | 0.816 | 0.0204 | 11,350 | 15.50 | 0.388 | 11.3 |
| | 40 | 525 | 1.020 | 0.02551 | 13,750 | 21.0 | 0.525 | 440 | 0.854 | 0.0214 | 12,100 | 18.50 | 0.463 | 12.0 |
| | 45 | 540 | 1.049 | 0.0262 | 14,800 | 23.0 | 0.575 | 460 | 0.893 | 0.0223 | 12,800 | 20.50 | 0.513 | 13.5 |
| 30 | 16 | 230 | 0.447 | 0.0149 | 8700 | 8.5 | 0.283 | 190 | 0.369 | 0.0123 | 7,400 | 7.00 | 0.233 | 14.9 |
| | 20 | 270 | 0.524 | 0.0175 | 9850 | 10.5 | 0.350 | 205 | 0.398 | 0.0133 | 8,250 | 8.25 | 0.275 | 16.2 |
| | 25 | 315 | 0.612 | 0.0204 | 11,000 | 13.0 | 0.433 | 230 | 0.447 | 0.0149 | 9,300 | 10.00 | 0.333 | 15.5 |
| | 30 | 340 | 0.660 | 0.0220 | 11,900 | 16.0 | 0.533 | 250 | 0.486 | 0.0162 | 10,400 | 12.50 | 0.417 | 12.6 |
| | 35 | 360 | 0.699 | 0.0233 | 12,000 | 18.0 | 0.600 | 260 | 0.505 | 0.0168 | 11,200 | 15.00 | 0.500 | 13.8 |
| | 40 | 378 | 0.734 | 0.0245 | 14,100 | 21.0 | 0.700 | 280 | 0.544 | 0.0181 | 12,000 | 18.00 | 0.600 | 14.9 |
| | 45 | 393 | 0.763 | 0.0254 | 13,200 | 22.5 | 0.750 | 295 | 0.573 | 0.0191 | 12,750 | 19.75 | 0.658 | 16.1 |
| 20 | 16 | 140 | 0.272 | 0.0136 | 9650 | 8.0 | 0.400 | 120 | 0.233 | 0.0117 | 7,500 | 5.25 | 0.263 | 22.3 |
| | 20 | 170 | 0.330 | 0.0165 | 10,700 | 10.0 | 0.500 | 145 | 0.282 | 0.0141 | 8,200 | 7.00 | 0.350 | 23.4 |
| | 25 | 195 | 0.379 | 0.0189 | 12,100 | 12.5 | 0.625 | 165 | 0.320 | 0.0160 | 9,200 | 8.50 | 0.425 | 24.0 |
| | 30 | 220 | 0.427 | 0.0214 | 13,200 | 14.5 | 0.725 | 180 | 0.350 | 0.0175 | 10,150 | 11.00 | 0.550 | 23.1 |
| | 35 | 240 | 0.466 | 0.0233 | 14,400 | 17.0 | 0.850 | 190 | 0.369 | 0.0184 | 10,850 | 13.00 | 0.650 | 24.7 |

Continued on next page.

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 250 | 0.486 | 0.0243 | 15,200 | 20.0 | 1.000 | 200 | 0.388 | 0.0194 | 11,500 | 15.00 | 0.750 | 24.3 |
| | 45 | 260 | 0.505 | 0.0252 | 16,400 | 22.0 | 1.100 | 208 | 0.404 | 0.0202 | 12,250 | 16.50 | 0.825 | 25.3 |

TABLE D.12.2

AIR PRESSURE - 25 in. OF WATER COLUMN

Cylindrical Nozzle - 2 x 1/4 in. dia. inlets. Vortex Tube 1 in. dia.

| Material Of Yarn And Count In Tex | Yarn Length In Vortex Tube (cm.) | With Static Elimination | | | | | | With Static Accumulation | | | | | | Loss In Yarn Speed Due To Static Charges (% age) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Torsional Deflection (Degrees) | Torque On Yarn (gf cm) | Torque Per cm. (gf.cm/cm) | Yarn Tail Speed (r.p.m) | Yarn Tension (gf) | Tension Per cm. (gf/cm) | Torsional Deflection. (Degrees) | Torque On Yarn (gf/cm) | Torque Per cm. (gf.cm/cm) | Yarn Tail Speed (r.p.m) | Yarn Tension (gf) | Tension Per cm. (gf/cm) | |
| Cotton (245) | 60 | 465 | 0.903 | 0.0151 | 9,600 | 14.50 | 0.242 | 420 | 0.816 | 0.0136 | 9,400 | 12.50 | 0.208 | 2.1 |
| | 50 | 445 | 0.864 | 0.0173 | 9,700 | 14.00 | 0.280 | 405 | 0.787 | 0.0157 | 9,500 | 12.00 | 0.240 | 3.1 |
| | 40 | 415 | 0.806 | 0.0201 | 10150 | 13.50 | 0.338 | 370 | 0.719 | 0.0180 | 9,500 | 11.25 | 0.281 | 6.4 |
| | 30 | 300 | 0.583 | 0.0194 | 10,650 | 13.00 | 0.433 | 230 | 0.447 | 0.0149 | 9,300 | 10.00 | 0.333 | 12.7 |
| | 20 | 195 | 0.379 | 0.0189 | 11,500 | 12.50 | 0.625 | 165 | 0.320 | 0.0160 | 9,200 | 8.50 | 0.425 | 20.0 |
| | 10 | 65 | 0.126 | 0.0126 | 13,500 | 13.00 | 1.300 | 50 | 0.097 | 0.0037 | 9,000 | 7.00 | 0.700 | 33.4 |
| Fibro (295) | 60 | 405 | 1.104 | 0.0184 | 9,200 | 16.75 | 0.267 | 355 | 0.967 | 0.0161 | 8,550 | - | - | 2.7 |
| | 50 | 380 | 1.036 | 0.0207 | 9,400 | 16.00 | 0.310 | 315 | 0.858 | 0.0172 | 9,050 | - | - | 3.7 |
| | 40 | 343 | 0.935 | 0.0234 | 9,700 | 15.00 | 0.375 | 255 | 0.695 | 0.0174 | 9,100 | - | - | 6.2 |
| | 30 | 215 | 0.586 | 0.0195 | 10,150 | 14.00 | 0.467 | 155 | 0.422 | 0.0141 | 9,00 | - | - | 11.3 |
| | 20 | 110 | 0.300 | 0.0150 | 10,850 | 13.00 | 0.650 | 80 | 0.218 | 0.0109 | 8,850 | - | - | 18.4 |
| | 10 | 45 | 0.123 | 0.0123 | 12,800 | 13.50 | 1.350 | 25 | 0.068 | 0.0068 | 8,750 | - | - | 31.6 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nylon (58) | 60 | 330 | 0.641 | 0.0107 | 9,700 | 2.50 | 0.042 | 290 | 0.563 | 0.0094 | 9,500 | - | - | 2.1 |
| | 50 | 300 | 0.583 | 0.0117 | 9,900 | 2.25 | 0.045 | 265 | 0.515 | 0.0103 | 9,500 | - | - | 2.1 |
| | 40 | 245 | 0.476 | 0.0119 | 10,300 | 2.00 | 0.050 | 225 | 0.437 | 0.0109 | 9,450 | - | - | 8.3 |
| | 30 | 150 | 0.291 | 0.0097 | 11,000 | 1.50 | 0.050 | 85 | 0.165 | 0.0055 | 9,400 | - | - | 14.5 |
| | 20 | 75 | 0.146 | 0.0073 | 11,900 | 1.25 | 0.063 | 45 | 0.087 | 0.0044 | 9,300 | - | - | 21.2 |
| | 10 | 20 | 0.039 | 0.0039 | 14,200 | 2.00 | 0.200 | 15 | 0.029 | 0.0029 | 9,250 | - | - | 34.9 |

TABLE D.12.3

"FIBRO YARN" (295 tex)

Nozzle - 2 x 1/4 in. dia. Tangential inlets. Vortex Tube - 1 in. dia.

| Yarn Length In Vortex Tube (cm) | Air Pressure In Vortex Tube (-in $H_2O$) | With Static Elimination | | | | | | With Static Accumulation | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm) | Torque Per cm. (gf.cm/cm) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm) | Torque Per cm. (gf.cm/cm) |
| 40 | 16 | 275 | 0.749 | 0.0187 | 7.900 | 9.5 | 0.238 | 220 | 0.600 | 0.0150 |
| | 20 | 312 | 0.850 | 0.0213 | 9.00 | 11.5 | 0.288 | 235 | 0.640 | 0.0160 |
| | 30 | 378 | 1.030 | 0.0258 | 11.100 | 17.5 | 0.425 | 270 | 0.736 | 0.0184 |
| | 35 | 401 | 1.093 | 0.0273 | 12,00 | 20.0 | 0.500 | 285 | 0.777 | 0.0194 |
| | 40 | 420 | 1.145 | 0.0286 | 13,100 | 23.5 | 0.588 | 305 | 0.831 | 0.0208 |
| | 45 | 430 | 1.172 | 0.0293 | 13,650 | 26.0 | 0.650 | 315 | 0.858 | 0.0215 |
| 30 | 16 | 160 | 0.436 | 0.0145 | 8,500 | 9.0 | 0.300 | 125 | 0.341 | 0.0114 |
| | 20 | 180 | 0.431 | 0.0164 | 9,350 | 11.0 | 0.366 | 140 | 0.382 | 0.0127 |
| | 25 | 215 | 0.586 | 0.0195 | 10,450 | 14.0 | 0.467 | 155 | 0.422 | 0.0141 |
| | 30 | 240 | 0.654 | 0.0218 | 11,600 | 16.5 | 0.550 | 170 | 0.460 | 0.0154 |
| | 35 | 265 | 0.722 | 0.0241 | 12,500 | 19.0 | 0.633 | 185 | 0.504 | 0.0168 |
| | 40 | 285 | 0.777 | 0.0259 | 13,400 | 21.0 | 0.700 | 195 | 0.531 | 0.0177 |
| | 45 | 300 | 0.818 | 0.0273 | 14,000 | 23.5 | 0.783 | 200 | 0.545 | 0.0182 |
| 20 | 16 | 85 | 0.232 | 0.0116 | 8,750 | 8.5 | 0.450 | 60 | 0.164 | 0.0082 |
| | 20 | 95 | 0.259 | 0.0129 | 9,700 | 10.5 | 0.525 | 65 | 0.177 | 0.0089 |

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|---|---|---|---|---|---|---|---|---|---|
| 25 | 110 | 0.300 | 0.0150 | 10,850 | 13.0 | 0.650 | 80 | 0.218 | 0.0109 |
| 30 | 128 | 0.349 | 0.0174 | 11,850 | 15.5 | 0.775 | 95 | 0.259 | 0.0129 |
| 35 | 140 | 0.382 | 0.0191 | 12,800 | 18.0 | 0.900 | 105 | 0.286 | 0.0143 |
| 40 | 160 | 0.436 | 0.0218 | 13,650 | 20.0 | 1.000 | 115 | 0.313 | 0.0157 |
| 45 | 165 | 0.450 | 0.0225 | 14,200 | 22.0 | 1.100 | 130 | 0.354 | 0.0177 |

Nozzle - 2 x 1/4 in. dia. Tangential inlets. Vortex Tube - 1 in. dia.

| Yarn Length In Vortex Tube (cm) | Air Pressure In Vortex Tube (-in $H_2O$) | With Static Elimination | | | | | | With Static .cumulation | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm) | Torque Per cm. (gf.cm/cm) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per cm. (gf/cm) | Torsional Deflection (Degrees) | Torque On Yarn (gf/cm) | Torque Per cm. (gf.cm/cm) |
| 40 | 16 | 175 | 0.340 | 0.0085 | 7,550 | 1.00 | 0.025 | 160 | 0.311 | 0.0078 |
| | 20 | 205 | 0.398 | 0.0100 | 8,500 | 1.50 | 0.038 | 185 | 0.359 | 0.0090 |
| | 25 | 245 | 0.476 | 0.0119 | 10,300 | 2.00 | 0.050 | 225 | 0.437 | 0.0109 |
| | 30 | 285 | 0.553 | 0.0138 | 11,000 | 2.50 | 0.063 | 250 | 0.486 | 0.0121 |
| | 35 | 315 | 0.612 | 0.0153 | 12,000 | 2.75 | 0.069 | 265 | 0.515 | 0.0129 |
| | 40 | 338 | 0.656 | 0.0164 | 13,200 | 3.250 | 0.081 | 285 | 0.553 | 0.0138 |
| | 45 | 360 | 0.699 | 0.0175 | 13,800 | 3.50 | 0.088 | 295 | 0.573 | 0.0143 |
| 30 | 16 | 115 | 0.223 | 0.0074 | 7,700 | 0.75 | 0.025 | 65 | 0.126 | 0.0042 |
| | 20 | 130 | 0.252 | 0.0084 | 8,600 | 1.00 | 0.033 | 75 | 0.146 | 0.0049 |
| | 25 | 150 | 0.291 | 0.0097 | 9,850 | 1.50 | 0.050 | 85 | 0.165 | 0.0055 |
| | 30 | 185 | 0.359 | 0.0120 | 11,100 | 2.00 | 0.067 | 105 | 0.204 | 0.0068 |
| | 35 | 200 | 0.388 | 0.0129 | 12,100 | 2.50 | 0.083 | 115 | 0.223 | 0.0074 |
| | 40 | 215 | 0.418 | 0.0139 | 13,300 | 3.25 | 0.108 | 125 | 0.243 | 0.008 |
| | 45 | 235 | 0.456 | 0.0152 | 13,900 | 3.50 | 0.117 | 130 | 0.252 | 0.0084 |
| 20 | 16 | 55 | 0.107 | 0.0054 | 7,850 | 0.75 | 0.025 | 35 | 0.068 | 0.0034 |
| | 20 | 65 | 0.126 | 0.0063 | 9,000 | 1.00 | 0.050 | 40 | 0.078 | 0.0039 |
| | 25 | 75 | 0.146 | 0.0073 | 10,500 | 1.50 | 0.063 | 45 | 0.087 | 0.0044 |
| | 30 | 85 | 0.165 | 0.0083 | 11,900 | 2.00 | 0.100 | 48 | 0.093 | 0.0047 |
| | 35 | 95 | 0.185 | 0.0092 | 12,900 | 2.25 | 0.113 | 50 | 0.097 | 0.0049 |
| | 40 | 100 | 0.194 | 0.0097 | 14,100 | 2.75 | 0.138 | 52 | 0.101 | 0.0051 |
| | 45 | 103 | 0.200 | 0.0100 | 14,700 | 3.00 | 0.163 | 55 | 0.107 | 0.0054 |

TABLE D.12.5

Cotton Yarn: 245 tex.
Nozzle: 1/4 x 1/4 in. inlets.
Tube: 3/4 in. dia.
Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in.$H_2O$) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm) |
|---|---|---|---|---|---|---|---|
| 60 | 16 | 370 | 0.719 | 0.0120 | 11300 | 16.25 | 0.271 |
| | 20 | 410 | 0.796 | 0.0133 | 12800 | 20.00 | 0.333 |
| | 25 | 450 | 0.874 | 0.0146 | 14300 | 24.50 | 0.408 |
| | 30 | 500 | 0.971 | 0.0162 | 16000 | 28.00 | 0.467 |
| | 35 | 540 | 1.049 | 0.0175 | 17600 | 32.00 | 0.533 |
| | 40 | 565 | 1.097 | 0.0183 | 18800 | 34.50 | 0.575 |
| | 45 | 585 | 1.136 | 0.189 | 19900 | 37.50 | 0.625 |
| 50 | 16 | 350 | 0.680 | 0.0136 | 12300 | 15.75 | 0.315 |
| | 20 | 390 | 0.757 | 0.0152 | 13700 | 19.25 | 0.385 |
| | 25 | 430 | 0.835 | 0.0167 | 15400 | 23.50 | 0.470 |
| | 30 | 480 | 0.932 | 0.0186 | 16800 | 27.50 | 0.550 |
| | 35 | 530 | 1.029 | 0.0206 | 18000 | 31.50 | 0.630 |
| | 40 | 550 | 1.068 | 0.0214 | 19400 | 34.500 | 0.690 |
| | 45 | 570 | 1.107 | 0.0221 | 20,200 | 38.00 | 0.760 |

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|---|---|---|---|---|---|---|---|
| 40 | 16 | 325 | 0.631 | 0.0158 | 13100 | 15.50 | 0.388 |
| | 20 | 365 | 0.709 | 0.0177 | 14500 | 19.00 | 0.475 |
| | 25 | 400 | 0.777 | 0.0194 | 16200 | 22.50 | 0.563 |
| | 30 | 450 | 0.874 | 0.0218 | 17900 | 26.50 | 0.663 |
| | 35 | 485 | 0.942 | 0.0235 | 19000 | 31.00 | 0.775 |
| | 40 | 515 | 1.000 | 0.0250 | 20500 | 33.50 | 0.838 |
| | 45 | 525 | 1.020 | 0.0255 | 21300 | 37.00 | 0.925 |
| 30 | 16 | 225 | 0.437 | 0.0146 | 1400 | 14.50 | 0.483 |
| | 20 | 260 | 0.505 | 0.0168 | 15400 | 17.500 | 0.583 |
| | 25 | 310 | 0.602 | 0.0201 | 16300 | 20.25 | 0.675 |
| | 30 | 330 | 0.641 | 0.0214 | 18600 | 24.25 | 0.808 |
| | 35 | 350 | 0.680 | 0.0227 | 20200 | 29.50 | 0.983 |
| | 40 | 369 | 0.717 | 0.239 | 21400 | 32.25 | 1.075 |
| | 45 | 383 | 0.744 | 0.0248 | 22400 | 35.50 | 1.183 |
| 20 | 16 | 135 | 0.262 | 0.0131 | 14400 | 12.50 | 0.625 |
| | 20 | 165 | 0.320 | 0.0160 | 15900 | 15.50 | 0.775 |
| | 25 | 190 | 0.369 | 0.0185 | 17900 | 17.75 | 0.888 |
| | 30 | 215 | 0.418 | 0.0209 | 19000 | 20.25 | 1.013 |
| | 35 | 235 | 0.456 | 0.0228 | 20800 | 23.50 | 1.175 |
| | 40 | 245 | 0.476 | 0.0238 | 21700 | 26.25 | 1.313 |
| | 45 | 253 | 0.491 | 0.0246 | 22800 | 29.00 | 1.450 |

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|---|---|---|---|---|---|---|---|
| 10 | 16 | 44 | 0.085 | 0.0085 | 14800 | 10.75 | 1.075 |
| | 20 | 52 | 0.101 | 0.0101 | 16200 | 12.75 | 1.275 |
| | 25 | 63 | 0.122 | 0.0122 | 1800 | 16.00 | 1.600 |
| | 30 | 73 | 0.142 | 0.0142 | 19700 | 17.50 | 1.750 |
| | 35 | 78 | 0.151 | 0.0151 | 21,100 | 20.50 | 2.050 |
| | 40 | 81 | 0.157 | 0.0157 | 22,300 | 22.50 | 2.050 |
| | 45 | 83 | 0.161 | 0.0161 | 23,200 | 25.00 | 2.500 |

TABLE D.12.6

Cotton Yarn: 245 tex.

Nozzle: 1/4 x 1/8 in. inlet.

Tube: 3/4 in. dia.

Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in.$H_2O$) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|---|
| 60 | 16 | 270 | 0.524 | 0.0087 | 9200 | 10.25 | 0.171 |
| | 20 | 295 | 0.573 | 0.0095 | 10300 | 12.50 | 0.208 |
| | 25 | 330 | 0.641 | 0.0107 | 11600 | 15.50 | 0.258 |
| | 30 | 360 | 0.699 | 0.0117 | 12600 | 17.50 | 0.292 |
| | 35 | 395 | 0.767 | 0.0128 | 13700 | 21.00 | 0.350 |
| | 40 | 410 | 0.796 | 0.0133 | 14600 | 23.50 | 0.392 |
| | 45 | 420 | 0.816 | 0.0136 | 15600 | 25.50 | 0.425 |

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|---|---|---|---|---|---|---|---|
| 50 | 16 | 255 | 0.495 | 0.0099 | 9600 | 9.50 | 0.190 |
| | 20 | 285 | 0.553 | 0.0111 | 10700 | 11.75 | 0.235 |
| | 25 | 310 | 0.602 | 0.0120 | 12000 | 14.25 | 0.285 |
| | 30 | 350 | 0.680 | 0.0136 | 13100 | 16.50 | 0.330 |
| | 35 | 380 | 0.738 | 0.0148 | 14000 | 19.25 | 0.385 |
| | 40 | 400 | 0.777 | 0.0155 | 15,400 | 21.75 | 0.435 |
| | 45 | 410 | 0.796 | 0.0159 | 16,200 | 23.75 | 0.475 |
| 40 | 16 | 235 | 0.456 | 0.0114 | 10,100 | 9.25 | 0.231 |
| | 20 | 265 | 0.515 | 0.0129 | 11,300 | 11.25 | 0.281 |
| | 25 | 295 | 0.573 | 0.0143 | 12,800 | 14.00 | 0.350 |
| | 30 | 295 | 0.573 | 0.0143 | 12,800 | 14.00 | 0.350 |
| | 35 | 325 | 0.631 | 0.0158 | 13,900 | 16.00 | 0.400 |
| | 40 | 370 | 0.719 | 0.0180 | 16,200 | 20.75 | 0.519 |
| | 45 | 380 | 0.738 | 0.0184 | 17,200 | 22.50 | 0.563 |
| 30 | 16 | 160 | 0.311 | 0.0104 | 11,200 | 7.50 | 0.250 |
| | 20 | 190 | 0.369 | 0.0123 | 12,600 | 9.25 | 0.308 |
| | 25 | 225 | 0.437 | 0.0146 | 14200 | 10.75 | 0.358 |
| | 30 | 240 | 0.466 | 0.0155 | 15500 | 13.00 | 0.433 |
| | 35 | 255 | 0.495 | 0.0165 | 16600 | 14.75 | 0.492 |
| | 40 | 267 | 0.519 | 0.0173 | 18000 | 16.50 | 0.550 |
| | 45 | 278 | 0.540 | 0.0180 | 19400 | 18.25 | 0.608 |
| 20 | 16 | 100 | 0.194 | 0.0097 | 11600 | 9.25 | 0.463 |
| | 20 | 120 | 0.233 | 0.0117 | 13400 | 11.25 | 0.563 |
| | 25 | 140 | 0.272 | 0.0136 | 14800 | 13.25 | 0.663 |

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|---|---|---|---|---|---|---|---|
| | 30 | 156 | 0.303 | 0.0152 | 16300 | 15.50 | 0.775 |
| | 35 | 170 | 0.330 | 0.0165 | 17700 | 18.50 | 0.925 |
| | 40 | 177 | 0.344 | 0.0172 | 19600 | 21.00 | 1.050 |
| | 45 | 185 | 0.359 | 0.0180 | 20,400 | 23.75 | 1.188 |
| 10 | 16 | 30 | 0.058 | 0.0058 | 12350 | 8.25 | 0.825 |
| | 20 | 40 | 0.078 | 0.0078 | 14000 | 10.00 | 1.000 |
| | 25 | 45 | 0.082 | 0.0087 | 15800 | 12.25 | 1.225 |
| | 30 | 53 | 0.103 | 0.0103 | 17400 | 13.50 | 1.350 |
| | 35 | 57 | 0.111 | 0.0111 | 18200 | 15.50 | 1.550 |
| | 40 | 60 | 0.117 | 0.0117 | 19700 | 16.75 | 1.475 |
| | 45 | 60 | 0.117 | 0.0117 | 20600 | 19.25 | 1.925 |

TABLE D.12.7

Cotton Yarn: 245 tex.
Nozzle: 1/4 x 3/16 in. inlets.
Tube: 3/4 in. dia.
Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in.$H_2O$) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|---|
| 60 | 16 | 330 | 0641 | 0.0107 | 10,600 | 12.75 | 0.213 |
| | 20 | 260 | 0.699 | 0.0117 | 11,800 | 15.75 | 0.263 |
| | 25 | 400 | 0.777 | 0.0129 | 13,300 | 18.50 | 0.308 |

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|---|---|---|---|---|---|---|---|
| | 30 | 440 | 0.854 | 0.0142 | 14,900 | 21.25 | 0.354 |
| | 35 | 480 | 0.932 | 0.0155 | 16,200 | 25.50 | 0.425 |
| | 40 | 500 | 0.971 | 0.0162 | 17,400 | 29.00 | 0.483 |
| | 45 | 515 | 1.000 | 0.0167 | 18,800 | 33.00 | 0.550 |
| 50 | 16 | 310 | 0.602 | 0.0120 | 11250 | 12.50 | 0.250 |
| | 20 | 345 | 0.670 | 0.0134 | 12800 | 15.50 | 0.310 |
| | 25 | 385 | 0.748 | 0.0150 | 13700 | 19.00 | 0.380 |
| | 30 | 420 | 0.816 | 0.0163 | 15700 | 22.25 | 0.445 |
| | 35 | 465 | 0.903 | 0.0181 | 17200 | 25.50 | 0.510 |
| | 40 | 485 | 0.942 | 0.0188 | 18600 | 28.50 | 0.570 |
| | 45 | 500 | 0.971 | 0.0194 | 19700 | 32.50 | 0.650 |
| 40 | 16 | 290 | 0.563 | 0.0141 | 11600 | 12.25 | 0.306 |
| | 20 | 320 | 0.621 | 0.0155 | 13400 | 15.25 | 0.381 |
| | 25 | 360 | 0.699 | 0.0175 | 15000 | 18.50 | 0.463 |
| | 30 | 400 | 0.777 | 0.0194 | 16600 | 22.00 | 0.550 |
| | 35 | 430 | 0.835 | 0.0209 | 18000 | 25.00 | 0.625 |
| | 40 | 450 | 0.874 | 0.0218 | 19400 | 27.25 | 0.681 |
| | 45 | 460 | 0.893 | 0.0223 | 20000 | 30.00 | 0.750 |
| 30 | 16 | 200 | 0.388 | 0.0129 | 12700 | 12.00 | 0.400 |
| | 20 | 230 | 0.447 | 0.0149 | 14200 | 15.00 | 0.500 |
| | 25 | 270 | 0.524 | 0.0175 | 16100 | 18.25 | 0.608 |
| | 30 | 290 | 0.563 | 0.0188 | 17500 | 21.00 | 0.700 |
| | 35 | 310 | 0.602 | 0.0201 | 19000 | 24.50 | 0.817 |
| | 40 | 325 | 0.631 | 0.0210 | 19800 | 27.00 | 0.900 |
| | 45 | 340 | 0.660 | 0.220 | 21000 | 29.50 | 0.983 |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 20 | 16 | 120 | 0.233 | 0.0117 | 13400 | 11.75 | 0.588 |
| | 20 | 150 | 0.291 | 0.0141 | 15400 | 14.25 | 0.713 |
| | 25 | 170 | 0.330 | 0.0165 | 17000 | 16.75 | 0.838 |
| | 30 | 190 | 0.369 | 0.0185 | 18500 | 19.50 | 0.975 |
| | 35 | 205 | 0.398 | 0.0199 | 20200 | 23.25 | 1.163 |
| | 40 | 215 | 0.418 | 0.0209 | 21600 | 26.25 | 1.313 |
| | 45 | 224 | 0.435 | 0.0218 | 22400 | 28.00 | 1.400 |
| 10 | 16 | 40 | 0.078 | 0.0078 | 14000 | 9.25 | 0.925 |
| | 20 | 48 | 0.093 | 0.0093 | 15800 | 11.25 | 1.125 |
| | 25 | 55 | 0.107 | 0.0107 | 18000 | 13.75 | 1.375 |
| | 30 | 65 | 0.126 | 0.0126 | 19100 | 16.50 | 1.650 |
| | 35 | 70 | 0.136 | 0.0136 | 20800 | 18.75 | 1.875 |
| | 40 | 72 | 0.140 | 0.0140 | 22000 | 20.25 | 2.025 |
| | 45 | 72 | 0.140 | 0.0140 | 23000 | 22.00 | 2.200 |

TABLE D.12.8

Cotton Yarn: 245 tex.
Nozzle: 1/4 x 1/16 in. inlets.
Tube: 3/4 in. dia.
Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in.$H_2O$) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|---|
| 60 | 16 | 190 | 0.369 | 0.0062 | 6500 | 7.00 | 0.117 |

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|---|---|---|---|---|---|---|---|
| | 20 | 210 | 0.408 | 0.0068 | 7400 | 7.75 | 0.117 |
| | 25 | 230 | 0.447 | 0.0074 | 8400 | 9.00 | 0.150 |
| | 30 | 250 | 0.486 | 0.0081 | 9100 | 10.00 | 0.167 |
| | 35 | 275 | 0.534 | 0.0089 | 10,000 | 11.50 | 0.192 |
| | 40 | 285 | 0.553 | 0.0092 | 10,600 | 13.00 | 0.217 |
| | 45 | 295 | 0.573 | 0.0096 | 11,300 | 14.50 | 0.242 |
| 50 | 16 | 180 | 0.350 | 0.0070 | 6800 | 6.25 | 0.125 |
| | 20 | 200 | 0.388 | 0.0078 | 7900 | 7.25 | 0.145 |
| | 25 | 220 | 0.427 | 0.0085 | 8900 | 8.25 | 0.165 |
| | 30 | 245 | 0.476 | 0.0095 | 9500 | 9.50 | 0.190 |
| | 35 | 265 | 0.515 | 0.0103 | 10,200 | 10.50 | 0.210 |
| | 40 | 280 | 0.544 | 0.0109 | 10,900 | 11.75 | 0.235 |
| | 45 | 290 | 0.563 | 0.0113 | 11,400 | 13.50 | 0.270 |
| 40 | 16 | 165 | 0.320 | 0.0080 | 7300 | 5.25 | 0.131 |
| | 20 | 185 | 0.359 | 0.0090 | 8000 | 6.50 | 0.163 |
| | 25 | 205 | 0.398 | 0.0100 | 9000 | 7.50 | 0.188 |
| | 30 | 230 | 0.447 | 0.0112 | 10,000 | 8.50 | 0.213 |
| | 35 | 250 | 0.486 | 0.0121 | 10,900 | 10.00 | 0.250 |
| | 40 | 260 | 0.505 | 0.0126 | 11,500 | 11.00 | 0.275 |
| | 45 | 265 | 0.515 | 0.0129 | 12,100 | 12.25 | 0.306 |
| 30 | 16 | 115 | 0.223 | 0.0074 | 7,750 | 5.25 | 0.175 |
| | 20 | 130 | 0.252 | 0.0084 | 8500 | 6.25 | 0.208 |
| | 25 | 160 | 0.311 | 0.0104 | 9400 | 7.50 | 0.250 |
| | 30 | 170 | 0.330 | 0.0110 | 10,300 | 8.75 | 0.292 |
| | 35 | 180 | 0.350 | 0.0117 | 11,100 | 10.50 | 0.350 |
| | 40 | 188 | 0.365 | 0.0122 | 11,900 | 11.75 | 0.392 |
| | 45 | 195 | 0.379 | 0.0126 | 12,700 | 13.00 | 0.433 |

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|---|---|---|---|---|---|---|---|
| 20 | 16 | 70 | 0.136 | 0.0068 | 9,900 | 6.50 | 0.325 |
| | 20 | 85 | 0.165 | 0.0083 | 10,900 | 7.50 | 0.375 |
| | 25 | 95 | 0.184 | 0.0092 | 12,100 | 9.25 | 0.463 |
| | 30 | 110 | 0.214 | 0.0107 | 13,300 | 10.25 | 0.513 |
| | 35 | 120 | 0.233 | 0.0117 | 14,300 | 11.75 | 0.588 |
| | 40 | 125 | 0.243 | 0.0122 | 15,500 | 12.75 | 0.638 |
| | 45 | 130 | 0.252 | 0.0126 | 16,400 | 14.25 | 0.713 |
| 10 | 16 | 20 | 0.039 | 0.0039 | 9,900 | 5.50 | 0.550 |
| | 20 | 27 | 0.052 | 0.0052 | 10,900 | 6.75 | 0.675 |
| | 25 | 32 | 0.062 | 0.0062 | 12,100 | 8.25 | 0.825 |
| | 30 | 37 | 0.072 | 0.0072 | 13,300 | 9.25 | 0.925 |
| | 35 | 40 | 0.078 | 0.0078 | 14,300 | 10.75 | 1.075 |
| | 40 | 41 | 0.080 | 0.0080 | 15,500 | 12.00 | 1.200 |
| | 45 | 42 | 0.082 | 0.0082 | 16,400 | 12.75 | 1.275 |

TABLE D.12.9

Cotton Yarn: 245 tex.
Nozzle: $\frac{1}{2}$ x 1/16 in. inlets.
Tube: 3/4 in. dia.
Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in.$H_2O$) | Yarn Tail Speed (r.p.m.) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|
| 60 | 16 | 9800 | 0.422 | 0.0070 | 13.25 | 0.221 |
| | 20 | 11050 | 0.463 | 0.0077 | 14.50 | 0.242 |
| | 25 | 12350 | 0.504 | 0.0084 | 17.25 | 0.288 |
| | 30 | 13500 | 0.529 | 0.0088 | 19.50 | 0.325 |
| | 35 | 14700 | 0.524 | 0.0089 | 22.25 | 0.371 |
| | 40 | 15800 | 0.540 | 0.0090 | 24.50 | 0.408 |
| | 45 | 16800 | 0.540 | 0.0090 | 27.50 | 0.475 |
| 50 | 16 | 10100 | 0.273 | 0.0055 | 12.25 | 0.245 |
| | 20 | 11400 | 0.327 | 0.0065 | 14.00 | 0.280 |
| | 25 | 13000 | 0.354 | 0.0071 | 16.75 | 0.335 |
| | 30 | 14300 | 0.371 | 0.0074 | 19.00 | 0.380 |
| | 35 | 15600 | 0.371 | 0.0074 | 21.50 | 0.430 |
| | 40 | 16600 | 0.382 | 0.0076 | 24.25 | 0.485 |
| | 45 | 17700 | 0.382 | 0.0076 | 27.50 | 0.550 |

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|---|---|---|---|---|---|---|
| 40 | 16 | 11000 | 0.218 | 0.0055 | 11.00 | 0.275 |
| | 20 | 12100 | 0.245 | 0.0061 | 13.25 | 0.331 |
| | 25 | 13700 | 0.273 | 0.0068 | 16.00 | 0.400 |
| | 30 | 15300 | 0.300 | 0.0075 | 18.25 | 0.456 |
| | 35 | 16600 | 0.316 | 0.0079 | 20.50 | 0.513 |
| | 40 | 17600 | 0.327 | 0.0082 | 22.75 | 0.568 |
| | 45 | 19000 | 0.327 | 0.0082 | 26.00 | 0.650 |
| 30 | 16 | 12000 | 0.191 | 0.0064 | 10.50 | 0.350 |
| | 20 | 13300 | 0.204 | 0.0068 | 12.50 | 0.417 |
| | 25 | 14900 | 0.218 | 0.0073 | 15.00 | 0.500 |
| | 30 | 16200 | 0.232 | 0.0077 | 17.50 | 0.583 |
| | 35 | 17700 | 0.245 | 0.0082 | 19.75 | 0.658 |
| | 40 | 19300 | 0.259 | 0.0086 | 22.25 | 0.742 |
| | 45 | 20200 | 0.267 | 0.0089 | 25.50 | 0.850 |
| 20 | 16 | 12700 | 0.164 | 0.0082 | 10.00 | 0.500 |
| | 20 | 14000 | 0.177 | 0.0089 | 12.00 | 0.600 |
| | 25 | 16100 | 0.191 | 0.0091 | 14.50 | 0.725 |
| | 30 | 17600 | 0.204 | 0.0102 | 16.25 | 0.813 |
| | 35 | 18400 | 0.218 | 0.0109 | 19.00 | 0.950 |
| | 40 | 19800 | 0.223 | 0.0112 | 21.50 | 1.075 |
| | 45 | 21006 | 0.245 | 0.0123 | 23.25 | 1.163 |

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|---|---|---|---|---|---|---|
| 10 | 16 | 13000 | 0.136 | 0.0136 | 9.50 | 0.950 |
| | 20 | 14400 | 0.164 | 0.0164 | 11.25 | 1.125 |
| | 25 | 16200 | 0.169 | 0.0169 | 13.25 | 1.325 |
| | 30 | 18000 | 0.191 | 0.0191 | 15.00 | 1.500 |
| | 35 | 18600 | 0.196 | 0.0196 | 17.00 | 1.700 |
| | 40 | 19900 | 0.204 | 0.0204 | 19.50 | 1.950 |
| | 45 | 21200 | 0.204 | 0.0204 | 21.25 | 2.125 |

TABLE D.12.10

Cotton Yarn: 245 tex.
Nozzle: 1/2 in. x 3/16 in. inlets.
Tube: 3/4 in. dia.
Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in. $H_2O$) | Yarn Tail Speed (r.p.m.) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|
| 60 | 16 | 13200 | 0.327 | 0.0055 | 22.50 | 0.375 |
| | 20 | 14700 | 0.409 | 0.0068 | 25.75 | 0.429 |
| | 25 | 16800 | 0.491 | 0.0082 | 30.00 | 0.500 |
| | 30 | 18600 | 0.545 | 0.0091 | 35.50 | 0.592 |
| | 35 | 20000 | 0.600 | 0.0100 | 40.50 | 0.675 |
| 50 | 16 | 13700 | 0.273 | 0.0055 | 21.00 | 0.420 |
| | 20 | 15600 | 0.354 | 0.0071 | 24.50 | 0.490 |
| | 25 | 17500 | 0.409 | 0.0082 | 29.50 | 0.590 |
| | 30 | 19100 | 0.491 | 0.0098 | 33.75 | 0.675 |
| | 35 | 20200 | 0.531 | 0.0106 | 40.00 | 0.800 |
| 40 | 16 | 14600 | 0.191 | 0.0048 | 19.25 | 0.481 |
| | 20 | 16000 | 0.218 | 0.0055 | 23.50 | 0.588 |
| | 25 | 18000 | 0.273 | 0.0068 | 28.00 | 0.700 |
| | 30 | 19400 | 0.300 | 0.0075 | 32.50 | 0.813 |
| | 35 | 20500 | 0.341 | 0.0085 | 38.50 | 0.963 |

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|---|---|---|---|---|---|---|
| 30 | 16 | 14700 | 0.164 | 0.0055 | 17.50 | 0.583 |
| | 20 | 16200 | 0.177 | 0.0059 | 21.00 | 0.700 |
| | 25 | 18400 | 0.218 | 0.0073 | 26.50 | 0.883 |
| | 30 | 19900 | 0.245 | 0.0082 | 30.50 | 1.017 |
| | 35 | 20700 | 0.273 | 0.0091 | 35.50 | 1.183 |
| 20 | 16 | 14910 | 0.177 | 0.0089 | 15.25 | 0.763 |
| | 20 | 16400 | 0.218 | 0.0109 | 19.00 | 0.950 |
| | 25 | 18800 | 0.354 | 0.0177 | 23.50 | 1.175 |
| | 30 | 20600 | 0.450 | 0.0225 | 26.50 | 1.325 |
| | 35 | 21200 | 0.586 | 0.0293 | 29.75 | 1.488 |
| 10 | 16 | 15400 | 0.204 | 0.0204 | 11.75 | 1.175 |
| | 20 | 17000 | 0.218 | 0.0218 | 13.50 | 1.350 |
| | 25 | 18900 | 0.245 | 0.0245 | 16.25 | 1.625 |
| | 30 | 20700 | 0.273 | 0.0273 | 19.50 | 1.950 |
| | 35 | 21600 | 0.286 | 0.0286 | 21.50 | 2.150 |

TABLE D.12.11

Cotton Yarn 245 tex.

Nozzle: 1/2 ins. x 3/16 ins. inlets.

Tube: 1 in. dia.

Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in. $H_2O$) | Yarn Tail Speed (r.p.m.) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|
| 60 | 16 | 10800 | 0.858 | 0.0143 | 17.00 | 0.283 |
| | 20 | 12000 | 0.940 | 0.0157 | 20.50 | 0.342 |
| | 25 | 13350 | 0.995 | 0.0166 | 26.00 | 0.433 |
| | 30 | 14650 | 1.049 | 0.0175 | 30.00 | 0.500 |
| | 35 | 15800 | 1.090 | 0.0182 | 34.50 | 0.575 |
| 50 | 16 | 11600 | 0.640 | 0.0128 | 16.50 | 0.530 |
| | 20 | 12400 | 0.709 | 0.0142 | 20.00 | 0.400 |
| | 25 | 14000 | 0.790 | 0.0158 | 25.00 | 0.500 |
| | 30 | 15300 | 0.831 | 0.0166 | 29.50 | 0.590 |
| | 35 | 16400 | 0.872 | 0.0174 | 34.00 | 0.680 |
| 40 | 16 | 11800 | 0.319 | 0.0079 | 16.00 | 0.400 |
| | 20 | 12850 | 0.382 | 0.0096 | 19.50 | 0.488 |
| | 25 | 14350 | 0.463 | 0.0116 | 23.50 | 0.588 |
| | 30 | 15800 | 0.572 | 0.0143 | 28.50 | 0.713 |
| | 35 | 17000 | 0.640 | 0.0160 | 32.00 | 0.800 |

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|---|---|---|---|---|---|---|
| 30 | 16 | 12200 | 0.273 | 0.0091 | 15.75 | 0.525 |
| | 20 | 13300 | 0.341 | 0.0114 | 18.75 | 0.625 |
| | 25 | 15400 | 0.436 | 0.0145 | 23.00 | 0.767 |
| | 30 | 16300 | 0.518 | 0.0173 | 27.50 | 0.917 |
| | 35 | 18000 | 0.613 | 0.0204 | 30.50 | 1.017 |
| 20 | 16 | 12900 | 0.395 | 0.0198 | 14.50 | 0.725 |
| | 20 | 14500 | 0.403 | 0.0202 | 17.50 | 0.875 |
| | 25 | 16100 | 0.409 | 0.0205 | 21.50 | 1.075 |
| | 30 | 17600 | 0.422 | 0.0211 | 25.25 | 1.263 |
| | 35 | 18900 | 0.422 | 0.0211 | 29.00 | 1.450 |
| 10 | 16 | 14100 | 0.313 | 0.0313 | 13.25 | 1.325 |
| | 20 | 15700 | 0.327 | 0.0327 | 15.75 | 1.575 |
| | 25 | 17500 | 0.332 | 0.0332 | 20.00 | 2.000 |
| | 30 | 19100 | 0.341 | 0.0341 | 22.50 | 2.250 |
| | 35 | 20500 | 0.341 | 0.0341 | 27.25 | 2.725 |

TABLE D.12.12

Cotton Yarn: 245 tex.
Nozzle: 3/4 in. x 1/16 in. inlets.
Tube: 3/4 in. dia.
Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in.$H_2O$) | Yarn Tail Speed (r.p.m.) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|
| 60 | 16 | 11100 | 0.300 | 0.0050 | 12.75 | 0.213 |
| | 20 | 12300 | 0.327 | 0.0055 | 15.25 | 0.254 |
| | 25 | 14000 | 0.354 | 0.0059 | 18.50 | 0.308 |
| | 30 | 15400 | 0.409 | 0.0068 | 22.00 | 0.367 |
| | 35 | 16900 | 0.491 | 0.0082 | 25.25 | 0.421 |
| | 40 | 18400 | 0.545 | 0.0091 | 28.00 | 0.467 |
| 50 | 16 | 11400 | 0.191 | 0.0038 | 12.50 | 0.250 |
| | 20 | 12700 | 0.204 | 0.0041 | 15.00 | 0.300 |
| | 25 | 14300 | 0.232 | 0.0046 | 18.00 | 0.360 |
| | 30 | 15600 | 0.245 | 0.0049 | 21.25 | 0.425 |
| | 35 | 17300 | 0.259 | 0.0062 | 25.00 | 0.500 |
| | 40 | 18800 | 0.286 | 0.0057 | 27.50 | 0.550 |
| 40 | 16 | 12000 | 0.164 | 0.0041 | 11.75 | 0.294 |
| | 20 | 13800 | 0.191 | 0.0048 | 14.25 | 0.356 |
| | 25 | 15400 | 0.213 | 0.0053 | 17.25 | 0.431 |
| | 30 | 16800 | 0.218 | 0.0055 | 21.00 | 0.525 |

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|---|---|---|---|---|---|---|
| | 35 | 18200 | 0.232 | 0.0058 | 24.50 | 0.613 |
| | 40 | 19400 | 0.232 | 0.0058 | 27.00 | 0.675 |
| 30 | 16 | 12800 | 0.123 | 0.0041 | 11.50 | 0.383 |
| | 20 | 14000 | 0.136 | 0.0045 | 14.00 | 0.467 |
| | 25 | 15600 | 0.164 | 0.0055 | 17.00 | 0.567 |
| | 30 | 17000 | 0.177 | 0.0059 | 19.50 | 0.650 |
| | 35 | 18300 | 0.191 | 0.0064 | 21.50 | 0.717 |
| | 40 | 19600 | 0.204 | 0.0068 | 25.50 | 0.850 |
| 20 | 16 | 13100 | 0.109 | 0.0055 | 10.50 | 0.525 |
| | 20 | 14500 | 0.123 | 0.0062 | 12.75 | 0.638 |
| | 25 | 16100 | 0.131 | 0.0066 | 15.00 | 0.750 |
| | 30 | 17500 | 0.142 | 0.0071 | 17.00 | 0.850 |
| | 35 | 18700 | 0.150 | 0.0075 | 20.00 | 1.000 |
| | 40 | 20200 | 0.153 | 0.0077 | 22.50 | 1.125 |
| 10 | 16 | 13600 | 0.109 | 0.0109 | 9.75 | 0.975 |
| | 20 | 15200 | 0.123 | 0.0123 | 11.50 | 1.150 |
| | 25 | 16800 | 0.136 | 0.0136 | 13.00 | 1.300 |
| | 30 | 18000 | 0.164 | 0.0164 | 14.75 | 1.475 |
| | 35 | 19600 | 0.169 | 0.0169 | 17.25 | 1.725 |
| | 40 | 2100 | 0.177 | 0.0177 | 19.50 | 1.950 |

TABLE D.12.13

Cotton Yarn: 245 tex.

Nozzle: 3/4 in. x 3/16 in. inlets.

Tube: 3/4 in. dia.

Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube ($-$in. $H_2O$) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|
| 60 | 16 | 0.109 | 0.0018 | 20.50 | 0.342 |
| | 20 | 0.164 | 0.0027 | 24.75 | 0.413 |
| | 25 | 0.327 | 0.0055 | 30.00 | 0.500 |
| | 30 | 0.409 | 0.0068 | 35.00 | 0.583 |
| | 35 | 0.422 | 0.0070 | 40.00 | 0.667 |
| 50 | 16 | 0.109 | 0.0022 | 19.75 | 0.395 |
| | 20 | 0.136 | 0.0027 | 23.50 | 0.470 |
| | 25 | 0.204 | 0.0041 | 28.50 | 0.570 |
| | 30 | 0.232 | 0.0046 | 33.00 | 0.660 |
| | 35 | 0.273 | 0.0055 | 37.50 | 0.750 |
| 40 | 16 | 0.845 | 0.0211 | 18.50 | 0.463 |
| | 20 | 1.090 | 0.0273 | 21.50 | 0.538 |
| | 25 | 1.417 | 0.0354 | 26.50 | 0.663 |
| | 30 | 1.799 | 0.0450 | 30.00 | 0.750 |
| | 35 | 2.235 | 0.0559 | 34.00 | 0.850 |
| 30 | 16 | 0.981 | 0.0327 | 16.00 | 0.533 |
| | 20 | 1.199 | 0.0400 | 19.00 | 0.633 |
| | 25 | 1.499 | 0.0500 | 22.00 | 0.733 |
| | 30 | 1.962 | 0.0654 | 25.50 | 0.850 |
| | 35 | 2.453 | 0.0818 | 28.50 | 0.950 |
| 20 | 16 | 1.390 | 0.0695 | 14.50 | 0.725 |
| | 20 | 1.690 | 0.0845 | 17.00 | 0.850 |
| | 25 | 2.153 | 0.1077 | 19.75 | 0.988 |
| | 30 | 2.562 | 0.1281 | 22.50 | 1.125 |
| | 35 | 2.861 | 0.1431 | 25.00 | 1.250 |
| 10 | 16 | 1.022 | 0.1022 | 13.50 | 1.350 |
| | 20 | 1.254 | 0.1254 | 15.25 | 1.525 |
| | 25 | 1.567 | 0.1567 | 17.50 | 1.750 |
| | 30 | 1.826 | 0.1826 | 19.50 | 1.950 |
| | 35 | 1.989 | 0.1989 | 22.00 | 2.200 |

TABLE D.12.14

Cotton Yarn: 245 tex.

Nozzle: 1 in. x 1/16 in. inlets.

Tube: 3/4 in. dia.

Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube ($-$in.$H_2O$) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tail Speed (r.p.m.) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|
| 60 | 16 | 320 | 0.872 | 0.0145 | 12400 | 0.872 |
| | 20 | 340 | 0.923 | 0.0154 | 14100 | 0.927 |
| | 25 | 380 | 1.036 | 0.0172 | 15400 | 1.036 |
| | 30 | 420 | 1.145 | 0.1910 | 17100 | 1.145 |
| 50 | 16 | 120 | 0.327 | 0.0065 | 13200 | 0.055 |
| | 20 | 150 | 0.409 | 0.0082 | 14800 | 0.109 |
| | 25 | 170 | 0.463 | 0.0093 | 16500 | 0.136 |
| | 30 | 190 | 0.518 | 0.1040 | 18100 | 0.218 |
| 40 | 16 | 240 | 0.654 | 0.0164 | 12600 | 0.095 |
| | 20 | 300 | 0.818 | 0.0027 | 14200 | 0.123 |
| | 25 | 380 | 1.036 | 0.0204 | 15600 | 0.177 |
| | 30 | 430 | 1.172 | 0.0259 | 16900 | 0.300 |
| 30 | 16 | 190 | 0.518 | 0.0173 | 13000 | 0.123 |
| | 20 | 225 | 0.613 | 0.0204 | 14200 | 0.150 |
| | 25 | 260 | 0.709 | 0.0236 | 15800 | 0.191 |
| | 30 | 290 | 0.790 | 0.0263 | 17400 | 0.313 |

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|---|---|---|---|---|---|---|
| 20 | 16 | 20 | 0.055 | 0.0027 | 13000 | 0.055 |
| | 20 | 45 | 0.123 | 0.0061 | 13800 | 0.068 |
| | 25 | 60 | 0.164 | 0.0082 | 15200 | 0.164 |
| | 30 | 80 | 0.218 | 0.0109 | 16000 | 0.245 |
| 10 | 16 | 10 | 0.027 | 0.0027 | 12700 | 0.041 |
| | 20 | 30 | 0.081 | 0.0081 | 14000 | 0.055 |
| | 25 | 50 | 0.136 | 0.0136 | 15400 | 0.136 |
| | 30 | 60 | 0.164 | 0.0164 | 16000 | 0.177 |

TABLE D.12.15

Cotton Yarn: 245 tex.

Nozzle: 1 in. x 3/16 in. inlets.

Tube: 3/4 in. dia.

Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in. $H_2O$) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tail Speed (r.p.m.) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|
| 60 | 16 | 900 | 2.453 | 0.0409 | 900 | 0.367 |
| | 20 | 1270 | 3.461 | 0.0577 | 1270 | 0.442 |
| | 25 | 1650 | 4.496 | 0.0749 | 1650 | 0.525 |
| | 30 | 1950 | 5.314 | 0.0886 | 1950 | 0.617 |

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|---|---|---|---|---|---|---|
| 50 | 16 | 800 | 2.180 | 0.0436 | 800 | - |
| | 20 | 1060 | 2.889 | 0.0578 | 1010 | - |
| | 25 | 1250 | 3.406 | 0.0681 | 1250 | - |
| | 30 | 1380 | 3.761 | 0.0752 | 1380 | - |
| 40 | 16 | 880 | 2.398 | 0.0600 | 880 | 0.450 |
| | 20 | 1150 | 3.134 | 0.0783 | 1150 | 0.538 |
| | 25 | 1390 | 3.788 | 0.0947 | 1390 | 0.588 |
| | 30 | 1520 | 4.142 | 0.1036 | 1520 | 0.625 |
| 30 | 16 | 475 | 1.294 | 0.0431 | 475 | - |
| | 20 | 580 | 1.581 | 0.0527 | 580 | - |
| | 25 | 750 | 2.044 | 0.0681 | 750 | - |
| | 30 | 900 | 2.453 | 0.0818 | 900 | - |
| 20 | 16 | 690 | 1.880 | 0.0940 | 660 | - |
| | 20 | 825 | 2.248 | 0.1124 | 825 | - |
| | 25 | 950 | 2.589 | 0.1294 | 950 | - |
| | 30 | 1060 | 2.889 | 0.1445 | 1060 | - |
| 10 | 16 | 360 | 0.981 | 0.0981 | 360 | - |
| | 20 | 480 | 1.308 | 0.1308 | 480 | - |
| | 25 | 575 | 1.567 | 0.1567 | 575 | - |
| | 30 | 660 | 1.799 | 0.1799 | 650 | - |

TABLE D.12.16

Cotton Yarn: 245 tex.
Nozzle: 1 in. x 1/4 in. inlets.
Tube: 3/4 in. dia.
Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in. $H_2O$) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|---|
| 60 | 16 | 940 | 2.562 | 0.0427 | 13600 | 23.00 | 0.383 |
| | 20 | 1320 | 3.597 | 0.0600 | 14800 | 27.50 | 0.458 |
| | 25 | 1770 | 4.823 | 0.0804 | 16000 | 34.50 | 0.575 |
| | 30 | 2120 | 5.777 | 0.0963 | 17300 | 40.50 | 0.675 |
| 50 | 16 | 885 | 2.412 | 0.0482 | 14000 | 22.50 | 0.450 |
| | 20 | 1150 | 3.134 | 0.0627 | 15600 | 25.50 | 0.510 |
| | 25 | 1340 | 3.652 | 0.0730 | 16600 | 31.25 | 0.625 |
| | 30 | 1480 | 4.033 | 0.0807 | 17500 | 36.25 | 0.725 |
| 40 | 16 | 930 | 2.534 | 0.0634 | 14500 | 19.25 | 0.481 |
| | 20 | 1200 | 3.270 | 0.0818 | 16000 | 23.25 | 0.581 |
| | 25 | 1420 | 3.870 | 0.0967 | 17100 | 29.25 | 0.731 |
| | 30 | 1480 | 4.033 | 0.1008 | 17900 | 34.50 | 0.863 |

Continued on next page.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 30 | 16 | 600 | 1.635 | 0.0545 | 14900 | 18.00 | 0.600 |
| | 20 | 720 | 1.962 | 0.0654 | 16600 | 21.50 | 0.717 |
| | 25 | 890 | 2.425 | 0.0808 | 17700 | 25.50 | 0.850 |
| | 30 | 1010 | 2.752 | 0.0917 | 18500 | 29.50 | 0.983 |
| 20 | 16 | 750 | 2.044 | 0.1022 | 15400 | 15.00 | 0.750 |
| | 20 | 880 | 2.398 | 0.1199 | 17200 | 17.50 | 0.875 |
| | 25 | 990 | 2.698 | 0.1349 | 18400 | 20.50 | 1.025 |
| | 30 | 1100 | 2.998 | 0.1499 | 19100 | 23.00 | 1.150 |
| 10 | 16 | 370 | 1.008 | 0.1008 | 16000 | 8.75 | 0.875 |
| | 20 | 510 | 1.390 | 0.1390 | 17900 | 9.50 | 0.950 |
| | 25 | 630 | 1.717 | 0.1717 | 19100 | 10.75 | 1.075 |
| | 30 | 720 | 1.962 | 0.1962 | 20000 | 12.25 | 1.225 |

TABLE D.12.17

Cotton Yarn: 245 tex.
Nozzle: 1 in x 1/8 in. inlets.
Tube: 3/4 in. dia.
Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in. $H_2O$) | Torsional Deflection (Degrees) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) | Yarn Tail Speed (r.p.m.) | Yarn Tension (gf) | Tension Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|---|---|---|
| 60 | 16 | 355 | 0.967 | 0.0161 | 13000 | 21.75 | 0.363 |
| | 20 | 400 | 1.090 | 0.0182 | 14400 | 25.50 | 0.425 |
| | 25 | 470 | 1.281 | 0.0213 | 15800 | 31.50 | 0.525 |
| | 30 | 550 | 1.499 | 0.0250 | 17100 | 37.00 | 0.617 |

Continued on next page.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 50 | 16 | 320 | 0.872 | 0.0174 | 13400 | 20.25 | 0.405 |
| | 20 | 370 | 1.008 | 0.0202 | 14800 | 25.00 | 0.500 |
| | 25 | 430 | 1.172 | 0.0234 | 16400 | 31.00 | 0.620 |
| | 30 | 510 | 1.390 | 0.0278 | 18200 | 35.00 | 0.700 |
| 40 | 16 | 630 | 1.717 | 0.0429 | 14000 | 19.50 | 0.488 |
| | 20 | 800 | 2.180 | 0.545 | 15600 | 22.50 | 0.563 |
| | 25 | 1050 | 2.861 | 0.0715 | 17200 | 27.00 | 0.675 |
| | 30 | 1250 | 3.401 | 0.0852 | 19400 | 29.50 | 0.738 |
| 30 | 16 | 335 | 0.913 | 0.0304 | 14500 | 18.00 | 0.600 |
| | 20 | 395 | 1.076 | 0.0359 | 16000 | 21.25 | 0.708 |
| | 25 | 475 | 1.294 | 0.0431 | 17500 | 25.50 | 0.850 |
| | 30 | 575 | 1.567 | 0.0522 | 20000 | 29.00 | 0.967 |
| 20 | 16 | 560 | 1.526 | 0.0763 | 14900 | 13.50 | 0.675 |
| | 20 | 630 | 1.717 | 0.0858 | 16400 | 16.25 | 0.813 |
| | 25 | 770 | 2.098 | 0.1049 | 18000 | 19.25 | 0.963 |
| | 30 | 900 | 2.453 | 0.1226 | 20200 | 22.25 | 1.113 |
| 10 | 16 | 340 | 0.927 | 0.0927 | 15400 | 11.00 | 1.100 |
| | 20 | 420 | 1.143 | 0.1143 | 17000 | 12.50 | 1.250 |
| | 25 | 510 | 1.390 | 0.1390 | 18600 | 14.75 | 1.475 |
| | 30 | 560 | 1.526 | 0.1526 | 20600 | 16.50 | 1.630 |

TABLE D.12.18

Cotton Yarn: 245 tex.
Nozzle: 1 in x 1/16 in. inlets.
Tube: 3/4 in. dia.
Axial Hole: 3/16 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in. $H_2O$) | Yarn Tail Speed (r.p.m.) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|
| 60 | 16 | 11600 | 0.095 | 0.0016 |
| | 20 | 12600 | 0.109 | 0.0018 |
| | 25 | 15400 | 0.123 | 0.0021 |
| | 30 | 16800 | 0.164 | 0.0027 |
| | 35 | 18200 | 0.218 | 0.0036 |
| 50 | 16 | 12100 | 0.095 | 0.0019 |
| | 20 | 13800 | 0.109 | 0.0022 |
| | 25 | 15400 | 0.123 | 0.0025 |
| | 30 | 16500 | 0.150 | 0.0030 |
| | 35 | 18000 | 0.273 | 0.0055 |
| 40 | 16 | 12800 | 0.068 | 0.0017 |
| | 20 | 14400 | 0.082 | 0.0021 |
| | 25 | 16300 | 0.095 | 0.0024 |
| | 30 | 17400 | 0.109 | 0.0027 |
| | 35 | 18900 | 0.123 | 0.0031 |
| 30 | 16 | 13000 | 0.027 | 0.0009 |
| | 20 | 14900 | 0.033 | 0.0011 |
| | 25 | 16500 | 0.041 | 0.0014 |
| | 30 | 18500 | 0.055 | 0.0018 |
| | 35 | 19800 | 0.068 | 0.0023 |
| 20 | 16 | 12600 | 0.109 | 0.0055 |
| | 20 | 14600 | 0.164 | 0.0082 |
| | 25 | 1600 | 0.204 | 0.0102 |
| | 30 | 17300 | 0.232 | 0.0116 |
| | 35 | 18700 | 0.245 | 0.0123 |
| 10 | 16 | 13600 | 0.068 | 0.0068 |
| | 20 | 15200 | 0.095 | 0.0095 |
| | 25 | 16600 | 0.123 | 0.0123 |
| | 30 | 17500 | 0.136 | 0.0136 |
| | 35 | 19100 | 0.164 | 0.0164 |

TABLE D.12.19

Cotton Yarn: 245 tex.
Nozzle: 1 in. x 1/16 in. inlets.
Tube: 3/4 in. dia.
Axial Hole 1/4 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in. $H_2O$) | Yarn Tail Speed (r.p.m.) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|
| 60 | 16 | 11500 | 0.252 | 0.0043 |
| | 20 | 14200 | 0.382 | 0.0064 |
| | 25 | 16200 | 0.450 | 0.0075 |
| | 30 | 17400 | 0.545 | 0.0091 |
| | 35 | 18200 | 0.613 | 0.0102 |
| 50 | 16 | 12500 | 0.300 | 0.0060 |
| | 20 | 14800 | 0.395 | 0.0079 |
| | 25 | 16500 | 0.491 | 0.0098 |
| | 30 | 17900 | 0.586 | 0.0117 |
| | 35 | 18600 | 0.654 | 0.0131 |
| 40 | 16 | 12300 | 0.109 | 0.0027 |
| | 20 | 12600 | 0.123 | 0.0031 |
| | 25 | 15000 | 0.150 | 0.0038 |
| | 30 | 15800 | 0.177 | 0.0044 |
| | 35 | 17200 | 0.204 | 0.0051 |
| 30 | 16 | 12800 | 0.327 | 0.0109 |
| | 20 | 14100 | 0.382 | 0.0127 |
| | 25 | 15600 | 0.436 | 0.0145 |
| | 30 | 16800 | 0.491 | 0.0164 |
| | 35 | 18000 | 0.600 | 0.0200 |
| 20 | 16 | 12600 | 0.273 | 0.0137 |
| | 20 | 13400 | 0.436 | 0.0218 |
| | 25 | 14800 | 0.654 | 0.0327 |
| | 30 | 16400 | 0.749 | 0.0375 |
| | 35 | 18300 | 0.818 | 0.0409 |
| 10 | 16 | 13300 | 0.232 | 0.0232 |
| | 20 | 14300 | 0.259 | 0.0259 |
| | 25 | 15700 | 0.382 | 0.0382 |
| | 30 | 17100 | 0.491 | 0.0491 |
| | 35 | 18200 | 0.573 | 0.0573 |

TABLE D.12.20

Cotton Yarn: 245 tex.

Nozzle: 1 in. x 1/16 in. inlets.

Tube: 3/4 in. dia.

Axial Hole: 5/16 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in.$H_2O$) | Yarn Tail Speed (r.p.m.) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|
| 60 | 16 | 10200 | 0.341 | 0.0057 |
| | 20 | 11200 | 0.436 | 0.0073 |
| | 25 | 14300 | 0.531 | 0.0089 |
| | 30 | 15400 | 0.613 | 0.0102 |
| 50 | 16 | 10400 | 0.273 | 0.0055 |
| | 20 | 11500 | 0.313 | 0.0063 |
| | 25 | 14600 | 0.368 | 0.0074 |
| | 30 | 15600 | 0.422 | 0.0084 |
| 40 | 16 | 11000 | 0.191 | 0.0048 |
| | 20 | 12200 | 0.218 | 0.0055 |
| | 25 | 15100 | 0.232 | 0.0058 |
| | 30 | 16300 | 0.245 | 0.0061 |
| 30 | 16 | 12300 | 0.382 | 0.0127 |
| | 20 | 13200 | 0.545 | 0.0182 |
| | 25 | 14500 | 0.709 | 0.0236 |
| | 30 | 15600 | 0.818 | 0.0273 |
| 20 | 16 | 12600 | 0.491 | 0.0246 |
| | 20 | 13700 | 0.640 | 0.0320 |
| | 25 | 14900 | 0.736 | 0.0368 |
| | 30 | 16000 | 0.845 | 0.0423 |
| 10 | 16 | 12900 | 0.763 | 0.0763 |
| | 20 | 14100 | 0.872 | 0.0872 |
| | 25 | 15400 | 1.117 | 0.1117 |
| | 30 | 16400 | 1.567 | 0.1567 |

TABLE D.12.21

Cotton Yarn: 245 tex

Nozzle: 1 in. x 1/16 in. inlets.

Tube: 3/4 in. dia.

Axial Hole: 3/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in. $H_2O$) | Yarn Tail Speed (r.p.m.) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf/cm.) |
|---|---|---|---|---|
| 60 | 16 | 9900 | 0.259 | 0.0043 |
| | 20 | 11700 | 0.300 | 0.0050 |
| | 25 | 12700 | 0.327 | 0.0055 |
| | 30 | 13700 | 0.383 | 0.0064 |
| 50 | 16 | 10200 | 0.218 | 0.0044 |
| | 20 | 11300 | 0.232 | 0.0046 |
| | 25 | 12100 | 0.245 | 0.0049 |
| | 30 | 13000 | 0.259 | 0.0052 |
| 40 | 16 | 10900 | 0.545 | 0.0136 |
| | 20 | 12200 | 0.763 | 0.0191 |
| | 25 | 11000 | 1.145 | 0.0286 |
| | 30 | 12500 | 1.853 | 0.0463 |
| 30 | 16 | 10000 | 0.886 | 0.0228 |
| | 20 | 10600 | 1.117 | 0.0372 |
| | 25 | 11000 | 1.526 | 0.0509 |
| | 30 | 12300 | 1.799 | 0.0600 |
| 20 | 16 | 10200 | 1.172 | 0.0586 |
| | 20 | 11400 | 1.363 | 0.0682 |
| | 25 | 12400 | 1.608 | 0.0804 |
| | 30 | 13400 | 1.826 | 0.0913 |
| 10 | 16 | 12100 | 0.818 | 0.0818 |
| | 20 | 11600 | 0.954 | 0.0954 |
| | 25 | 14400 | 1.036 | 0.1036 |
| | 30 | 15800 | 1.158 | 0.1158 |

TABLE D.12.22

Cotton Yarn: 245 tex.

Nozzle: 1 in. x 1/8 in. inlets.

Tube: 1 in. dia.

Axial Entry: 1/8 in.

| Yarn Length In Tube (cm.) | Air Pressure In Tube (-in. $H_2O$) | Torque On Yarn (gf.cm.) | Torque Per Unit Length Of Yarn (gf.cm/cm.) |
|---|---|---|---|
| 60 | 16 | 345 | 0.940 |
| | 20 | 400 | 1.065 |
| | 25 | 265 | 1.268 |
| | 30 | 550 | 1.499 |
| 50 | 16 | 360 | 0.981 |
| | 20 | 420 | 1.145 |
| | 25 | 505 | 1.376 |
| | 30 | 600 | 1.635 |
| 40 | 16 | 375 | 1.022 |
| | 20 | 415 | 1.131 |
| | 25 | 530 | 1.445 |
| | 30 | 640 | 1.744 |
| 30 | 16 | 400 | 1.065 |
| | 20 | 475 | 1.294 |
| | 25 | 560 | 1.526 |
| | 30 | 700 | 1.907 |
| 20 | 16 | 730 | 1.989 |
| | 20 | 810 | 1.294 |
| | 25 | 1000 | 1.526 |
| | 30 | 1150 | 1.907 |
| 10 | 16 | 440 | 1.199 |
| | 20 | 545 | 1.486 |
| | 25 | 665 | 1.812 |
| | 30 | 730 | 1.989 |

TABLE D.12.23

| S.No. | 'Z' TWIST (Sliding) Tangential Inlet (in. x in.) | Axial Inlet (in.) | Hydraulic Mean Length (cm.) | Remarks | S.No. | 'S' TWIST (Rolling) Tangential Inlet (in. x in.) | Axial Inlet (in.) | Hydraulic Mean Length (cm.) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 1. | 1/2 x 1/16 | 1/8 | 0.0833 | | 1. | 1 x 1/16 | 3/16 | 0.0803 | |
| 2. | 1/4 x 1/16 | " | 0.0866 | | 2. | 1 x 1/16 | 1/8 | 0.0810 | |
| 3. | 1/4 x 1/8 | " | 0.1237 | | 3. | 3/4 x 1/16 | 1/8 | 0.0818 | 'Z' to 'S' at 10 cm. |
| 4. | 1/4 x 3/16 | " | 0.1506 | | 4. | 1 x 1/16 | 1/4 | 0.0876 | 'Z' to 'S' at 20 cm. |
| 5. | 1/4 dia. | " | 0.1750 | | 5. | 1 x 1/16 | 5/16 | 0.1024 | 'Z' to 'S' at 30 cm. |
| 6. | 1/4 x 1/4 | " | 0.1707 | | 6. | 1 x 1/16 | 3/8 | 0.0433 | 'Z' to 'S' at 40 cm. |
| 7. | 1/2 x 3/16 | " | 0.1821 | 'Z' to 'S' at 10 cm. | 7. | 1 x 1/8 | 1/8 | 0.1100 | |
| | | | | | 8. | 3/4 x 3/16 | 1/8 | 0.1971 | 'Z' to 'S' at 40 cm. |
| | | | | | 9. | 1 x 3/16 | 1/8 | 0.2052 | |
| | | | | | 10. | 1 x 1/4 | 1/8 | 0.2581 | |

TABLE D.12.24

Cotton Length: 245 tex

Yarn Length in Tube: 40 cm.

Nozzle: 2 x 1/4 in. dia. inlets.

Tube: 1 in. dia.

Air Pressure: -16 in. $H_2O$.

| Linear Density Of Yarn. (c.c.) | (te ) | Rotational Speed Of Yarn (r.p.m.) |
|---|---|---|
| 60s | 9.8 | 14,500 |
| 48s | 12.3 | 14,200 |
| 36s | 16.4 | 13,800 |
| 24s | 24.6 | 13,000 |
| 12s | 49.2 | 11,800 |
| 6s | 98.4 | 10,100 |
| 5/24s | 123 | 9,500 |
| 5/12s | 245 | 8,300 |
| 3/6s | 295 | 8,000 |

TABLE D.12.25

| Upstream Pressure (in $H_2O$) | EXPRESSED IN | | | | | | Upstream Pressure (in $H_2O$) |
|---|---|---|---|---|---|---|---|
| | $lbf/in^2$ | $lbf/ft^2$ | atm | mm $H_2O$ | mm Hg | $kgf/cm^2$ | |
| 12 | 0.434 | 62.43 | 0.0295 | 305 | 22.42 | 0.0305 | 3.464 |
| 14 | 0.506 | 72.83 | 0.0344 | 356 | 26.16 | 0.0356 | 3.742 |
| 16 | 0.578 | 83.24 | 0.0393 | 406 | 29.89 | 0.0406 | 4.000 |
| 20 | 0.723 | 104.05 | 0.0492 | 508 | 37.37 | 0.0508 | 4.472 |
| 25 | 0.903 | 130.06 | 0.0615 | 635 | 46.71 | 0.0635 | 5.000 |
| 30 | 1.084 | 156.07 | 0.0737 | 762 | 56.05 | 0.0762 | 5.477 |
| 32 | 1.156 | 166.47 | 0.0787 | 813 | 59.79 | 0.0813 | 5.657 |
| 32.5 | 1.174 | 169.08 | 0.0799 | 826 | 60.72 | 0.0826 | 5.701 |
| 35 | 1.264 | 182.08 | 0.0860 | 889 | 65.39 | 0.0889 | 5.916 |
| 40 | 1.445 | 208.09 | 0.0983 | 1016 | 74.73 | 0.1016 | 6.325 |
| 43 | 1.553 | 223.70 | 0.1057 | 1092 | 80.34 | 0.1092 | 6.557 |
| 44 | 1.590 | 228.90 | 0.1082 | 1118 | 82.21 | 0.1118 | 6.633 |
| 45 | 1.626 | 234.10 | 0.1106 | 1143 | 84.07 | 0.1143 | 6.708 |

1) density of air at 78°f. and 746.0 mm. of Hg.

$$(p) = 0.07150 \text{ lb/ft}^3$$

$$\sqrt{p} = 0.2674$$

2) volume rate of air flow

$$(Q) = 347 \times K \times \sqrt{h} \text{ cmft/hr.}$$

$$(q) = \frac{Q}{3600} \text{ ft}^3\text{/sec.}$$

3) Reynold's number

$$(R) = 54.52 \times Q.$$

4) kinematic viscosity (stokes) $= \dfrac{\text{viscosity (poise)}}{\text{density of fluid (gf/cm}^3\text{)}}$

TABLE D.12.26

Tension Measurements

with Rothschild electronic tensiometer. 200 oscillations/second.

American Carded Cotton (1 1/8 in staple length)

| Yarn Take-up Rate m/min. | Ring Frame Draft | Air Pressure (-in $H_2O$) | Linear Density Of Yarn | | Av-Tension (T) (gf) | c.c.x T. | tex x T. |
|---|---|---|---|---|---|---|---|
| | | | c.c. | tex | | | |
| **I Yarn Speed Vs Tension** | | | | | | | |
| 3.5 | 12 | 25 | 2.68 | 220.5 | 31.7 | 85.0 | 6989 |
| 4.3 | " | " | 2.73 | 216.0 | 31.5 | 86.0 | 6802 |
| 5.1 | " | " | 2.63 | 224.2 | 34.7 | 91.3 | 7778 |
| 6.0 | " | " | 2.66 | 221.6 | 35.1 | 93.4 | 7778 |
| 6.7 | " | " | 2.63 | 224.6 | 35.8 | 94.2 | 8041 |
| 7.9 | " | " | 2.64 | 224.6 | 35.3 | 93.2 | 7894 |
| 8.5 | " | " | 2.61 | 226.1 | 35.0 | 91.4 | 7914 |
| 10.0 | " | " | 2.57 | 229.6 | 36.1 | 92.8 | 8289 |
| 11.9 | " | " | 2.59 | 227.6 | 35.8 | 92.7 | 8149 |
| 14.3 | " | " | 2.58 | 228.7 | 35.3 | 91.1 | 8072 |
| 15.3 | " | " | 2.60 | 226.9 | 35.0 | 91.0 | 7940 |
| **II Ring Frame Draft Vs Tension** | | | | | | | |
| 6.0 | 12 | 25 | 2.58 | 229.0 | 31.7 | 81.8 | 7258 |
| " | 15 | " | 3.21 | 183.8 | 26.0 | 83.5 | 4778 |
| " | 18 | " | 3.72 | 158.8 | 21.0 | 78.1 | 3335 |
| " | 21 | " | 4.36 | 135.5 | 17.9 | 78.0 | 2425 |
| " | 25 | " | 5.68 | 113.9 | 14.0 | 79.5 | 1595 |
| " | 30 | " | 6.80 | 86.9 | 9.2 | 62.6 | 800 |
| " | 35 | " | 7.71 | 76.6 | 7.2 | 55.5 | 552 |
| " | 40 | " | 9.57 | 61.7 | 5.1 | 48.8 | 315 |
| " | 45 | " | 12.60 | 46.9 | 4.3 | 54.2 | 201 |
| " | 50 | " | 13.39 | 44.1 | 3.8 | 50.9 | 168 |
| **III Air Pressure Vs Tension** | | | | | | | |
| 6.0 | 12 | 11 | 2.78 | 212.5 | 21.8 | 60.6 | 4632 |
| " | " | 13 | 2.67 | 221.4 | 26.5 | 70.8 | 5867 |
| " | " | 15 | 2.76 | 213.9 | 28.5 | 78.7 | 6096 |
| " | " | 17 | 2.73 | 216.6 | 32.4 | 88.5 | 7018 |
| " | " | 20 | 2.69 | 219.6 | 36.4 | 97.9 | 7995 |

Continued on next page.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| " | " | 22 | 2.71 | 218.1 | 38.5 | 104.3 | 8396 |
| " | " | 25 | 2.75 | 214.7 | 41.4 | 113.9 | 8888 |
| " | " | 28 | 2.70 | 218.9 | 43.6 | 117.7 | 9542 |
| " | " | 31 | 2.71 | 217.8 | 45.6 | 123.6 | 9932 |
| " | " | 34 | 2.74 | 215.4 | 52.5 | 143.9 | 11,307 |
| " | " | 36 | 2.78 | 212.1 | 52.8 | 146.8 | 11,198 |

TABLE D.12.27

Tension Measurements

with Rothschild electronic tensiometer. 200 oscillations/second.
Egyptian Combed Cotton (1 7/16 in. staple length)

| Yarn Take-up Rate m/min. | Ring Frame Draft | Air Pressure (-in $H_2O$) | Linear Density Of Yarn | | Av-Tension (T) (gf) | c.c. x T. | tex x T. |
|---|---|---|---|---|---|---|---|
| | | | c.c. | tex | | | |
| I Yarn Speed Vs Tension | | | | | | | |
| 4.4 | 12 | 25 | 3.18 | 185.5 | 21.9 | 69.6 | 4061 |
| 4.2 | " | " | 3.13 | 188.4 | 22.2 | 69.5 | 4183 |
| 5.2 | " | " | 3.12 | 189.3 | 22.4 | 69.9 | 4241 |
| 5.9 | " | " | 3.12 | 189.5 | 22.1 | 69.0 | 4188 |
| 6.9 | " | " | 3.15 | 187.4 | 21.4 | 67.4 | 4010 |
| 8.2 | " | " | 3.13 | 189.0 | 22.4 | 70.1 | 4233 |
| 8.8 | " | " | 3.12 | 189.4 | 22.8 | 71.1 | 4317 |
| 11.4 | " | " | 3.03 | 194.6 | 24.9 | 75.5 | 4846 |
| 12.3 | " | " | 3.07 | 192.5 | 24.7 | 75.8 | 4754 |
| 14.2 | " | " | 2.97 | 199.1 | 24.2 | 71.9 | 4817 |
| 14.6 | " | " | 3.10 | 190.2 | 24.3 | 75.3 | 4623 |
| II Ring Frame Draft Vs Tension | | | | | | | |
| 6.0 | 12 | 25 | 3.11 | 189.8 | 24.6 | 76.5 | 4669 |
| " | 15 | " | 3.87 | 152.5 | 21.0 | 81.3 | 3203 |
| " | 18 | " | 4.62 | 127.9 | 18.6 | 85.9 | 2379 |
| " | 21 | " | 5.44 | 108.5 | 15.6 | 84.9 | 1692 |
| " | 25 | " | 6.47 | 91.3 | 13.1 | 84.8 | 1196 |
| " | 30 | " | 7.62 | 77.5 | 11.0 | 83.8 | 853 |
| " | 35 | " | 9.66 | 61.1 | 8.8 | 85.0 | 538 |

Continued on next page.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| " | 40 | " | 11.67 | 50.6 | 6.3 | 73.5 | 319 |
| 4.4 | 45 | " | 12.24 | 48.3 | 7.2 | 88.1 | 347 |
| 4.0 | 50 | " | 14.80 | 39.9 | 6.0 | 88.8 | 239 |
| " | 60 | " | 19.30 | 30.6 | 4.4 | 84.9 | 135 |
| " | 70 | " | 22.96 | 25.7 | 3.5 | 80.4 | 90 |
| III Air Pressure Vs Tension | | | | | | | |
| 6.0 | 12 | 11 | 3.31 | 178.4 | 14.0 | 46.3 | 2497 |
| " | " | 13 | 3.27 | 180.7 | 16.4 | 53.6 | 2963 |
| " | " | 15 | 3.49 | 169.0 | 17.4 | 60.7 | 2941 |
| " | " | 17 | 3.30 | 178.9 | 18.8 | 62.0 | 3363 |
| " | " | 20 | 3.24 | 182.3 | 22.8 | 73.9 | 4157 |
| " | " | 22 | 3.33 | 177.5 | 24.0 | 79.9 | 4259 |
| " | " | 25 | 3.35 | 176.1 | 26.0 | 87.1 | 4579 |
| " | " | 28 | 3.75 | 165.2 | 26.3 | 93.9 | 4346 |
| " | " | 31 | 3.24 | 182.5 | 28.8 | 93.3 | 5255 |
| " | " | 34 | 3.14 | 187.9 | 31.8 | 99.9 | 5974 |
| " | " | 36 | 3.22 | 183.6 | 33.2 | 106.9 | 6094 |

TABLE D.12.28

Tension Measurements

with Rothschild electronic tensiometer. 200 oscillations/second

Fibro (1.5 den. 1.5 in. staple length)

| Yarn Take-up Rate m/min | Ring Frame Draft | Air Pressure (-in $H_2O$) | Linear Density Of Yarn | | Av-Tension (T) (gf) | c.c.x T. | tex x T |
|---|---|---|---|---|---|---|---|
| | | | c.c. | tex | | | |
| 1 Yarn Speed Vs Tension | | | | | | | |
| 3.1 | 25 | 25 | 5.80 | 101.8 | 21.8 | 126.4 | 2219 |
| 4.2 | " | " | 5.34 | 110.7 | 21.4 | 114.3 | 2369 |
| 5.1 | " | " | 5.53 | 106.7 | 19.3 | 106.7 | 2060 |
| 5.6 | " | " | 5.16 | 114.4 | 17.2 | 88.8 | 1967 |
| 6.6 | " | " | 5.22 | 113.2 | 15.0 | 78.3 | 1698 |
| 7.7 | " | " | 5.09 | 116.0 | 19.2 | 97.7 | 2228 |
| 8.6 | " | " | 5.13 | 115.0 | 16.3 | 83.6 | 1875 |
| 10.7 | " | " | 5.03 | 117.3 | 15.6 | 78.5 | 1831 |

Continued on next page

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| II Ring Frame Draft Vs Tension | | | | | | | | | |
| 6.0 | 12 | 25 | 2.48 | 238.5 | 38.3 | 95.0 | 9135 | | |
| " | 15 | " | 3.05 | 193.3 | 28.2 | 86.0 | 5451 | | |
| " | 18 | " | 3.69 | 160.2 | 24.7 | 91.1 | 3957 | | |
| " | 21 | " | 4.33 | 136.3 | 21.8 | 94.4 | 2972 | | |
| " | 25 | " | 5.30 | 111.4 | 18.2 | 96.5 | 2027 | | |
| " | 30 | " | 6.68 | 86.1 | 13.6 | 93.3 | 1171 | | |
| " | 38 | " | 8.26 | 31.5 | 9.3 | 76.8 | 665 | | |
| " | 40 | " | 11.11 | 53.1 | 6.9 | 76.7 | 367 | | |
| " | 45 | " | 12.40 | 47.6 | 5.8 | 71.9 | 276 | | |
| " | 50 | " | 15.08 | 39.2 | 4.9 | 73.9 | 192 | | |
| " | 60 | " | 19.50 | 30.3 | 3.6 | 70.2 | 109 | | |
| " | 70 | " | 23.71 | 24.9 | 2.2 | 52.2 | 55 | | |
| III Air Pressure Vs Tension | | | | | | | | | |
| 6.0 | 25 | 11 | 4.48 | 122.0 | 11.7 | 56.6 | 1427 | | |
| " | " | 13 | 4.72 | 125.1 | 13.3 | 62.8 | 1664 | | |
| " | " | 15 | 4.86 | 121.6 | 15.3 | 74.4 | 1860 | | |
| " | " | 17 | 4.83 | 122.3 | 16.7 | 80.7 | 2042 | | |
| " | " | 20 | 4.93 | 119.7 | 19.6 | 96.6 | 2346 | | |
| " | " | 22 | 4.75 | 124.2 | 23.1 | 109.7 | 2870 | | |
| " | " | 25 | 4.83 | 122.2 | 26.0 | 125.6 | 3177 | | |
| " | " | 28 | 4.79 | 123.3 | 28.1 | 134.6 | 3466 | | |
| " | " | 31 | 4.77 | 123.7 | 31.0 | 147.9 | 3836 | | |
| " | " | 34 | 4.76 | 124.1 | 32.2 | 153.3 | 3996 | | |
| " | " | 35.5 | 4.77 | 123.7 | 33.5 | 159.8 | 4143 | | |

| (1) Spinning Tube Dimension: Tangential Inlet (in) | (2) Axial Entry (in) | (3) Total Area Of Opening ($in^2$) | (4) Vortex Tube Bore (in) | (5) Up Stream Pressure (in $H_2O$) | (6) Venturi Pressure Difference (in $H_2O$) | (7) Discharge Coefficient. | (8) Volume Rate Of Air Flow ($ft^3$-$sec^{-1}$) | (9) Approx. Velocity Of Air Flow: Through Inlet (ft-$sec^{-1}$) | (10) Approx. Velocity Of Air Flow: Through Tube (ft-$sec^{-1}$) | (11) Calculated Power Consumption (Watts) | (12) Reynolds' Number |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/4 dia. | 1/8 | 0.111 | 1 | 16 | 3.45 | 0.968 | 0.174 | 225 | 31.76 | 19.56 | 15,945 |
| | | | | 20 | 4.50 | 0.956 | 0.196 | 254 | 35.91 | 27.65 | 18,025 |
| | | | | 25 | 5.80 | 0.944 | 0.219 | 284 | 40.16 | 38.65 | 20,159 |
| | | | | 30 | 7.10 | 0.932 | 0.239 | 311 | 43.88 | 50.68 | 22,027 |
| | | | | 35 | 8.50 | 0.920 | 0.259 | 335 | 47.38 | 63.84 | 23,785 |
| | | | | 40 | 9.95 | 0.908 | 0.276 | 358 | 50.60 | 77.93 | 25,405 |
| | | | | 43 | 10.70 | 0.905 | 0.285 | 370 | 52.29 | 86.57 | 26,250 |
| 1/4 x 1/8 | 1/8 | 0.044 | 3/4 | 16 | 0.65 | 0.994 | 0.077 | 252 | 25.17 | 8.72 | 9477 |
| | | | | 20 | 0.80 | 0.992 | 0.086 | 279 | 27.88 | 12.07 | 10,496 |
| | | | | 25 | 0.95 | 0.990 | 0.093 | 304 | 30.32 | 16.41 | 11,417 |
| | | | | 30 | 1.20 | 0.988 | 0.104 | 341 | 35.01 | 22.73 | 13,180 |
| | | | | 35 | 1.35 | 0.987 | 0.110 | 361 | 36.03 | 27.29 | 13,515 |
| | | | | 40 | 1.55 | 0.985 | 0.118 | 386 | 38.54 | 33.40 | 14,510 |
| | | | | 45 | 1.75 | 0.983 | 0.125 | 409 | 40.85 | 39.79 | 15,382 |

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| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/4 x 1/8 | 1/8 | 0,075 | 3/4 | 16 | 1.25 | 0.988 | 0.107 | 204 | 34.72 | 12.02 | 13,074 |
| | | | | 20 | 1.55 | 0.985 | 0.118 | 227 | 38.54 | 16.68 | 14,510 |
| | | | | 25 | 1.95 | 0.981 | 0.132 | 253 | 43.04 | 23.29 | 16,204 |
| | | | | 30 | 2.40 | 0.977 | 0.146 | 280 | 46.57 | 30.89 | 17,911 |
| | | | | 35 | 2.90 | 0.972 | 0.160 | 306 | 52.01 | 39.39 | 19,580 |
| | | | | 40 | 3.50 | 0.967 | 0.174 | 335 | 56.83 | 49.20 | 21,397 |
| | | | | 45 | 4.05 | 0.961 | 0.186 | 358 | 60.78 | 59.19 | 22,883 |
| 1/4 x 3/16 | 1/8 | 0.106 | 3/4 | 16 | 2.05 | 0.980 | 0.135 | 184 | 44.08 | 15.27 | 16,597 |
| | | | | 20 | 2.60 | 0.975 | 0.152 | 206 | 49.40 | 21.38 | 18,598 |
| | | | | 30 | 4.30 | 0.959 | 0.192 | 260 | 62.50 | 40.58 | 23,533 |
| | | | | 35 | 5.10 | 0.952 | 0.207 | 282 | 67.56 | 51.17 | 25,436 |
| | | | | 40 | 6.00 | 0.942 | 0.222 | 302 | 72.51 | 62.77 | 27,302 |
| | | | | 45 | 6.90 | 0.933 | 0.236 | 321 | 77.01 | 75.00 | 28,996 |
| 1/4 x 1/4 | 1/8 | 0.137 | 3/4 | 16 | 2.90 | 0.972 | 0.160 | 168 | 52.01 | 18.00 | 19,580 |
| | | | | 20 | 3.70 | 0.965 | 0.179 | 188 | 58.33 | 25.25 | 21,962 |
| | | | | 25 | 5.00 | 0.952 | 0.205 | 216 | 66.91 | 36.20 | 25,190 |
| | | | | 30 | 6.30 | 0.940 | 0.227 | 239 | 74.14 | 48.14 | 27,196 |
| | | | | 35 | 7.60 | 0.928 | 0.247 | 259 | 80.40 | 60.90 | 30,273 |
| | | | | 40 | 9.00 | 0.916 | 0.265 | 279 | 86.37 | 74.77 | 32,519 |
| | | | | 45 | 9.90 | 0.909 | 0.276 | 290 | 89.89 | 85.60 | 33,845 |

Continued on next page.

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ½ x 3/16 | 1/8 | 0.200 | 1 | 16 | 8.60 | 0.920 | 0.260 | 187 | 47.67 | 29.36 | 23,932 |
| | | | | 20 | 11.15 | 0.902 | 0.290 | 209 | 53.21 | 40.97 | 26,710 |
| | | | | 25 | 14.05 | 0.890 | 0.322 | 232 | 58.94 | 56.73 | 29,590 |
| | | | | 30 | 17.10 | 0.888 | 0.354 | 255 | 64.86 | 74.92 | 32,562 |
| | | | | 32 | 18.40 | 0.888 | 0.367 | 264 | 67.30 | 82.92 | 33,786 |
| | | | | 32.5 | 18.75 | 0.888 | 0.371 | 267 | 67.93 | 84.99 | 34,099 |
| ½ x 1/16 | 1/8 | 0.075 | 3/4 | 16 | 1.85 | 0.983 | 0.099 | 197 | 32.18 | 11.14 | 12,116 |
| | | | | 20 | 2.30 | 0.978 | 0.143 | 274 | 46.63 | 20.18 | 17,555 |
| | | | | 25 | 2.95 | 0.971 | 0.161 | 309 | 52.43 | 28.37 | 19,740 |
| | | | | 30 | 3.50 | 0.967 | 0.174 | 335 | 56.86 | 36.92 | 21,409 |
| | | | | 35 | 4.10 | 0.961 | 0.188 | 360 | 61.17 | 46.33 | 23,030 |
| | | | | 40 | 4.70 | 0.955 | 0.200 | 383 | 65.08 | 56.34 | 24,503 |
| ½ x 3/16 | 1/8 | 0.200 | 3/4 | 16 | 7.7 | 0.927 | 0.248 | 178 | 80.83 | 27.99 | 30,432 |
| | | | | 20 | 9.7 | 0.911 | 0.274 | 197 | 89.18 | 38.60 | 33,375 |
| | | | | 25 | 12.6 | 0.894 | 0.306 | 220 | 99.74 | 53.97 | 37,552 |
| | | | | 30 | 15.2 | 0.888 | 0.334 | 240 | 108.80 | 70.65 | 40,965 |
| 3/4 x 1/16 | 1/8 | 0.106 | 3/4 | 16 | 2.90 | 0.972 | 0.160 | 217 | 52.01 | 18.01 | 19,580 |
| | | | | 20 | 3.65 | 0.965 | 0.178 | 241 | 57.94 | 25.08 | 21,815 |
| | | | | 25 | 4.65 | 0.956 | 0.199 | 270 | 64.79 | 25.05 | 24,392 |
| | | | | 30 | 5.65 | 0.946 | 0.217 | 294 | 70.66 | 45.87 | 26,602 |
| | | | | 35 | 6.65 | 0.831 | 0.233 | 316 | 75.87 | 57.47 | 28,566 |
| | | | | 40 | 7.70 | 0.927 | 0.248 | 337 | 80.83 | 69.97 | 30,432 |

Continued on next page.

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3/4 x 3/16 | 1/8 | 0.294 | 3/4 | 12 | 8.10 | 0.923 | 0.253 | 124 | 82.56 | 21.44 | 31,083 |
| | | | | 16 | 11.10 | 0.900 | 0.289 | 142 | 94.26 | 32.64 | 35,490 |
| | | | | 20 | 14.00 | 0.888 | 0.320 | 157 | 104.43 | 45.20 | 39,320 |
| | | | | 25 | 17.90 | 0.888 | 0.362 | 177 | 118.06 | 63.88 | 44,452 |
| | | | | 30 | 21.95 | 0.888 | 0.401 | 196 | 130.75 | 84.89 | 49,227 |
| 1 x 1/8 | 1/8 | 0.262 | 3/4 | 12 | 8.40 | 0.920 | 0.257 | 141 | 83.80 | 29.02 | 31,549 |
| | | | | 16 | 10.60 | 0.905 | 0.284 | 156 | 92.60 | 40.08 | 34,864 |
| | | | | 20 | 13.30 | 0.892 | 0.314 | 172 | 102.25 | 55.32 | 38,498 |
| | | | | 25 | 16.45 | 0.888 | 0.347 | 191 | 113.17 | 73.48 | 42,610 |
| 1 x 3/16 | 1/8 | 0.387 | 3/4 | 12 | 10.85 | 0.903 | 0.287 | 107 | 93.48 | 24.28 | 35,195 |
| | | | | 16 | 14.65 | 0.888 | 0.328 | 122 | 106.85 | 37.00 | 40,229 |
| | | | | 20 | 18.70 | 0.888 | 0.370 | 138 | 120.67 | 52.23 | 45,434 |
| | | | | 25 | 23.65 | 0.888 | 0.416 | 155 | 135.70 | 73.43 | 51,093 |
| 1 x 1/4 | 1/8 | 0.512 | 3/4 | 12 | 13.60 | 0.890 | 0.316 | 89 | 103.16 | 26.80 | 38,841 |
| | | | | 16 | 19.10 | 0.888 | 0.374 | 105 | 121.94 | 42.23 | 45,912 |
| | | | | 20 | 24.90 | 0.888 | 0.427 | 120 | 139.26 | 60.27 | 52,431 |
| | | | | 25 | 32.00 | 0.888 | 0.484 | 136 | 157.87 | 85.42 | 59,440 |
| 1 x 1/16 | 1/8 | 0.137 | 3/4 | 12 | 3.50 | 0.967 | 0.174 | 183 | 56.86 | 14.77 | 21,409 |
| | | | | 16 | 4.60 | 0.956 | 0.198 | 208 | 64.43 | 22.31 | 23,257 |
| | | | | 20 | 5.85 | 0.944 | 0.220 | 231 | 71.76 | 31.06 | 27,000 |
| | | | | 25 | 7.55 | 0.929 | 0.246 | 259 | 80.21 | 43.40 | 30,199 |
| | | | | 30 | 9.25 | 0.914 | 0.268 | 282 | 87.35 | 56.72 | 82,888 |
| | | | | 35 | 11.00 | 0.902 | 0.288 | 303 | 94.03 | 71.22 | 35,404 |

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| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 x 1/16 | 3/16 | 0.153 | 3/4 | 12 | 4.80 | 0.954 | 0.202 | 190 | 65.70 | 17.07 | 24,736 |
| | | | | 16 | 6.50 | 0.938 | 0.231 | 217 | 75.15 | 26.02 | 28,296 |
| | | | | 20 | 8.20 | 0.923 | 0.255 | 240 | 83.08 | 35.96 | 31,279 |
| | | | | 25 | 10.40 | 0.906 | 0.282 | 265 | 91.82 | 49.68 | 34,569 |
| | | | | 30 | 12.50 | 0.895 | 0.305 | 287 | 99.45 | 64.57 | 37,442 |
| 1 x 1/16 | 1/4 | 0.174 | 3/4 | 12 | 6.90 | 0.934 | 0.237 | 196 | 77.11 | 20.03 | 29,033 |
| | | | | 16 | 9.40 | 0.913 | 0.270 | 228 | 87.97 | 30.46 | 33,131 |
| | | | | 20 | 11.95 | 0.897 | 0.299 | 247 | 97.46 | 42.18 | 36,693 |
| | | | | 25 | 15.00 | 0.888 | 0.332 | 274 | 108.08 | 58.48 | 40,695 |
| | | | | 30 | 18.20 | 0.888 | 0.365 | 302 | 119.04 | 77.30 | 44,820 |
| 1 x 1/16 | 5/16 | 0.211 | 3/4 | 12 | 10.10 | 0.908 | 0.278 | 190 | 90.67 | 23.55 | 34,140 |
| | | | | 16 | 13.65 | 0.890 | 0.317 | 216 | 103.36 | 35.79 | 38,915 |
| | | | | 20 | 17.25 | 0.888 | 0.356 | 243 | 115.91 | 50.17 | 43,641 |
| | | | | 25 | 21.80 | 0.888 | 0.399 | 273 | 130.29 | 70.50 | 49,055 |
| | | | | 30 | 25.80 | 0.888 | 0.435 | 297 | 141.73 | 92.03 | 53,364 |
| 1 x 1/16 | 3/8 | 0.235 | 3/4 | 12 | 12.85 | 0.894 | 0.309 | 189 | 100.72 | 26.16 | 37,921 |
| | | | | 16 | 17.40 | 0.888 | 0.357 | 219 | 116.40 | 40.31 | 43,825 |
| | | | | 20 | 21.90 | 0.888 | 0.401 | 245 | 130.62 | 56.53 | 49,178 |
| | | | | 25 | 27.70 | 0.888 | 0.451 | 276 | 146.89 | 79.48 | 55,304 |
| | | | | 30 | 32.35 | 0.888 | 0.487 | 298 | 158.72 | 103.06 | 59,760 |

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