CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This section summarizes the literature review that was performed for the relevant research related to air jet spinning and other integrated spinning systems. Development of these spinning systems is given, and the principles of them are described.

In the preparation of the literature survey many sources were consulted. Oxenham is the pioneer in this area and his papers and the M.S., and Ph.D., theses done under his supervision on rotor and compact spinning systems at the North Carolina State University provided a lot of useful information. In this Chapter, some of the significant works on rotor spinning are discussed. Other literatures that help in understanding the current work are also presented.

Oxenham (2002) has discussed from time to time the development which has occurred in short staple sector and his reviews are very useful to have an idea of the current status of the technology. Current and future trends in yarn production, a plenary paper presented to the Textile Institute 82nd World Conference at Cairo in 2002 by him, reviews the current state of technological innovation in yarn production and examines the relative merits and disadvantages of the system. Since most of these papers are concerned with the developments which have occurred in the Textile Fairs and
exhibitions, they were very informative to have an idea of the several systems of yarn production, their advantages and disadvantages.

2.2 SIGNIFICANT RESEARCH WORKS ON ROTOR SPINNING AND OTHER AREAS


On air jet texturising, Chaithanya (2002) and Dani (2004) have carried out work and the latter’s thesis has discussed the nozzle geometries. Bilgin et al (1996) have studied the effect of nozzle geometry on air jet texturing process. Cai (2003), in his thesis, describes the use of air flow in many areas.

2.3 BACKGROUND

Having seen the use of nozzle in cone winding and also in ring spinning for reduction of yarn hairiness in yarns, a thought came that if air jet nozzle could be installed in rotor spinning what would be its effects on yarn quality. Kwasniak (1996) was interested in producing a fancy yarn in Rotor spinning by incorporating an additional pressurized air flow to disturb the air flow field. Thus, the installation of air jet nozzle on rotor spinning will result in modifying the yarn quality. In considering attempts to improve the yarn quality, it should be noted that there are three types of limitation on the rotor speed, which are (i) technological (ii) mechanical and (iii) economic.
Small rotors should be capable of operating economically at speeds of up to 1,00,000 rev/min but as Oxenham (2002) has demonstrated that with them the yarn quality will deteriorate and that an alternative solution is to be found.

Very little has been published on the technology of open end rotor spinning with air jet nozzles and nothing at all has been published concerning the properties of the yarns produced with it.

An air jet nozzle was therefore designed and built that was capable of being fitted to the rotor frame. The general properties of the yarns produced with this nozzle were determined and reported in the thesis. Although Grosberg and Mansour (1975) have reported an increase in strength of open end rotor yarns with the increase in rotor speed as demonstrated by Oxenham (2002), the trend noticed is for a particular rotor diameter namely 46mm only; But when the diameter is shortened, the yarn tenacity has exhibited a decline compared to a bigger diameter used (Oxenham 2002).

Technologically, the main effect of increasing rotor speeds is to increase the spinning tension, which will ultimately cause excess ends down. The maximum possible speeds will depend, on the rotor diameter and on the yarn strength and its variability. Since the higher rotor speeds are not advisable, the other alternative way of producing yarns with improved properties is to install the air jet nozzle in the machine; also it may be expected that when the yarn is passing through the air jet nozzle, the yarn tension would increase. It is well known that open-end –rotor spun yarns are weaker, more extensible and more regular with respect to linear density and breaking load. It is frequently claimed that this improvement in regularity of breaking load more than offsets the lower mean strength and that as a result, open end rotor spun yarns give fewer breakages during further processing.
2.4 PRINCIPLES OF SPINNING

The staple fibres are short and discontinuous. In order to convert these short and discontinuous fibres, it is necessary that these fibres are first arranged in a form of continuous strand and should be adhered to each other by some binding to avoid slippage. Although various methods for binding have been tried, twist is being used traditionally and most successfully. Twist increases the frictional forces between fibres and prevents fibres from slipping over one another by generating the radial forces directed towards the yarn interior. Two concepts should be taken into consideration as twist is defined; real twist and false twist. Real twist is the result of clamping one end of a parallel fibre bundle and applying a torque movement to the other end. Consequently, the fibres are no longer parallel to the bundle axis, but are arranged in helical path. False twist is a result of applying twist to a fibre strand between the two ends the strand which are clamped firmly. The result of this is a net twist of zero since the strand will take up the same number of twists on each side of the twisting element with opposite directions. If the clamps are replaced by rotating rollers, the fibre strand will take up twist only between the first cylinder and twisting element and the twist will be cancelled after the fibre strand departs the twisting element.

This principle is used to give a temporary twist to the fibre strand such as in false twist texturising but it typically does not impart strength to a yarn since fibres are still without twist beyond the twisting element. It is possible to produce spun yarns by this principle if the system is modified. For example, a fibre strand is fed through the twisting element from the nip line of the feed roller in the form of a spread sheet. As a result of this, a substantial number of edge fibres do not obtain the twisting element. Only the core part which is the main part of the fibre bundle enters the twisting element in the fully twisting form. The opposing turns imparted by the twisting element
cancel the twist inserted to the core fibres earlier and give twist to the surface fibres which are originally untwisted. When the fibre strand departs from the twisting element, core fibres will no longer have any twist. “Surface fibres” on the other hand obtain twist in the opposite direction and wrap around the parallel core fibres. The term “fasciated”, which stems from fasces meaning a bundle of rods wrapped with ribbons, is used to describe the resulting yarn structure which is observed in the yarns produced by a false twisting process. Because of different type of twist insertion, structures of the yarns are quite different from those made by other methods. The importance of yarn structure comes from its determining role on the yarn physical properties and consequently the performance characteristics of yarns and fabrics.

2.5 NEW SPINNING TECHNOLOGIES

Ever since the ring system replaced the mule, the former has been dominating the spun yarn production. However due to several inherent limitations in the system, there is a continuous search for better technologies for replacing ring spinning. Rotor spinning entered the market and gradually established itself as an important method of yarn production in coarse and medium count ranges up to 30 Ne. DREF technology came in the eighties but has been only marginally successful that too for coarse counts only. Thus both are successful new technologies of spun yarn production and limited to coarse counts only.

Air jet entered into the market in the mid eighties as a promising new technology to replace ring spinning. It can operate over a wide count range (10 to 80 Ne) and can handle a variety of raw materials including cotton. It enjoys all the advantages associated with high technology like high productivity, reduced stages of processing, reduced labour and adaptability to process control or automation. An additional advantage with air jet is its easy maintenance due to less number of revolving parts.
The penetration of the air jet spinning is rather slow in various parts of the world. The major difference between the air jet spinning and rotor spinning is that former is a false twist process and does not involve open end technology.

2.6 HISTORY OF AIR JET SPINNING

2.6.1 The DuPont Fasciated Yarn System

The principle on which air jet spinning is based was first introduced by Dupont in 1956, though at that time it was not commercially successful for 100% short staple spinning. The invention, which E1 DuPont De Nemours and company, U.S., claimed, consisted of a number of spinning methods using air jet twisting nozzles. In these systems, filaments were either false twisted and subsequently heat set (i.e. texturised) or simply false twisted together with a certain amount of staple fibre. The plasticizing and adhesive application and the feed of filament can be omitted all together from the process and thus pure staple fibres could be spun. This product was called ‘Sheaf’ yarn. In the sheaf yarn, staple fibres were tied at random intervals along the yarn length by other staple fibres which were firmly twisted about the yarn surface.

In one of the DuPonts’ patents, the first arrangement consisted of a stretch breaking unit to break the filament supplied, an air operated collecting aspirator an air jet false twister and a cheese type winding unit. At the front roller nip, the filaments are stretched to break into staple form and made into the desired thickness. It is necessary that the staple fibre bundles at the front roller nip are in ribbon form and preferably spread over a wide distance. The primary function of the aspirating jet is to remove the fibres from the front drafting rollers so as to prevent roller wraps and to guide the fibres for twisting. The twisting jet applies a torque to the fibre bundle by means of a
vortex formed in it. A system claimed to be suitable for spinning natural fibre is a modification of the earlier system. An additional aspirating jet is attached to forward a proportion of fibres from the front roller nip to join the main branch at a distance upstream of the twisting jet.

It was in 1971 that Dupont announced that it had developed yarn under the trade mark “Nandle” which was fasciated structure of staple fibres held together by surface fibres unwrapped around the bundle. This was patented as the ‘Rotofil’ process and it is shown in Figure 2.1

Torray Murata and Suessen have promoted air jet spinning systems.

**Figure 2.1** The Dupont principle of producing fasciated yarn with a single jet

### 2.6.2 Air Jet Spinning

A description of the air jet spinning process is found in the patents filed by the inventors of the process, Nakahara (1981). In the air jet spinning process (Figure 2.2), the staple fibre sliver, S, is drafted to the required count by a 3-over-3 drafting system and then passed through the first and second nozzles, N₁ and N₂ respectively. Air is introduced at high pressures though fluid jets J₁ and J₂ drilled in the nozzles to produce swirling air currents in mutually opposite direction A and B, in the two nozzles as shown in Figures 2.3 and 2.4.
Figure 2.2  Air jet spinning system

Figure 2.3  Murata principle of producing fasciated yarn with two jets $B_1$ and $B_2$
Referring to Figure 2.4, the drafted strand is vibrated violently by an unstable secondary balloon, formed between the front roller and the inlet of the first nozzle N_1. This secondary balloon is produced by a stable balloon, B_1, formed by the revolution of the yarn within the nozzle N_1. Due to the vibration of the secondary balloon, a minor or major part of the drafted sliver S, is detached from the main strand forming detached fibres, S_2, and unseparated fibres, S_1. At this time the trailing ends of the detached fibres S_2 are still held by the front roller nip while the leading ends are separated from the main fibre strand. These leading ends are drawn into nozzle N_1, come under the influence of the swirling air currents, and are wound positively in the direction around the undetached fibres S_1.

![Figure 2.4 Action of the nozzles on the fibre strand](image)

The pressure in the nozzle N_2 is generally greater than that in nozzle N_1. This causes the yarn revolving force in the second nozzle N_2 to be greater than that in the nozzle N_1. The result is S twist in the unseparated fibres
between the roller nip and the nozzle N2. Therefore, the structure of the fibre strand consists of Z twisted fibres wound around a S twisted strand.

The fibre strand emerging from the second nozzle is subjected to an untwisting action by the nozzle N2. This increases the twist in the Z twisted fibres and reduces the twist in the S twisted fibres. As a result, the S twisted fibres are bound firmly by the surrounding twisted fibres to give cohesion and strength to the yarn.

Fluid vortices have been used before by Lord et al (1984) These served the dual purpose of assembling and consolidating (by twisting) the fibres. But, as explained before, in air jet spinning process, fluid nozzles are used only for the purpose of consolidation.

Recently Murata has come with MVS, (Murata Vortex Spinner) which is basically suitable for producing 100% cotton yarn. The production speed is 400 m/min, and it greatly simplifies the processes.

### 2.6.3 Raw Material Requirements

Fibres should have

1) High strength
2) Fairly high fibre to fibre friction
3) Low bending stiffness
4) Low resistance to twist
5) Smaller percentage of short fibres.

Major aspects which separate air jet from ring spinning are:

a) A high draft ratio in the range of 150 to 250
b) A low spinning tension due to the method of twisting employed
c) High delivery speeds in the range of 150 to 300 mpm.

d) A core flux held tightly by wrapper fibres.

2.6.4 Twin Spinner

One of the salient features in Murata twin spinner is that the width of the cots and the active parts of the bottom rollers are increased to accommodate the drafting of two slivers, simultaneously without touching each other. Sliver guides on providing behind the back roller and between the back roller and apron to avoid intermingling of the two slivers during drafting. The advantages of producing doubled yarn by air jet spinning machines are the productivity of two spinners is 17 to 37 times higher than that of ring spinners depending on yarn count Gobbel (1991). With the yarn count becoming finer, the labour and space-saving are greater. The capital cost can be reduced by 38-48% compared with ring spinners depending on yarn count. The yarns obtained are free from defects since yarn faults such as slubs which are produced in the middle of the spinning are eliminated and a knotter /splicer is used for joining. Recently Nergis and Ozipek (2001) have reported on the properties of two ply air jet spun yarns produced on the PLY-fil 1000 system. The Murata twin spinner and the Suessen Plyfil are commercial twin-air-jet-systems used for producing two fold wrap spun yarns.

2.6.5 Vortex Spinner

Murata Vortex Spinner (MVS-851) by Ms. Murata Machinery Limited, Japan uses four lines drafting with vortex system to impart the twist (Ishtiaque 1988). The feed material is 100% cotton sliver. The drafting system is claimed to be capable enough to give draft range of 10s to 50s at a delivery speed of 300 to 400 mpm. The draft conditions can be set by one touch and machine is equipped with monitoring and managing system for yarn quality.
control. Its novel yarn formation principle is claimed to produce less hairy with good strength at extremely high speeds in a shortened process.

Murata’s No.851 Vortex Spinner was displayed in OTEMAS ’97. This is a false twist process and the twist insertion in this system is achieved by air jets. The claimed benefits are a low maintenance cost due to fewer moving parts, elimination of roving frame stage and improved fully automatic piecing system. Yarns produced by this method have low hairiness compared to normal ring yarns. This is claimed due to “air-singed” and “air-combed” which in turn results in reduced fabric pilling and fabrics made from Vortex yarns have outstanding abrasion resistance, moisture absorption, colour fastness and fast drying characteristics. It is claimed by the machinery manufacturer that MVS is best suited by far to the high volume production of medium count yarns from carded cotton.

The disadvantage of this spinning technology is the high speed drafting which is 10 times higher than that of ring spinning. Fiber loss during spinning and the frequent contamination in the jet nozzles since fiber material may be fed to the spinning unit without being adequately cleaned (by combing for example) is another major problem.

2.6.5.1 Principles of vortex spinning

In the MVS system, a sliver is fed directly to a 4-line drafting system. When the fibres leave the front roller of the drafting device, they are drawn into a fiber bundle passage by air suction created by the nozzle. The fibre bundle passage consists of a nozzle block and a needle holder. The needle holder has a substantially central, longitudinal axis. A pin-like guide member associated with the needle holder protrudes towards the inlet of the spindle.
Following the fiber passage, fibers are smoothly sucked into a hollow spindle. Twist insertion starts as the fibre bundle receives the force of the compressed air at the inlet of the spindle. The twisting motion tends to propagate from the spindle toward the front rollers. This propagation is prevented by the guide member and drawn into the spindle by the preceding portion of the fiber bundle.

After fibres have left the guide member, the whirling force of the air jet separates fibres from the bundle. Since the leading ends of all the fibres are moved forward around the guide members and drawn into the spindle by the proceeding portion of the fiber bundle being formed into a yarn, they present a partial twist and are less affected by the air flow inside the spindle. On the other hand when the trailing ends of the fibers which have left the front rollers move to a position where they receive the powerfully whirling force of the nozzle they are separated from the fiber bundle, entered outwardly and twine over the spindle. Subsequently, these fibres are spirally wound around the fiber core and formed into a vortex spun yarn as they are drawn into the spindle.

The yarn is wound onto the package after its defects have been removed. During the yarn formation as the twist propagation is prevented by the guide member, most of the fibers do not receive the false twist. A number of wrapping fibers in the yarn are formed due to the fiber separation recurring everywhere in the entire outer periphery of the bundle. This is the reason why the vortex yarns present much more wrapper fibres than the jet spun yarns.

2.7 AIR JET – SPINNING WITH OTHER SYSTEMS

Yu (1999) has studied the characteristics of open end jet yarn by fabricating a device which combines the advantage of both air-twisting and open end spinning. Attempts were made in the past for improving the
performance of rotor spun yarns by introducing long staple viscose fibers, which led to the formation of belts. Sengupta et al (1980) have studied the fiber belts in rotor spun yarns.

Sawhney et al (1993) have reported a novel way of producing polyester staple core cotton wrap yarn; they have used air jet spinning and friction spinning in tandem to produce the yarn. It was possible to spin all staple wrap composite yarn with a relatively fine size and low core content. These yarns could be used in knitting and weaving without stripping. Mahmoudi and Oxenham (1996) have used air jet nozzles to improve the bulkiness of worsted yarns. Sawhney and Kimmel (1997) have carried out work on a new tandem spinning system which combines ring spinning and air jet spinning technologies; the main object of developing this method was to boost the spinning productivity.

Wang and Miao (1997) have used an air jet nozzle on a winding machine to control the hairiness of wound ring and rotor spun yarns. Chellamani, Chattopadhyay and Kumarasamy (2000) have reported that by using an air jet nozzle in cone winding machine, the hairs in ring yarn show a decrease by 50 – 75%.

It may be stated the mechanism of air jet application in winding machine is similar to that N₁ nozzle of air jet spinning machine. The ring yarn from the bobbin on its way to the winding drum is in a twisted configuration. If, by application of gyrating air jet, the yarn is de-twisted for a short while and then re-twisted, the following action may logically be expected to occur:

1. Some of the short protruding hairs in the yarns may be detached from the main body and may be lost as fly.

2. If the direction of gyrating of the air jet is opposite to the direction of yarn traverse, the protruding ends may get embedded in the yarn body. Since the yarn is in the loosened
form in the detwisting zone, the embedded fibres may be tucked in upon exit of the yarn from the de-twisting zone. The embedded fibres, which are not tucked-in, may become wrappers around yarns.

Appendix 3 shows the details of the research carried out on ring and winding machines by many research workers using air jet nozzles.

Jet ring spinning is a hybrid technology in that principles of ring and jet spinning are combined. Usually the system consists of a single air jet below the yarn forming zone of a conventional ring spinning system. Wang, Miao and How (1997), Ramachandralu (2002), Subramanian et al (2007) have shown the improvement in hairiness of yarns with the system.

Attempts have been made to combine the mechanism of air jet spinning with that of ring spinning; this systems consists of a single air jet below the yarn-forming zone of conventional ring spinning system by Wang et al (1997). This jet acts in a way similar to the first nozzle in twin nozzle air jet spinning. It is claimed that, with the application of lower air pressure (0.5bar) when compared with air jet spinning, the yarns can be produced with less hairiness. It has been found that these yarns are somewhat weaker compared with ring spun yarns.

It was Kalyanaraman (1992) who did pioneering work in ring frame by inserting a pressure column between the front roller and the lappet. By allowing the twisting yarn to pass through this column, he found that hairiness could be considerably decreased. However, his work did not address any issues on other yarn characteristics. Boong Soo Jeon (2000) has conducted studies with air suction nozzle instead of air jet nozzle in ring frame and demonstrated that hairiness reduction was possible with air suction nozzle.
Air vortex and air jet developments led to air-jet machine, which are not truly open end spinning machines. In OE spinning, there is an open-end, which can be rotated, whereas in some of the yarns, continuity in flow is given by the core. Fibres outside that core can be arranged and trapped in the structure to give different yarn characteristics. It was shown that air jets entering tangentially with respect to the bore of the nozzle cause a vortex within it, and the high speed rotation of the air can be used to twist yarn passing coaxially through the vortex. The pure air-vortex spinners did not succeed commercially but they laid the ground work for the modern air-jet spinning system. They also laid the ground work for some of the textured and composite yarns. If the jet in the nozzle is inclined in the direction of air flow, it can help transport the yarn. The production of fasciated yarn is accomplished in the spinning technology. Fasciated refers to wrapped yarns. The original idea was based on the addition of fibres to a flowing, false twisted structures followed by removal of torque at the exit of the false twister. The hairs in the yarn are also wrapped and thus the hairiness is reduced. These entrapped in the structures give enhanced cohesion to the strand even after untwisting. Several patents disclose several types of processes and apparatus.

The hairs are laid on the core of false twisted yarn leaving the twist triangle, and the false twist is removed with the hairs in place. The spinning action wraps the hairs around the core and there is enough lateral fibre migration to lock the structure. The yarn has little or no twist in the core but has a twisted sheath which gives the structure integrity.

Muratas MJS and MTS produce yarns called “Vortex”. In MTS and MJS systems the fibres used are polyester; viscose and polyester cotton and the counts produced range from 10 Ne to 80 Ne. The claims made are good moisture absorbency, quick drying and durability. Because of the integration of roving, spinning and winding processes, the cost can be cut down and the
doubling processes may be eliminated. The process flow chart for MJS and MTS vis-à-vis ring spun yarn is shown in Figure 2.5.

![Process flow chart](image_url)

**Figure 2.5 Process flow chart**

When the MJS and MTS were introduced, the delivery speeds were 300 and 330 m/min. One of the advantages of the Murata air jet spinning system was that it was able to spin finer counts than that of the rotor spinning. However, they are not suitable for pure cotton fibres. High energy cost associated with high consumption of compressed air due to two nozzles and due to regularly wound wrapper fibres when the fibre length increases owing to unstable ballooning during spinning are the other short comings of the system.

Murata have also launched several other revisions of MTS which were an improvement over their first model.
2.8 NOZZLES

The nozzle plays an important role in that yarn coming out of the front roller is acted by the air currents which swirl the fibres. The action is more or less similar to what happens to a filament yarn following wetting in air texturing.

2.8.1 Location of Nozzle in Rotor Frame

The nozzle assembly comprising of air jet nozzle and air-jacket is fitted in the rotor spinning machine in between the rotor withdrawal tube and winding head.

2.8.2 Nozzle Material

The nozzle is made up of aluminum metal and the air jacket is made up of brass.

2.8.3 History of Nozzle Development

Nozzles were used for producing air jet textured yarns from polyester, nylon and other fibers. Starting from 1952, the various modifications that have been made on nozzle design in order to reduce air consumption and productivity have been well documented in the literature Acar et al (1986) and Hoffsomer (1980). There are different type of nozzles such as converging, diverging type and cylindrical. Hoffsomer (1980) states that the evolution of jet configurations can be divided into three groups:

1. Yarn entering into the air stream at an oblique angle (typified by DuPont 9 system)
2. Yarn entering into the air stream on the same axis as the existing air stream (DuPont types 10 & 11)

3. The addition of external plates and baffles into the air stream exhausting out of the venture (DuPont types 14 & 15 and Heberlein) Figure 2.6 shows the various types of nozzles.

![Figure 2.6 Various types of nozzles](image)

Bock and Lunenschloss (1981), Acar et al (1986) and Rwei (2001) have dealt with the design and function of nozzles.

When the nozzles have been fixed in the ring frame between front roller and lappet, the kind of interaction between the yarn and air currents has been discussed by many research workers. That no detailed studies on the
interaction between yarn and air current in the case of air texturising is noticed.

A considerable amount of research has been carried out on the structure and properties of air jet yarns. Basu’s research on air jet spinning culminated in a number of publications (1992, 1999, 2000). The air jet spun yarn consists of a core of parallel fibres wrapped by surface fibres. The structure-property relationship of air jet spun yarns from polyester fibres has been studied by Chasmawala, Hansen and Jayaraman (1990). These authors used tracer fibres to determine the effects of yarn structure and properties of front zone and back zone draft ratios and compressed air applied to the first of the two jets on a Murata air jet spinning system. Increases in these variables increased the wrapper fibre frequency and improved the yarn tensile properties but increased in the yarn regularity.

2.9 MORPHOLOGY OF AIR JET YARN

A considerable amount of work has been done on the morphology of air jet yarns by Chasmawala et al (1987), Lawrence and Baqui (1991) and Soe et al (2004).

Lawrence and Baqui (1991) have carried out a detailed analysis of air jet fasciated yarns, as affected by other spinning machine variables. They used acrylic fibres and 30 Tex yarns were produced by altering air pressure, production speed, thread tension, draft and inter jet distance. The effects of the parameters on the properties of the air jet fasciated yarns were examined. According to them the yarn can be classified into three types of structure. Class I structure consists of twistless core, which at times crimped but wrapped uniformly by a “thin fine ribbon with a uniform helix angle and direction. Class II consists of a twist less core randomly wrapped by fibres in singular state and in groups, showing ‘Z’ and ‘S’ direction of wrap with
different helix angles. Class III structure contains unwrapped sections of yarn core at times having residual twist. The relative frequency of different classes and their mean lengths can be varied by varying the process parameters.

How et al (1991) observed that the yarn produced by air jet spinning is different from other spinning methods. Polyester cotton blended 65/35 yarns are formed by two parts: bundle of fibres and outside wrapping fibres. In the bundle of fibres, a majority fibres are inclined at an angle of 5-10° in S and Z directions; sometimes the fibres are parallel to each other or crossed together. The outside wrapping fibres are gripped on the bundle fibres in different styles such as cork-screw-like wrapping, irregular wrapping, kinked wrapping, even wrapping featuring the edge free and fibres wrapped evenly on the bundles, loose wrapping and non wrapped portions.

Miao (1998) and Basu (2000) have used the following classifications of 100% polyester, 50/50 blend polyester and cotton and 100% cotton yarns.

Class 1: The part of the yarn that has regular helical wrappings and the yarn core crimped. This core strand appears to be a spatial curve similar to a helix. According to them, yarn crimpness is due to the buckling force generated by wrapping fibre torque and tension.

Class 2: This structure has no wrapping fibres on the surface and has geometry similar to a ring yarn but with a low twist level.

Class 3: This class of structure consists of a straight yarn core wrapped by regularly twisted wrapping fibres. Generally, these wrapping fibres are less tight.
Class 4: This type of structure has a straight yarn core with wrappers of regular twist.

Basu and Oxenham (1992) have reported that in the case of 100% polyester, polyester/cotton blended yarn and 100% cotton yarns, the relative frequency of class 1 structure is around 50%. The frequency of the other classes was not very much different for different materials. The average length of wrapped structure was found to be different for yarns made of different materials which may be due to the differences in fibre type and fibre length. The cotton yarn had the highest core twist and the polyester the lowest. The explanation advanced by these authors is that due to the higher efficiency of twist transference (i.e., conversion of twist into wrapper fibres) in the case of polyester, the residual twist was maximum in polyester yarns.

Soe et al (2004) have reported on a very interesting study on the structure and properties of Murata Vortex spinning yarns in comparison with ring and rotor yarns. For this purpose three 100% cotton yarns of 30 Ne (19.68 tex) were produced on Rieter G 30 ring frame, Schlafhorst Autocoro SE11 and MVS 851. The yarns were studied for their structure using a microscope and the number of core, wild, wrapper, wrapper wild and belly band fibres were studied. This was essentially based on the scheme for air jet spun yarns provided by Chasmawala et al (1990).

The yarn samples were tested for tenacity, evenness, imperfections, hairiness, compression and bending properties. The yarn bulkiness of the three yarns was also examined.

The results show that Murata Vortex spun yarn was the bulkiest of the three types of yarns which were examined. Yarn tenacity of ring spun yarn was found to be higher than those of the other two types of yarns. It was found that open end rotor spun yarn was 38.7% lower in strength in
comparison with ring spun yarns, while Murata Rotor Spun Yarn (MVS) was 33.6% lower. It was interesting to note that while the number of imperfections namely thick places is lower for OERS (Open end rotor spinning), they are relatively higher for MVS yarn.

Compression and bending properties were found to be the highest for MVS yarns either compared to ring spun or open end rotor spun yarns. These are attributed to structural differences of the three yarns. The overall conclusion is that the Murata Vortex yarns are stiffer than either ring or open end rotor spun yarns.

The importance of yarn hairiness has been emphasized by many in view of its ill effects in warping, sizing and weaving. With hairy yarns, the cloth appearance also gets adversely affected. Therefore reducing yarn hairiness by using air nozzles during winding will be of importance to industry as the production rate of winding is high. Placing a nozzle in one spinning position in rotor spinning is equivalent to placing several nozzles between front roller and lappet in ring spinning as the production rate of rotor spinning is about 10 times faster than that of ring spinning. Further, any increase in number of hairs during spinning process will also be subject to suppression when the rotor yarn passes through nozzle. Thus when compared to the ring spun yarn which contains a considerable amount of hairs in comparison with rotor spun yarns and subsequently reducing them by passing the yarn through the nozzle in ring spinning, fixing nozzle in rotor spinning is most desirable as rotor spinning has a component of yarn winding. Thus nozzle serves a dual purpose if it is fitted to rotor spinning unit.

Wang and Miao (1997) and Zang and Yu (2004) have reported on jet winding in which a nozzle is incorporated in winding. All these research work were carried out at low winding speeds of 200 – 250 m/min. Reducing yarn hairiness in ring spun yarn by introducing a nozzle in winding involves
two processes, namely, spinning and winding whereas for rotor spun if the nozzle fitted in the machine, it amounts to a single process. Thus fitting nozzle to a rotor spinning machine appears to be an attractive proposition.

Chellamani et al (2000) studied the influence of air pressure and nozzle axial angle in Jet Wind system. They found that nozzle with axial angle of 60° and 1.0 bar (gauge) pressure led to a higher reduction in yarn hairiness.

Axial angle of air inlets and yarn channel diameters do affect air flow characteristics and thereby affect the magnitude of hairiness reduction.

Soe et al (2004) have provided data on yarn diameter of ring spun open-end ring spun and MVS yarns, which show that MVS is characterized by higher values. Higher diameter of yarns refers to greater bulk and lower packing density. Also, a comparison of the coefficient of variation (CV %) of the yarn helix angle shows that ring spun and MVS yarns possess highest core fibre parallelisation than open-end ring spun yarn. The reason for the bulkiness in MVS is attributed to the wrapper fibres formed by swirling air around the spindle under no tension and also by the creation of the loops of wild fibres.

Acar and Wray (1986) have discussed the developments of nozzle designs for air texturing. The progressive developments in nozzle design since the early 1950s has considerably improved the productivity of the nozzle and has led to increased texturing speeds from about 50 to 500 m/min, reduced compressed air consumption, elimination of the necessity for a pre twisted supply yarn and improved yarn quality. While the nozzle used in texturising improves the bulk of the continuous filament yarn, the application of nozzle in Ring frame improves the compactness of yarns.
Chellamani (2000) has carried out extensive studies on air jet yarns in order to find out the effects of fibre length and fibre fineness on low stress mechanical properties and surface properties of yarns. Additionally, the process parameters were identified for air jet yarns. Also, the scope of reducing the yarn hairiness in cone winding by the application of air jets has been explored. Subramanian et al (2007) have investigated the effect of double and triple nozzle on yarn characteristics. Wickability has been conducted in depth by them and for compact yarns interesting observations have been made.

Chellamani et al (2008) have evaluated the comfort and dyeing characteristics of fabrics made out of regular and compact yarns. Their major conclusions are that tensile strength of compact yarn fabrics is higher than that of regular yarn fabrics by 4 to 5% which is attributed to the higher packing density of compact yarns. Air resistance value for fabrics made out of compact yarns was higher by 20 to 25%. This would imply that plain fabrics of dense fabrics made out of compact yarns are less breathable. However, in twill construction, compact yarns had shown better breathability. Pilling propensity was less for compact yarn fabrics by about one grade. Flexural rigidity of compact yarn fabrics was higher than those of ring yarn fabrics by about 22%. Ring yarn fabrics exhibited better crease recovery which is attributed to the relatively lower packing of fibres in those yarns. Ring yarn fabric wicks faster than compact yarn fabrics. This is attributed to higher packing density of compact yarns. No significant difference in the colour strength values between compact and ring spun fabrics was observed.

2.10 COMPACT SPINNING SYSTEM

In order to improve the production of ring frame, different approaches have been made such as rotating rings and use of high tech materials for the ring and traveler such as ceramic Oxenham (2003). Compact
spinning is another approach to get the improvement in the yarn. While the idea is not new (originally proposed by Fehrer as part of the Dref Ring concept) a considerable amount of interest has been taken by many machinery manufacturers. Rieter have launched the compact spinning frames in 1995. The ring frame continues to be popular in view of its cheap cost and its flexibility. Recently, Ramco group, the biggest spinning mills in South India have installed 84000 spindles of compact spinning. At ITMA ’99 in Paris three textile machinery makers: Rieter of Switzerland, Suessen and Zinser of Germany demonstrated their compact or condenser spinning systems. There is some difference between them but all of them are based on the same principle of the “elimination” of the spinning triangle by pushing the staple fibre together or condensing them to attain much smaller spinning triangle than with conventional ring frames. The fibre ends are much more tightly incorporated into the fibre mass. Suessen claimed that its technology would be applied virtually to the entire current spread of ring spun yarn counts and types at ITMA ‘99.

Although compact spinning systems have been launched, the production is low and depends on the traveler and spindle speeds. Apart from these limitations, the ring spun yarn sets the standard against which all-alternate yarn types are measured at present.

The spinning triangle is considered to be the weak point of a ring spinning system but also provides an opportunity for improvement in ring spinning. So far, Rieter, Suessen have developed the compact yarn spinning systems which are used in Ring spinning. There have been criticisms also about compact spinning and the suitability of this system for different counts is questionable.
2.11 AIRFLOW IN TEXTILE PROCESSES

Cai (2003) gives an excellent summary of air flow in textile processes. Air flow is currently being used to a very large extent in textile industry. The use of air flow in many textile processes is quite wide spread. The optimal use of air flow is an essential component of many processes such as: a) Rotor spinning b) Air jet c) Vortex spinning d) Air texturising e) Friction Spinning f) Melt blown and spun bond nonwoven. g) Air jet weaving.

Air is also used for applying pressure to top rollers in draw frames, roving and ring frames. The use of air in testing fibre fineness is well known. Also, air is used in testing the bursting strength of fabrics. It appears that without the use of air and heat, no textile material can be processed into yarn from natural and manmade fibres. Air management thus plays a very crucial role in the processes which involve the use of air.

At the Swedish Institute of Textile Research, Eeg-Olofsson used air currents for the spinning of fibres as early as 1960. This work examined the role of air currents in various textile processing areas such as blow room and carding.

2.12 A BRIEF DESCRIPTION OF VARIOUS PROCESSES

2.12.1 Rotor Spinning

Edberg (1968) has studied the fibre behaviour subjected to the aerodynamic forces and fibre behaviour in both laminar and turbulent airflow was studied. The experiments were carried out in a wind tunnel and the parallelisation of the airflow on the fibre was tested at different flow velocities. Acar and King (1993) used high speed photography to study fibre alignment and straightening properties in rotor spinning.
In rotor spinning, air flow need not only be used to transport paralleled fibres. For producing fancy yarns, Kwasniak (1996) has used an additional pressurized air flow to disturb the air flow field and then to produce fancy yarns. At first pressurized air flow was directed to different locations inside the rotor spinning box to evaluate the most suitable way to disturb the fibre. These locations are

1) Rotor bottom
2) Rotor groove
3) Opening roller
4) Fibre transport channel

It was found by Kwasniak that the best location at which the pressurised inflow was placed to disturb the fibre flow to produce fancy yarn was in the fibre transfer channel. A specific location in the transport channel was found to give the optimal effect; the direction of the pressurised airflow was against the direction of the fibre flow. A series of experiments was carried out to test the configuration of this new method and the effect of the following parameters on the characteristics of the fancy yarn was examined.

1) Nozzle
2) Rotor diameter and rotor groove
3) Opening roller speed
4) Rotor speed

In addition, continuous blowing and intermittent blowing were used to test different fancy yarn effects. A theoretical analysis was carried out in another paper by Kwasniak and Peterson (1997). Kwasniak also tested the methods in commercial rotor spinning machines. The most commonly used
methods for producing fancy yarns on rotor spinning are feeding excess material to the rotor but the disadvantage is that effects can not be shorter than the roller circumference. Kwasniak and Peterson (1997) developed the technology to make it possible to divide long effects into short ones by blowing pressurised air to the fibre transportation channel.

2.12.2 Air Jet Spinning

Air flow is used in air jet spinning to generate the action of “false twist” to the drafted sliver that goes into the twist chamber. This is achieved by a high speed air flow that is injected from the nozzle. A vortex is formed by the circular shape of the twist chamber and the direction of the nozzle outlet.

A considerable amount of work has been done on the properties of air jet spun yarns by Grosberg, Oxenham and Miao (1987); they compared air jet yarn properties on three different arrangement of air jets. A theoretical analysis of the kinematics of the yarn was carried out. They made an assumption with regard to the rate of twist flow to make a prediction agreeable with the experimental results.

Oxenham and Basu (1992) studied the influence of jet design on the strength of cotton air jet spun yarns and showed that if the jet orifice was inclined more than 60° to the axis of the yarn there was difficulty in spinning, but at 45°, spinning went on well.

Chasmawala et al (1990) have investigated the structure and properties of air jet spun yarn. They also studied the relationship of the following interactive factors using “computer simulation”.
Yarn count and fibre fineness,
Fibre tenacity and fibre friction
Fibre length and fibre friction,
Number of wrapper fibres and wrap angle.

Suitable suggestions of yarn engineering guidelines were given by the authors to optimize yarn strength using the results of each of the four simulations.

2.12.3 Air Jet Texturising

A multifilament yarn can be textured in the air jet nozzle, as yarn is “overfed” into the nozzle. By doing so, longitudinal displacements of yarns and loops will be formed in the extremely violent air flow stream. There is much literature concerning the mechanism of the air jet texturing process. Acar and King (1993) have dealt with the development of understanding of air texturing technology. Chaithanya and Dani (2002) have carried out research on air textured Kevlar yarns which has expanded the application of this important branch of yarn technology. Some of the findings obtained by Dani (2004) are found to be contradictory to the findings of earliest workers. The role of water, overfeed and mechanism of loop formation have been investigated, and some fresh ideas have been provided by him. A number of research workers, Wray and Entwistle (1968), Sen and Wray (1970), Sivakumar (1975), Bock and Lunenschloss (1981) have studied the mechanism of loop formation in air textured yarn. Acar, Turton and Wray (1986) carried out their study on the mechanism of air jet textured by using a scaled up model of the Hema jet nozzle. Aerodynamic forces acting on the filaments during air jet texturing were also studied theoretically by Acar, Turton and Wray (1986).
2.12.4 Air Jet Weaving

Mohamed and Salama (1986) have studied the effect of nozzle design on the air velocity for an air jet filling insertion system. Nozzles were used to study the influence of nozzle structure on the air flow characteristics at the exit. Theoretical analysis based on the dimensional flow was carried out to explain the nozzle performance. Relationship among air velocity turbulence and flow rate at the nozzle exit and the nozzle air tube length and air tube diameter were reported.

2.12.5 Air Flow in Non Wovens

Air flow plays a very important role in the production of non woven fabrics. Melt blown technology is one such process in which polymer is melt extruded through a die into a high velocity stream of hot air which converts into fine and relatively short fibres. After quenching by a cold stream, the fibres are collected as a sheet on a moving screen. Cai (2003) has carried out research on computer modeling of fibre motion in high speed air flow which can effectively simulate the interactions between fibres and air flows in processing machines. A three-dimensional structure of an aerodynamic component of a textile machine was developed. A commercial CFD (computerized fluid dynamics) software package was used to compute the air flow field of this model and the results were analysed to study the air flow fields characteristics. Resultant data were used as input for the fibre movement model by using one-way coupling method.

The mathematical model of fibre movement was constructed by integrating the governing equations with a model that describes the fibre configurations. A numerical method was developed to solve these equations and visualization programs were established to illustrate and animate the simulated fibre movements. The results obtained were studied and compared
under different initial and boundary conditions. Recently Rengasamy et al (2006) studied air flow simulation in nozzle for hairiness reduction of ring spun yarns and particularly carried out CFD (Computational Fluid Dynamics) modeling of air flow.

2.13 EXPERIMENTAL STUDIES ON THE RELATIONSHIP BETWEEN THE YARN STRENGTH AND GAUGE LENGTH

Hussain et al (1990) conducted experiments on the effect of tensile specimen gauge length on cotton yarn strength. It was found that yarn tenacity was “a modified power-law function of gauge length” manifesting lower mean strength values at longer gauge lengths. They also found that significant differences in this gauge length effect occurred between pairs of ring vs. rotor spun yarns of comparable structures (29.5 tex and 4.0 twist multiple) and of three different cotton varieties. The gauge length effect which was expressed as a ratio between the tenacity of a given gauge and that of a cm length showed no significant difference between ring and rotor spun yarns at relatively short lengths. But the differences were statistically significant at long (70cm) lengths. The extent of decrease is greater for ring spun yarns than for OE yarns, indicating that the rotor yarns are more uniform with respect to ring yarn yarns. Reallf et al (1991) proposed that mechanism of failure might also change due to a decrease in test length. They observed different range of failure zone size for ring spun and air jet spun yarns for different gauge lengths (Table 2.1). According to their observations, as compared to the air jet spun yarns, ring spun yarns yield higher strength, many broken fibres and a small failure zone size at longer gauge length. But at gauge lengths well below the fibre staple length, air jet spun yarn, shows more strength than ring spun yarn because the difference in surface helix angle ($\theta$), since $\theta > 0$ for ring spun yarn, $\theta \geq 0$ and $\theta \leq 0$ for the core fibres of air jet yarn. While comparing the influence of gauge length on yarn failure for ring spun and
open end spun yarn, they found that ring spun yarns failed by fibre breakage at both long and short gauge lengths. But the open-end yarns show a change in breakage mechanism from a fibre slippage dominant failure at long gauge length (127 mm) to a fibre breakage dominant failure at short gauge lengths (12.7 mm and < 2 mm).

Table 2.1  Range of failure zone size for different gauge lengths (Realff et al 1991)

<table>
<thead>
<tr>
<th>Yarn system</th>
<th>Gauge length (mm)</th>
<th>Failure Zone size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring spun</td>
<td>127</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>Ring spun</td>
<td>76.2</td>
<td>2-4</td>
</tr>
<tr>
<td>Ring spun</td>
<td>&lt; 2</td>
<td>0.5 – 2</td>
</tr>
<tr>
<td>Air – jet spun</td>
<td>76.2</td>
<td>3.5 – 10.5</td>
</tr>
<tr>
<td>Air jet spun</td>
<td>12.7</td>
<td>3-8</td>
</tr>
<tr>
<td>Air jet spun</td>
<td>&lt; 2</td>
<td>0.5 -2</td>
</tr>
</tbody>
</table>

Oxenham et al (1992) compared the effect of gauge length on the strength of ring and open-end friction spun yarns and found that the strength of the ring spun yarns shows a sharp drop as the gauge length increases from 1mm to 40 mm (which is approximately the fibre length). The strength of the friction spun yarns also drops sharply as gauge length increases from 1 mm to 20 mm (which is almost equal to the fibre extent in the yarn). For gauge length greater than 40 mm, the strength of ring spun yarns appears to be fairly constant whereas the friction spun yarn continues to reduce as gauge length increases, reflecting the discontinuities in the yarn formation zone in friction spinning.
2.13.1 Spun Yarn Strength as a Function of Rate of Extension

Increase of extension rate has led to a decrease in time to break a yarn specimen. Between the time to break and extension rate there is a following relationship.

\[ t = \frac{E \cdot \ell \cdot 60}{100V} \]  

(2.1)

where \( E \) = % breaking elongation of yarn, \( \ell \) = test length in mm, \( t \) = time to break the specimen in seconds and \( V \) = extension rate in mm/min

The rate of extension during tensile testing influences yarn tenacity. Rapid straining of a yarn results in a higher breaking load. Midgley and Peirce (1926) were the first to study the effect of extension rate on yarn tenacity and showed that the breaking load of a 36s Sakel cotton ring spun yarn was inversely proportional to the logarithm of time \( t \) to break the yarn. This relationship was approximately valid over a range of times from 1/50 second to a month.

Meredith (1950) tested yarns over a million fold range of rates of extension and found that the relationship between breaking load and strain rate was approximately linear (actually slightly concave to the breaking load – axis) for most fibres. He established that the following empirical equation for breaking times ranging between a second and an hour.

\[ F_1 - F_2 = kF_1 \log_{10} \left( \frac{t_2}{t_1} \right) \]  

(2.2)

where \( F_1 \) is the breaking load at a time \( t_2 \), and \( k \) is the strength – time coefficient. The strength – time coefficient is the gradient of the average slope of the lines obtained when the breaking loads are plotted against the logarithm
of the time to break. He observed that the strength of cotton yarn decreases by approximately 9% for a 10 fold increase in time to break and the value of \( k \) is close to 0.09. He also stated that the same formula applies to constant rate of loading and constant rate of extension.

Balasubramanian and Salhotra (1985) failed to observe a steady increase in tenacity with increasing rate of extension. They found that tenacity reaches a peak value around an extension rate of 20 cm/min and thereafter declines gradually. This behaviour was found to be true for both ring and rotor yarns spun from three different cotton varieties at three twist levels. The authors thus concluded that maximum tenacity occurs not at a maximum rate of extension as observed by Midgley and Peirce (1926) but at an optimum extension rate. They attributed these results to the following facts: as the rate of extension increases, the percentage of rupture fibre increases resulting in higher breaking strength i.e., a greater number of fibres are contributing to the breaking load. At still larger extension rates (when yarn tenacity decreased) they proposed that the short time available may not be sufficient for the realignment of fibres, this factor could therefore cause a drop in tenacity of individual fibres which is more than what could be offset by the increase in tenacity due to a higher percentage of fibre rupture.

Kaushik et al (1989) found that as the rate of extension increased, yarn tenacity increased reached a maximum and then decreased or remained constant for ring and rotor spun yarns. Luca and Thibodeax (1992) reported that tenacity of the 49.2 tex cotton yarns increased linearly with the logarithm of rate of extension from 10 to 100 mm/min. at 200mm/min, yarn tenacity increased slightly and at 5000 mm/min it decreased abruptly. The 16.4 tex cotton yarn data showed a similar increase in tenacity from 100 mm to 200 mm/min as found for the tenacity of the 49.2 tex yarn over the range 100 to 500 mm/min. However, yarn tenacity for the 16.4 tex yarn was
constant from 100 to 5000 mm/min. Chattopadhyay (1999) showed that with an increase in the strain rate, the values of tenacity increased up to an extension rate of 10 mm/s for both ring and air jet spun yarns and then followed a sharp reduction.

Oxenham et al (2003) compared the tenacity and elongation of different blended yarns tested with Tensojet (400 m/min) and Tensorapid (5m/min) and found that the tenacity values of ring rotor and air jet spun yarns tested with Tensojet are higher than those obtained from the Tensorapid. However, in the case of air jet yarns, the tenacity values measured in Tensojet and Tensorapid showed the least difference than those for the ring and rotor spun yarns. Also, the difference between the Tensojet and the Tensorapid is not significant for 50/50 polycot blend. They also found that the yarn tenacity showed a continuous increase with the logarithm of the testing speed in both Tensorapid and Tensojet tensile testers for 100% cotton and 50/50 polyester–cotton blended yarns.

2.13.2 **Spun Yarn Strength as a Function of Gauge Length**

It has been found that the presence of flaw in the yarn leads to localization of stress in excess of theoretical strength whereby the rupture process is initiated. It thus follows that the fall in strength of the material with the increasing test length is due to the presence of a distribution of flaw of wide ranging magnitude since the probability of encountering a large fatal flaw increases with length.

Peirce (1926) in his pioneering study on strength variability of yarns proposed the “chain weak link” theory. His theorem has been based on the following assumptions:
1) A yarn of length $l$ may be considered as a chain of $m$ links having the same length $l_0$ but various resistance of stretch.

2) Breaking loads of adjacent links are independent variables, i.e., the link of maximum strength may follow immediately one of minimum strength.

Using classical weakest link sealing due to Peirce (1926) one can predict the probability distribution $F_l(x)$, for the strength of a yarn at any gauge length $l$, from a knowledge of the strength distribution, $F_{l_0}(x)$, at a given length, $l_0$, by:

$$F_l(x) = 1 - \left[1 - F_{l_0}(x)\right]^m$$  \hspace{1cm} (2.3)

where $m = \frac{\ell}{\ell_0}$. Moreover if $F_{l_0}(x)$ follows a two-parameter Weibull distribution (Lewis, 1987)

$$F_{l_0}(x) = 1 - \exp\left[-\left(\frac{x}{x_0}\right)^r\right]$$  \hspace{1cm} (2.4)

where $x_0$ and $r$ are positive constants called the scale parameter and the shape parameter (modulus) respectively, then;

$$F_l(x) = 1 - \exp\left[-\left(\frac{x}{x_\ell}\right)^r\right];$$  \hspace{1cm} (2.5)

where $x_\ell = x_0 m^{\frac{1}{r}}$. For data following a Weibull distribution with scale parameter $x_0$ and shape parameter, $r$, the mean and variance are given (Lewis 1987).
\[ \mu_2 = x_0 \Gamma \left( 1 + \frac{1}{r} \right); \]  

(2.6)

\[ \sigma^2 = x_0^2 \left\{ \Gamma \left( 1 + \frac{2}{r} \right) - \left[ \Gamma \left( 1 + \frac{1}{r} \right) \right]^2 \right\} \]  

(2.7)

where \( \Gamma(\cdot) \) is the classical gamma function. The coefficient of variation \( \frac{\sigma}{\mu} \) is a function of \( r \) alone.

### 2.14 RESEARCH ON AIR JET ROTOR SPINNING

Yu (1999) combined the use of an air twisting device, roller drafting and open-end spinning technology into a new spinning concept. Yu has used a roller drafting method assisted by a high pressure air draft to separate the fibres strand into “individual fibres” in order to form an open end. This approach would aid in reducing fibre damage and would not disrupt fibre straightness and parallelisation in feed material. This system which was developed by Yu (1999) dispensed with the opening roller. The yarns produced with this system when compared with the rotor and traditional jet yarns showed poor strength although it had the structure of a rotor yarn. Very limited studies have been reported by him.

Wang (1998a, 1998b) and Wang and Chang (1999) have studied the effect test speed on yarn hairiness which provided valuable insight into the study of air jet nozzles in rotor spinning. Although Grosberg and Mansour (1975) investigated the effect of rotor speed on the tenacity and elongation of the open end yarns, they did not consider yarn hairiness. To day, yarns are spun faster now than ever before. Wang (1999) first conducted studies on the hairiness of worsted ring spun and siro spun at different speeds in the Zweigle G 565 hairiness meter and demonstrated that yarn hairiness was significantly
There are similarities between yarn hairiness testing and winding process for the staple fibre yarns and whatever results that are being observed in testing yarn hairiness at higher speeds may be relevant to fixing air jet nozzle in rotor spinning machine.

Wang (1998) in another paper reports on the hairiness of a rotor spun yarn of 18.5 tex tested at three speeds namely 25, 100 and 400 m/min. This phenomenon was attributed to frictional rubbing of the yarn surface by the yarn guides on the tester. Surprisingly, there was no change in evenness for both original and rewound yarns were significantly lower at 400 m/min than at 25 and 100 m/min. In another paper, Wang reports that yarn hairiness increases with increase in test speed. Air drag and frictional rubbing were attributed to the increase in hairiness. Wang and Chang (1999) in another study relating to the same subject used Shirley hairiness tester instead of Zweigle yarn hairiness tester which they used in earlier work. The hairiness of ring and rotor spun yarns at different speeds namely 20, 60,100 and 140 m/min was tested and it was found that hairiness fell with increasing speeds. Obviously the contradictory results are attributed to the type and design of testers.

Rengasamy et al (2006) have conducted studies on air flow stimulation in nozzle, was for hairiness reduction of ring spun yarns. The influence of air flow diversion, nozzle distance and air pressure was studied and it was found that all these affected hairiness. An air pressure of 0.5 kgf/cm² was found to reduce S3 values which represent hairiness.

Jet rotor spinning combines the features of rotor and air jet spinning technology. The single nozzle placed between the rotor withdrawal tube and winding head. The single nozzle placed acts in a way similar to the first nozzle in air jet spinning. The swirling air current inside the nozzle is capable
of wrapping the protruding hairs around the yarn body thereby reducing yarn hairiness (Wang et al 1997, Cheng and Li 2002, Patnaik et al 2006).

2.15 GENERAL QUALITY ATTRIBUTES OF AIR- JET YARNS

2.15.1 Tensile Properties

Air jet spun yarn is weaker than that of ring spun yarn. The tenacity of cotton air jet spun yarn is 55-60% of similar ring spun yarn, and this value becomes 80-85% for polyester or polyester/cotton blended yarns, Stalder (1988). Similar observations were reported by Kato (1986), Nierhaus (1984) and Lunenschloss et al (1986). It is observed by Sreenivasamurthy, Chattopadhyay, Parthasarathy and Srinathan (1993) that single yarn tenacity is found to be lower for air jet spun yarns in comparison with ring yarns. The difference between the two types of yarns is lower (30-59%) for polyester/cotton blended yarns than for all cotton yarns (about 55%). Elongation at break for air jet spun cotton yarns is more or less similar to respective ring yarns. However, it is 15% lower in finer yarns. For polyester/cotton yarns, it is about 7-19% lower and the difference widens with decreases in yarn fineness. The work of rupture of yarns is lower by 55-64% compared to ring spun yarns of cotton and by 34-60% for polyester blended material. Contrary to many researchers’ observation, the tensile properties of polyester/cotton (65/35) air jet spun yarns are not inferior as compared to ring spun yarn but loop strength is little lower owing to difference in single yarn structure, Murata (1982).

Kaushik et al (1992) have found that polyester/viscose blended air jet spun yarn is 14-18% weaker than that of ring spun yarns. In general, MJS yarns are more extensible than their ring counterparts. The tenacity of acrylic/cotton 70/30 blended air jet spun yarn is reported to be 22-30% lower
than that of OE rotor counterparts. The trends for breaking extension are found to be similar to those observed in case of tenacity (Tyagi et al 1997):

The tenacity and breaking elongation of polyester air jet spun is lower as compared to ring yarn at all extension rates and gauge lengths, Punj et al (1998). With the increase in extension rate, tenacity increases up to a certain limit beyond which a further increase in extension rate, causes drop in tenacity. In long gauge lengths, the maximum tenacity is achieved at an extension rate of 200 mm/min. The tenacity either remains almost same or drops when the extension rate is increased to 500 mm/min. In short gauge lengths, the maximum tenacity is obtained at lower rate of extension than is obtainable with the long gauge lengths. The effect of change in extension rate and gauge length is more pronounced on air jet spun yarn that of ring spun yarn. At high extension rate, the tenacity difference between ring and air jet spun yarns is minimum. The effects of extension rate and gauge length on breaking extension separately or combined are statistically significant but there is no specific trend for ring and air jet spun yarns. After doubling, the increase in tenacity of air jet polyester/viscose yarn is greater (14-46%) than that of ring spun yarn (around 12%), Punj et al (1997).

2.15.2 Evenness and Imperfections

Air jet spun yarn is more than equivalent to ring spun yarn, (Deussen (1989), Kaushik et al (1992), Lunenschloss et al (1986), Nierhaus (1984) Punj et al (1997) and Stalder (1990)). Unevenness of air jet spun yarns is lower by 25% and 20% respectively for cotton and polyester/cotton blended materials as compared to similar ring spun yarn, (Sreenivasamurthy et al (1993)). Where the effective fibre length is mainly influenced by the cut length of polyester fibre, actual unevenness follows the trend of theoretical irregularity. The U% decreases with increasing number of fibers in the cross section. Yarn imperfections, in term of thin places, thick places and neps are
lower for air jet yarn as compared with ring yarn. Total imperfections are lower by about 70%. If ring spun irregularity is taken as 100%, the air jet yarn irregularity lies between 65-95% (Duessen 1989).

Rotor spun yarns, which are usually considered more even than ring spun yarns, cannot achieve the results obtained by air jet spun yarn. According to Uster Statistics, evenness of air jet spun yarns is better than the upper quartile values, i.e. the results obtained by best 25% of all spinning mills in the world for ring spun yarns. Artzt and Conzelmann (1989) have reported the advantages of air jet yarns in that thin places are lower than that of either ring or rotor yarn. The lower count CV% of polyester/cotton –65/35 yarn may be due to the feeding of very uniform sliver with a low weight CV% (Wang and Jordan 1984).

After doubling, the unevenness and imperfections of air jet yarns decreases by 23-30% and 25-84% respectively. The corresponding values for ring spun are 20% and 69% respectively for polyester/viscose –70/30 blended yarns (Punj et al 1997).

The number yarn defects (slubs) of air jet yarn is far less as compared to that of ring spun yarn (Basu and Oxenham 1999). In the case of ring spun carded cotton (polyester/cotton - 40-60), there are large quantity of trash and neps classified as A1 according to Uster Classimat. Many of these are separated and blown off by high speed ballooning when passed through the air-nozzles. Accordingly, air jet spun yarn contains fewer minor slubs belonging to the A1 class. Major slubs (6 classes A4 to D4, C3, D3) generated are fewer in number. As regards the strength of the two fold air jet yarns. Basu and Oxenham (1999) stated that it might be insensitive to changes in folding twist. On the other hand, the strength of cotton air jet spun yarns increases significantly with increased doubling twist, but these yarns are substantially weaker than equivalent ring spun yarns. Punj et al (1996)
produced plied air jet spun yarns using the Murata jet spinning system with doubling twists of 3.1, 4.1, 5.1, 5.9, 6.7 and they conducted that MJS yarns from polyester / viscose with 4.1 tp cm doubling twist can provide optimum process performance and yarn quality. After doubling, the tenacity of MJS yarns was still lower than that of the tenacity of ring spun yarn, whereas the increase in the tenacity of MJS yarn was greater than that of ring spun yarn. Chattopadhyay (1996) investigated the influence of ply twist and its direction on the properties of air jet spun yarn. He concluded that an optimum level of ply twist in the opposite direction of the wrapping fibres increased the strength and reduced the hard feel of air jet spun yarn.

2.15.3 Bending Rigidity of Air Jet Spun Yarns

Air jet spun yarns have higher bending stiffness when compared with ring spun yarns (Basu 1999, Kaushik et al 1992, Punj et al 1996). Vohs, Barker and Mohamed (1985), found the air jet spun yarn to be less compressible than that of ring spun yarns.

Flexural rigidity of air jet, spun acrylic / cotton blended yarn is 15-20% higher that that of rotor spun yarn (Tyagi et al 2000). In the air jet spun yarns, the clustering effect of core fibres due to their parallel arrangement and winding by tight wrapper fibres, allows little freedom of movement of fibres during bending, causing higher flexural rigidity.

Bending rigidity can be reduced by changing various process parameters but this is achieved with a significant loss in yarn strength and increase in yarn hairiness (Wang and Jordan 1984). After doubling, the increase in bending rigidity of air jet spun yarn is lower (1.3 to 16%) when compared with that of ring spun yarn (41-86) consisting of polyester / viscose – 70/30 blend proportion (Punj et al 1997). If ring yarn diameter is taken as 100% the diameter of air jet spun yarn of same linear density is 75-100%.
Recently, Mukhopadhyay et al (2002) have discussed the low stress behavior of air jet yarns by using Box-Behnken design of experiments. They studied the influence of first nozzle pressure, gauge length, main draft and condenser width on the initial modulus and flexural rigidity of polyester and viscose yarns. It has been found that the initial modulus and flexural rigidity of jet-spun yarn increase with the increase in first nozzle pressure gauge length and condenser width individually when the other variables are set at lower levels. However, the above yarn characteristics may decrease with the change of one variable at a time keeping the other variables at higher levels. The changes in flexural rigidity with the process variables can be predicted from the yarn initial modulus. However, these authors state that the lower initial modulus may not imply lower yarn flexural rigidity.

2.15.4 Abrasion Resistance

Nikolic et al (1993) have reported that the abrasion resistance of air jet spun yarn is higher than that of ring yarn. In acrylic / cotton blended yarn (70/30), air jet yarn exhibited lower abrasion resistance than those of rotor spun yarns (Tyagi et al 1993). The tight wrappers in air jet yarn make sheath immobile unlike the rotor spun yarn sheath which is mobile and thus enhances the abrasion resistance. Toughness index, which is an indicator of the ability of a textile substrate to absorb work, also significantly affects the abrasion resistance.

After doubling of air jet spun, polyester/viscose blended yarn, the improvement in abrasion resistance was found to be greater than that of ring spun yarn (Punj et al 1997).
2.15.5 Hairiness of Air Jet Spun Yarns

It has been found that air jet spun yarns are less hairy when compared with ring spun yarns, Lord (1984), Vohs Barker and Mohamed (1985), Wang and Jordan (1984).

In general, the range in values of hairiness is lower for rotor spun yarns compared to ring spun yarn. Air jet spun yarns are similar to ring spun yarns for 1 to 2 mm intervals, but they fall to the level of rotor spun yarn for 3 to 4 and 4 to 6 mm intervals and finally they drop below the other two yarns. Tyagi and Dhamija (1998) have observed that in a blend of cotton and acrylic air jet yarns, the cotton rich yarns are relatively more hairy than those having higher acrylic content, although the latter are more bulky.

Punj et al (1997) have observed that the hairiness of air jet decreases after doubling process by 62-89%.

2.15.6 Frictional Properties

Kalyanaraman (1988), who undertook studies on the static and dynamic frictional behavior of cotton and acrylic air jet spun yarns, found that air jet yarn was characterized by higher coefficient and more abrasion on machine parts in processing as compared to cotton yarns. As regards polyester cotton blended yarn, the friction of air jet spun yarn was found to be higher than that of ring spun yarn Murata (1994).

2.15.7 Structure – Properties Relationship

Yarn properties are affected by their structure Chasmawalla (1987), Chasmawalla et al (1990) derived the following regression equations for polyester yarns.
Breaking load \((g) = 515 - 3.12 \times \# \text{core}\)

Evenness \((CV\%) = 15.6 + 0.191 \# W_r - 0.230 \# W_r - W_i\)

Hairiness \(= 4561 - 42.8 \# W_r - W_i - 92.4 \# W_i - 35.1 \# \text{core}\).

where

- \# Core - number of core fibres
- \# W r - number of wrapper fibres
- \# W r – Wi - number of wrapper wild fibres and
- \# Wi - number of wild fibres

It was further reported by them that as the number of core fibres increases, the breaking load decreases. The number of wrapper fibres has a greater influence on yarn evenness when compared with wrapper wild fibres. As the number of core fibres increases, the proportion of protruding fibres is reduced resulting in lower yarn hairiness.

The length and frequency of wrapper fibres influence the tensile properties of air jet spun yarns, Basu and Oxenham (1999). How et al (1991) have found that the type of wrapper fibres determines the strength of yarns produced. Grosberg et al (1987) reported that of the three jet arrangement (single jet, two jets in one direction and two jets in opposite directions), the two jets imparting twists in opposite directions produced the strongest yarn. Measurements made on the polyester yarns indicate that this is due to a reduction in the proportion of unwrapped structure.

With changes in various processes parameters, the yarn properties change which can be explained by the change of structural parameters such as the extent of wrappers and the percentage of migrated core fibres, as, studied by Lawrence and Baqui (1991) for acrylic yarns and How, Cheng and Wong (1991) for polyester cotton 65/35 blended yarns.
Xie et al (1989) Krause and Soliman (1985) have shown that yarn strain is related to wrapper fibre strain by the equation

\[ e_y = (2 \sin^2 a_0 - 1) + \left[ (2 \sin^2 a_0 - 1)^2 + e_w (2 + e_w) \right]^{1/2} \quad (2.8) \]

where \( e_y \) is the yarn strain, \( e_w \) is the wrapper fibre strain and \( a_0 \) is the initial angle of wrap of the wrapper fibre.

From the above, it is evident that for a given yarn strain, wrapper fibres with the lowest wrapping angles are strained more, and since the modulus of all fibres is assumed to be the same, wrapper fibre with the lowest wrapping angle breaks first. This happens when the yarn strain is such that wrapper fibre stress (given by the product of wrapper strain and fibre modulus) equal fibre tenacity. However, the stresses in the other wrapper fibres with a higher angle of wrap under the same yarn strain will be less than \( e_y \), and these stresses can be calculated from the above equation and the fibre modulus.

Rajamanickam (1995) attempted predicting the yarn strength from various parameters including the number of wrapper fibres, the wrapping angle of the different wrapper fibers and the length of the structural classes using computer simulation as a tool. They observed that the yarn strength initially increases with an increased wrapping angle, but then decreases at high wrapping angles. Moreover, there is a significant interaction between the number of wrapper fibres and the wrapping angle.

In analytical modeling, certain parameters that are random variables are very difficult to deal with. The mathematical models relate yarn strength to the number of wrapper fibres in the yarn, but the number of wrapper fibres is not constant at all points of the yarn. Therefore, yarn strength, which is determined in part by the number of wrapper fibres, is not the same at all
points of the yarn and is a random variable with a certain distribution. Using mean values of the random variation may lead to a large prediction error. To avoid this problem, computer simulation may be used which can capture the inherent randomness in yarns very accurately. But the simulation model shows the predictive error to be in the range of 37.7-154.7% when compared with experimentally determined yarn strength.

Lawrence and Baqui (1991) have observed for acrylic yarns that the wrapped structures should have imparted strength to the yarn and found that the parameters for the class I (uniformly wrapped) structure were inversely related to those of class III (unwrapped) structure whereas the two parameters for class II (random wrapped) structure shared no relation. As the frequency of unwrapped places in the yarn increased, the breaking load and extension of the spun yarn decreased. The mean length of the class increased as the frequency of the class increased as the tensile values. It was concluded that the uniformly wrapped portion was important for obtaining increased yarn strength. An increase in the parameters of frequency and average length for class I has led to better evenness whereas for class II they show a direct relation to yarn neppiness. The registered neps were identified as the class II structures.

Basu (1991) has carried out a study on the structure – properties relationship using a microscope. The parameters studied were in were incidence of wrappers per unit length (l) average number of wraps in a wrapped zone (AN) and average wrapped length of wrapped zone (AL). The structural parameters were broadly classified as tight belts and loose belt. Within each category, the major three parameters (l, AN and AL) were studied. These parameters are found to be well correlated with the yarn physical properties (r= 0.41 to 0.74). The influence of structural parameter
altogether, like loose and tight wrappers jointly on the CSP, tenacity breaking elongation and hairiness or air jet spun yarns are high (r= 0.63 to 0.91).

Punj et al (2000) have found that the increase in tenacity was found maximum when air jet spun viscose single yarns were twisted in ‘Z’ direction. Increase in flexural rigidity was also high when, the direction of ply twist was ‘Z’.

### 2.15.8 Influence of Fibres Quality Attributes on Yarn Properties

Fibre properties such as fibre length, strength, fineness, frictional characteristics and cleanliness significantly influence the properties of air jet spun yarn.

### 2.15.9 Fibre Length and Fineness

Kato (1986) and Santjer (1991) have emphasized the importance of fibre length for fasciated yarns and in particular for twisted yarns. The longer the fibre, the better the chance that the fibre will adhere to the bundle. According to Santjer (1991) the shorter the fibre, the lower the chance and this results in sharply increasing fibre loss. Longer fibre can be found more number of times with some angle of twist and thus can securely hold the fibre bundle. At the same twist angle, shorter fiber can be wound around the core only once or twice, scarcely enough to secure the fibre bundle and thus the yarn strength will be low. For short staple fibres, it is necessary to increase the number of turns by making the pitch as short as possible.

Looney (1984) observed that the use of 50% fibre shorter than 38 mm (polyester) increased yarn non-uniformity by 10% and the total imperfections almost by 100% relative to the use of totally 38 mm fibre. Yarn non-uniformity (CV %) increased by 30% when combed cotton was replaced
by carded cotton. Similarly yarn imperfections were four times greater, and yarn strength also tended to be lower.

In polyester / cotton blended yarn, there is a need for long staple cotton fibres as well as high concentration of polyester to maximize yarn strength. The strength of yarn core results largely from frictional effect and fibre migration. As a result, yarn strength would be expected to be highly dependent on fibre length (Deussen 1989, Lord 1987, Puji et al 1998, Puttachiyong 1986). The effect of fibre length on evenness of air jet spun yarn is far higher than those for ring spun yarns (Sreenivasamurthy et al 1993).

Krause and Soliman (1989, 1990) have shown by theoretical analysis of wrapping twist in single jet false twist spinning that this technique requires relatively long fibres of an even distribution. Longer fibre length and minimal short fibre content contribute to improved quality in 100% cotton air jet spun yarns as reported by Kametches (1991).

Artzt and Dallman (1989) have observed that increase of 50% span length of fibres by 3 mm has led to an increase of yarn tenacity by 1 cN/tex. In cotton and polyester/cotton blended air jet yarns, the short fibre has the most significant effect on yarn quality as reported by Gilbert (1985): An increase in short fibre had led to reduction in yarn strength higher U%, increased hairiness, increased thin and thick places and increased classimat long think places; this is more pronounced for finer yarn. On the contrary, Sanjiter (1991) has shown that in a polyester sheath core yarn with various cut lengths in the sheath and core, fibre length in the core is the most important to yield higher yarn strength. Coefficient of variation of yarn tenacity improves with longer fibres. Yarn uniformly does not improve as much with long sheath fibres and the unmatched fibre length in drafting becomes important in the “non-intimately blended” yarns. Le Blanc (1989) has pointed out that for polyester yarns, the fibre length does not influence unevenness of the yarn.
It is a well known fact that the number of fibres per cross section increases the tenacity of the yarns. Lord (1987) and Kaushik et al (1993) have observed a similar trend. The long coarse fibre (Lord, 1987) tends to create more imperfections and machine stops than finer fibres. Air jet spun viscose yarn produced from fine fibres has shown considerably lower flexural rigidity and higher elastic recovery (Kaushik et al 1993). The coefficient of friction of ring spun 100% cotton and viscose yarns is lowered by the reduction in area of contact between yarn and guide (Chattopadhyay and Banarjee 1996).

In contrast, it has been commented by Miao (1996), Puttachiyong (1986) and Basu and Oxenham (1992) that the ratio of wrapper to core fibre decreases when the fine fibres are used resulting in decrease in yarn strength. Gilbert (1985) has reported that the yarn strength peaked at medium level micronaire for both 100% cotton and polyester / cotton blended yarns and again reduced with higher micronaire cottons. The breaking load of a fibre increases with the increase in fibre denier. For a given yarn count, however, the number of fibres in a cross section decreases as the fiber denier increases. The resultant yarn strength is the function of two opposing factors – (a) the tendency of the weaker fibre to decrease yarn strength, (b) the number of increased the of fibres in the yarn cross section to increase yarn strength and (c) the tendency of increased number of fibres in the cross-section to increase yarn strength.

The results of simulation showed that the effect of the decreased number of fibres in the cross section predominates in fine counts and this causes yarn strength to level off when coarser fibres are used for fine count yarns. Bhortakke et al (1997, 1999) have reported that coarser polyester fibres, combed cotton fibres and combed cotton in a polyester/cotton blend lead to a higher number of hairs in air jet spun yarns. Fine polyester fibre in the mixing can increase the production of the machine without significant loss.
in yarn strength and unevenness but with a considerable deterioration in yarn imperfection level and hairiness due to predominant effect of higher delivery speed. Artzt and Steinbach (1993) opined that fibre fineness has no effect on yarn strength as long as sufficient number of fibre are present in the cross section. In another paper, they reported that for processing 100% polyester through air jet spinning 1.3 d tex is the optimum fineness for good spinning stability (Artzt and Steinbach 1993).

In ring and rotor spinning systems, it would be expected that the quality of the fibre would be reflected in the quality of the resultant yarn [i.e., longer, finer and stronger fibres produce better yarns]. Oxenham (1985) has pointed out that jet spun yarn fails to exhibit the expected trend. Indeed, none of the normal aspects associated with better quality fibre appeared to demonstrate any benefit to yarn quality and surprisingly it appeared that for finer counts, the yarn tenacity is higher when using coarser and shorter fibres. Artzt et al (1992) have shown that the optimum length of polyester during air jet spinning of polyester / cotton yarns lies in the region of 38 mm. Special length such as the 32 mm used for rotor spinning are found to be disadvantageous for false twist spinning. With increasing fibre count, there is decline in the tightness of wrapping and as a consequence, there is decline on yarn tenacity.

Polyester microfibres of denier less than 1 have been found to produce air jet yarns with higher strength and better evenness (Murata 1994) and also help to increase the spinning speed to the tune of 10 to 20%. Hairiness is found to decrease as fibre becomes finer and the amount of reduction in long hairs was especially noticeable in polyester / cotton MJS yarns over a wide range of yarn linear densities.
2.15.10 Fibre Strength and Elongation

The fibre strength and elongation have maximum influence on the tensile properties of air–jet spun yarn (Basu and Oxenham 1992, Artzt and Steinback 1993). The correlation coefficient of elongation at break with yarn tenacity is found to be 0.98–0.99 and the same for fibre tenacity is 0.86. The wrapping formed by higher extensible fibres can hold the core fibres with a tight grip for longer period when the yarn goes through stress. A study by Tyagi et al (1997) on the characteristic of rotor spun 100% cotton and cotton/viscose blended yarns showed that the wrappers under strained condition extend and thereby reinforce the yarn matrix to restrict fibre slippage.

As yarn strength is significantly influenced by fibre strength, generally stronger fibres should be preferred for producing air jet spun yarn. However, this aspect should always be considered along with fibre elongation. In the case of polyester, it has been observed that fibre tenacity beyond 7.0 g/den offers in such super high tenacity fibres. Those fibres have high orientation and brittleness, and as such are easily damaged during mechanical operations at fibre producers end and in opening and carding at the mills.

In a core-sheath yarn, the yarn strength continues to increase as fibre tenacity is increased and for load–bearing the core of the yarn is especially important (Santjer 1991).

2.15.11 Frictional and Other Properties

Santjer (1991) has commented that air jet spun yarn structure depends very much on fibre to fibre friction for good yarn strength. High static fibre to fibre friction is helpful. Also, for improved yarn uniformity good drafting at high speed is essential. Uniform coating of the fibres with a
wettability finish is essential here. While spinning 100% polyester fibre, a special requirement is a non-depositing finish. In cotton blends, the polyester fibres, which might have problems in ring spinning due to spin finishes, can be successfully spun without jet deposits. In 100% polyester spinning, nozzle deposits cause twist irregularities resulting in weak ends and nozzle chokes.

Rajamanickam et al (1997) have studied the effects of fibre friction and fibre tenacity on the characteristics of air–jet yarns. For this study, three levels of fibre friction (= 0.05, 0.1 and 0.15) and fibre tenacity (2, 4 and 6 grams/denier) were considered. It is observed that the yarn tenacity increases slightly with increase in fibre to fibre friction and it depends more on fibre tenacity than on fibre friction. An increase in the total frictional force will generally increase the number of breaking fibres. An analysis of the interaction between fibre friction (= 0.05, 0.1 and 0.15) and fibre length (30, 45 and 65mm) shows that there is a significant interaction between the two towards yarn strength. The effect of increased fibre friction is more pronounced at lower fibre strength. The total frictional force acting on a fibre depends on frictional force per unit length and fibre length. For a given value of fibre friction coefficient, the total frictional force acting on a fibre will increase with increased fibre length.

The cleanliness of cotton fibre is very important for air jet spinning. Any trash particles or fibrous aggregates such as neps hinder the rotation of the yarn in the narrow air path of the air–jet (Santjer 1991). This leads to a short-term interruption of twist insertion, creating weak places and end breaks. The machine life is also adversely affected by such abrasive trash particles.

Chellamani et al (1995) have reported that it is possible to produce jute/polyester blended yarn by air jet spinning despite the brittle nature of jute fibres. The maximum permissible limit for the jute proportion appears to be
20%. Higher proportions of jute lead to significant deterioration in all the major yarn properties.

The influence of level of added fibre finish on characteristics of polyester MJS yarns has been studied by Dhamija et al (2001). It was observed that a higher level of fibre finish upto 0.25% significantly improves the tensile properties but adversely affects flexural rigidity. Both yarn hairiness and abrasion resistance showed an initial improvement with increase in fibre finish upto 0.05% followed by deterioration with further increase in fibre finish.

Improvement in yarn tenacity with increase in added fibre finish is attributed to an increase in inter-fibre cohesion. Increase in inter-fibre cohesion restricts the freedom of movement of fibres, resulting in higher flexural rigidity.

The increase in abrasion resistance upto 0.05% of fibre finish occurs because inter-fibre friction which resists pulling out of fibres from the yarn body during abrasion increases with increasing fibre finish (Dhamija et al 2001). A higher level of fibre finish, on the other hand, inhibits the separation of edge fibres during drafting resulting in reduced number of wrappers. The rupture of fewer wrappers during abrasion thus causes a rapid exposure to abrasion of the unprotected core, leading to an early rupture. Above 0.05% of fibre finish, hairiness shows increase in the number of protrusions. The initial decrease (upto 0.05% of fibre finish) may be ascribed to reduced spreading of fibres during drafting due to increase in inter fibre cohesion. This would result in a reduced ribbon width delivered at the front roller nip thereby bringing down the hairiness. This would be counteracted to some extent by lower number of edge fibres. The increase in number of hairs beyond 0.05% level of fibre finish is possibly due to greater effect of reduced number of wrappers.
2.15.12 Influence of Process Parameters on Yarn Quality Attributes

In air jet spinning, the major process parameters that influence yarn properties are (i) delivery speed, (ii) draft, (iii) air pressure, (iv) design of air–jet nozzle, (v) first nozzle to front roll distance, (vi) feed ratio and condenser width.

It should be noted that the spinning machine settings (tension, sliver size, drafting roller speed air – jet pressure, distance between rollers, distance between air jet) for all these systems will change the structure of the yarn. The different structures obtained by changing these settings have been studied, along with the effect these structures on the yarn response to tensile loading (Chasmawala et al 1990, Krause and Soliman 1989, 1990, Vohs 1985).

2.15.13 Delivery Speed

Punj et al (1998) have observed that at high spinning speed, the air flow at front roller nip causes the edge fibres to move away from the fibre bundles and this increase the wrapper fibre proportion. High spinning speed also influences the ballooning action which causes more edge fibres to move away from the fibre bundles and this increases the wrapper fibre proportion.

The tenacity of the acrylic yarn improves with increased delivery speed but the thick places and neps become higher (Lawrence and Baqui 1991). This conclusion was drawn based on an experimental spinning unit where maximum delivery speed was much lower as compared to commercial machines.

It has been found that in air jet spinning machines, the yarn strength improves with increases in delivery speed upto a certain limit after which there is a deterioration (Punj and Debnath 1988). Tenacity of polyester/cotton
increases with spinning speed upto 180 mpm and afterwards it starts deterioration with further increase in speed (Doraissamy and Chellamani 1999). In the case of polyester / viscose yarns, spinning speed above 190 mpm is found to be detrimental as far as yarn strength is concerned. The yarn hairiness increases rapidly with the increase in delivery speed whereas unevenness is not significantly affected. Tyagi et al (2000) have reported that the unevenness of polyester/ viscose MJS yarns increases with increase in spinning speed. A study by Punj et al (1997) showed that the average fibre extent in air jet spun polyester, viscose blended yarns increases with increase in spinning speed.

Tyagi et al (1998) have observed that acrylic / cotton air jet spun yarn exhibits an increase in abrasion resistance with increase in wrapped in length and the number of wrapping fibres which effectively shield the core leads to higher abrasion resistance, and consequently the flexural rigidity value of yarns increases with increasing production speed. Tyagi et al (2000), in another study, have reported that acrylic rich acrylic/ cotton MJS yarn are more regular than the yarns containing higher proportion of cotton fibres. Tenacity and abrasion resistance show an improvement with spinning speeds upto 200 mpm.

Dhamija and his coworkers (2001) have reported that in respect of 100% polyester jet spun yarns, the yarn evenness characteristics generally show a deterioration with increasing speed (within the speed of 150 -210 mpm) whereas the yarn tensile properties improved: the flexural rigidity showed a minimum at a spinning speed of 150 mpm.

Artzt and Conzelmann (1989) have reported that yarn twist increases with the increase in delivery speed. For blends of viscose and modal fibres with cotton, the realistic spinning speed is around 180 mpm for 20 tex to achieve satisfactory yarn tenacity. Imperfections such as thick place and
neps show an increase after 180 mpm but the numbers of thin places are independent of delivery speed. Miao (1986) has concluded that, for cotton yarns the optimum speed in air jet spinning is around 150 mpm.

2.15.14 Draft

The main draft has a significant influence on the breaking load, elongation and hairiness of polyester air jet spun yarns. All these parameters increase with increase in main draft. The effect of a specific first nozzle pressure on the yarn evenness is different at different speeds. This implies that the number of wrapper fibres is affected as draft changes and hence a simple change in draft can affect yarn structure also (Chasmawale et al 1990).

An increase in main draft increases the abrasion resistance and flexural rigidity in an acrylic rich MJS yarn (Tyagi et al 2000): this seems to be due to the higher incidence of wrapper fibres and wrapped-in-length. Yarns produced with a higher main draft give slightly lower unevenness. MJS yarns made out of 100% viscose rayon displayed an improvement in yarn evenness as the main draft is increased from 30-40 (Kaushik et al 1993). An increase in total draft from 150-200 in respect of polyester MJS yarn has led to a significant increase in yarn unevenness and yarn imperfections. Other conditions remaining the same, higher draft results in wider stream of fibres emerging from the delivery rollers as a result of increased thickness of feed sliver. This produces an erratic or uncontrolled movement particularly of edge fibres in the main drafting zone which leads to higher yarn unevenness. In addition, the spreading of fibres also results in higher incidence of wrapper fibres which adversely affects the yarn unevenness due to their contribution to short term mass irregularity of yarn (Tyagi et al 1997). Fibres with different levels of fibre finish exhibit different levels of behaviour at different drafts showing significant interactions.
Overall drafts of up to 170 can be used to produce yarns with very good regularity indices using a three roller drafting system (Artzt et al. 1985). However, break drafts and main drafts are governed by limits. The mean tenacity and elongation values increase with increase in main draft. One would have to use as high a main draft as possible and a low preliminary draft. The high main draft stretches the fibre well resulting in high level of fibre orientation and the useful length of fibres. At the same time, however the variation in tenacity and breaking elongation can become higher. The yarn imperfections increase sharply with an increase in the main draft and because of poor consolidation, the thick places lead to weak spots in the yarn. The optimum main draft is 35 and maximum break draft can be up to 5. The three roller drafting system does not show any disadvantages over four roller drafting system in the case of a constant sliver weight. Despite the two drafting zones, three line drafting system operates just as well as four-line drafting system up to specific preliminary and main draft levels. In particular, there are no differences regarding yarn tenacity and elongation at break which are very important criteria for evaluating false twist yarns. The advantage of four roller drafting system is that whilst keeping the main draft constant, the total draft can be increased due to three drafting zones which means heavier sliver can be processed.

2.15.15 Air Pressure

It was Miao (1986) who found that an increase in the first nozzle pressure (from delivery roller) with the twin jet system improves the yarn tenacity for polyester. Puttachiyong (1986) reached the same conclusion for polyester cotton blends.

Lawrence and Baqui (1991) have shown that, while using long staple acrylic fibres in their experiments at lowest first nozzle pressure (within their experimental range), strongest yarn is produced. The tensile properties
deteriorate with increase in first and second nozzle pressure. The increase in first nozzle pressure increases the irregularity and imperfections whereas second nozzle pressure has no significant influence on the irregularity and imperfections of air jet spun yarns.

In contrast, it was observed by Punj et al (1997) that the tenacity and breaking extension of polyester viscose 42/58 blended air jet spun yarns increased with first nozzle pressure upto a certain limit. Further increase in first nozzle pressure decreased the yarn tenacity. Increase in percentage of wrapper fibres by increasing the first nozzle pressure caused increase in transverse forces but wrapper extent decreased due to increase in random wrapping. Unwrapped portions in yarn increased resulting in lower tensile strength. An increase in the second nozzle pressure increased the yarn tenacity and breaking elongation for polyester / viscose blended yarns (Punj et al 1997, 1998). Increase in second nozzle pressure also resulted in increase in the percentage of tight wrappers and wrapper extent. The increase in percentage of long wrappers along with decrease in percentage of short wrappers caused the increase in tenacity. Flexural rigidity of the yarn increased with increase in first and second nozzle pressure. Unevenness and imperfections showed no regular trend with the first or second nozzle pressure.

Acrylic – rich acrylic / cotton blended MJS yarns showed higher values of tenacity, abrasion resistance and breaking elongation with increase in injector – jet pressure. However, the yarns spun with higher injector – jet pressure showed significant deterioration in evenness, irrespective of the fibre composition and yarn linear density. The injector-jet pressure is an important factor controlling flexural rigidity, a higher value leads to higher flexual rigidity (Tyagi et al 2000).
Rajamanickam and coworkers (1997) have reported a regression equation between yarn tenacity and nozzle pressure.

\[
\text{Yarn tenacity (grams/tex)} = 6.121 - [0.082 \times (\text{yarn count in tex})] + [0.113 \times (\% \text{ polyester})] + [0.256 \times \text{first nozzle pressure in kg/cm}^2] - [0.219 \times (\text{second nozzle pressure in kg/cm}^2)].
\]

They observed a very good correlation \((R^2 = 94.6\%)\) with actual values.

Rajamanickam et al (1997) have also formulated a regression equation regarding material process structure relationships. As per their observation, the class I structure is affected by polyester content, first nozzle pressure and second nozzle pressure, whereas class II and III structures are affected by yarn count in addition to these three factors. There are strong relationships between (i) process parameters and yarn structure, (ii) process parameters and yarn properties, (iii) material parameters and yarn structure, (iv) material properties and yarn properties and (v) yarn structures and yarn properties. In addition, there is a weak relationship between material properties and process conditions.

There is an interaction between first nozzle pressure and second nozzle pressure towards yarn tenacity (Rajamanikam et al 1998). This is because the total number of wrapper fibres in a give yarn section and length of wrappings formed at a given first nozzle pressure depend on the level of second nozzle pressure and vice versa. The optimum number of wrapper fibres and wrapping lengths can be obtained at several different nozzle pressure combinations. However, it would be advantageous to use the lowest of these nozzle pressure combinations to gain significant savings in energy.
2.15.16 Design of the Air Jet Nozzle

Basu and Oxenham (1999) and Miao (1986) have described design features of the nozzle used in the ring frame.

Grosberg et al (1987), who conducted studies with single nozzle, two nozzles twisting in the same direction and two nozzles twisting in opposite directions, have shown that the twin nozzle arrangement (based on the Murata principle) produces the strongest yarn. Measurements made on the yarn structure indicated that this was due to a reduction in the proportion of the unwrapped portions. Also, the twin nozzle arrangement produces a yarn with the most and longest wrapping fibres.

Grosberg et al (1987) have observed that the construction of the second nozzle favours the production of a high speed vortex since it is designed to have a less sharp axial – orifice angle jetting air to the twisting chamber and the conical outlet of the jet utilises the exhausting air to twist the yarn further.

The rotational speed of the vortex in an air jet spinning nozzle is of the order of two million turns per minute (Krause 1985). The yarn rotated at a much slower speed during false twisting. This speed lies between 1,50,000 and 2,50,000rpm.

The air-flow in the twist insertion channel has been studied by Wang (1987). High speed cinematography revealed that the low is supersonic, turbulent and irregular.

The effects on the yarn properties of different design parameters of the second nozzle such as axial orifice angle, twisting chamber diameter and the surface friction of twisting chambers were investigated by Oxenham and
Basu (1999, 1993) and Chen (1998). These parameters have significant influence on yarn properties (Oxenham and Basu 1999). For cotton or polyester / cotton yarn, the yarn quality improves with the increase of axial orifice angle upto 50° and then it starts deteriorating. For polyester fibre, the optimum yarn properties are achieved at a jet orifice angle of 45°. The optimum angle was found to be dependent on the presence of short fibres in the mix. A lower friction coefficient of the twisting chamber improves the yarn strength.

2.15.17 First Nozzle to Front Roll Distance

Wang and Jordan (1984) have found that increases in the gap between the first nozzle and the nip of the front roller from 0.8 to 1.4 cm at increments of 0.1 cm have small favourable effect on polyester cotton – 65/35 blended yarn properties. However, this provides for only marginal improvement. The improvement in stiffness is accompanied by a small reduction in yarn strength and a small increase in hairiness.

For polyester / viscose MJS yarns, smaller distance between first nozzle and the front roller of the drafting system reduces yarn imperfections and elastic recovery (particularly thick places and reps). The increase in elastic recovery (Tyagi et al 1996) with increase in N1 – front roll distance is possibly due to the frictional hold on the fibres caused by increase in the number of wrapper fibres.

The distance between the two nozzles is also important though on commercial machine, this parameter cannot be changed. The studies on experimental unit using acrylic fibres show that as the inter nozzle distance increases, the yarn tenacity and breaking elongation improves (Lawrence and Baqui 1991).
2.15.18 Feed Ratio

The tenacity of acrylic air jet yarn increases marginally with but then passes through a maximum value. The elongation at break follows a similar trend (Lawrence and Baqui 1991). The yarn uniformity is improved with increased feed ratio. Optimum level was found to be 0.98 (ratio of surface speed of delivery roller and surface speed front roller). With the increase in feed ratio, the frequency and the average length of loosely wrapped portions and unwrapped portions come down whereas the frequency and average length of tightly wrapped portions show an increase.

The increment of feed ratio progressively increases the polyester/cotton yarn stiffness and measured twist. The strength curve goes through a maximum at a nominal feed ratio of 0.98. The higher the value of feed ratio, the higher the yarn tension during twisting and greater the representation of false twist effect.

For acrylic air jet spun yarn, with increase in feed ratio from 0.96 to 0.98, yarn tenacity, breaking elongation and flexural rigidity show an increase. Yarn hairiness also tends to increase to a small extent. There is no significant effect on yarn evenness and imperfections.

For viscose MJS yarns, there is a consistent improvement in yarn unevenness and imperfections with increase in feed ratio. This improvement is expected to be due to the increased wrapped-in portion and uniformity of structure brought about by the improved fibre orientation. There is a considerable increase in the elastic recovery of yarn when the feed ratio increased from 0.96 to 0.98 while spinning polyester/viscose yarns. This apparent increase is ascribed to the improved propagation of strain arising from improved alignment of fibres in the yarn.
2.15.19 Condenser Width

For air jet spun yarn, the yarn strength is attained mainly by the resultant normal force of the fibres wrapped around the parallel core fibres which give rise to the frictional forces necessary in the yarn assemblage to effect the transfer of tensile strength. These wrappings are caused by fibre standing out from the main body of the yarn whilst false twisting the fibre assemblage and they wrap around the yarn during untwisting. As the band width increases, more fibres go out of control of the false twist and they form more wrappers. But after a certain limit, the fibres get out of control completely and some of them are blown away by the air turbulence caused by high speed of the front drafting roller and the majority of the fibres become wrappers, leaving a few as core fibres. The optimum setting was observed between 10-12 mm for cotton yarns.

At a condenser width of 10mm, the strongest polyester yarn could be produced with maximum number of wrappers.

The effect of condenser width on yarn properties for polyester/viscose MJS yarns has been investigated by Punj et al (1998). They showed that the condenser width had a significant influence on yarn imperfections and hairiness. A narrower condenser width offers better guide to the silver approaching to injector nozzle and therefore helps to produce yarns with lower imperfections and hairiness.

Tyagi et al (1997, 2000) have observed that wider condenser increases the tenacity of air jet spun acrylic/cotton yarn along with some increase of unevenness and abrasion resistance. As a natural consequence, the flexural rigidity increase due to higher number of wrappers. In their experiments, they might not have reached the maximum limit as observed by others.
In contrast to others, Kampl and Leitner (1989) have reported that for modal viscose fibres, only minor improvement of the yarn tensile properties can be achieved by using a narrower condenser.

### 2.15.20 Heat Treatment of Air Jet Yarns

Tyagi et al (1998) were concerned with the heat treatment of polyester/viscose ring and MJS yarns under relaxed conditions (160°C for 5 minutes). It was found that following this treatment, there was a decrease in flexural rigidity. The decrease was higher for yarns either having higher linear density on relatively higher polyester content or produced at lower speed.

Although heat treatment has led to a decline in flexural rigidity of both ring spun and air jet spun yarns, the decrease in flexural rigidity is relatively higher for air jet spun yarn. The heat treatment has led to a drop in tenacity to the extent of 6-10%. The loss is at lower side when the air jet spun yarns are produced at higher speeds. In the case of 29.5 tex yarn air jet spun from 85/15 polyester viscose blend, the increase in diameter of about 26% due to heat treatment was only 16.5% when the polyester content was 35%. The corresponding increases in diameter for ring spun yarn are 22% and 18% respectively. In the production speed range 180-200 mpm, the increase in diameter on heating steadily decreases with increase in speed. On heat treatment, a slight increase in unevenness is noticed in all the cases.

Air jet spun yarns of 26.8 tex and 9.08 tex and ring spun yarns of 24.3 tex and 9.8 tex were produced from polyester fibres and they were annealed (by dry heat) at a constant temperature of 160°C for 5 minutes in a hot chamber under relaxed and tensioned (0.9 gram/tex) conditions. Slack annealing reduces tenacity and increases breaking extension of both types of yarns and increases the tenacity of air jet yarns. While slack annealing
reduces modulus with concomitant decrease in flexural rigidity, tension annealing reverses the trend and there is an appreciable rise in the modulus of air jet yarns following tension annealing. Abrasion resistance of both types of yarns increases after slack annealing which is attributed to the increase in compressibility of the yarns because of the opening up of the structure and extensibility of the yarns which in turn reduces the intensity of abrading action. Tension annealing on the contrary reduces the abrasion resistance for air jet yarns; this is mainly due to the enhancement of structural integrity which restricts the possibility of fibre slippage during load cycling, resulting in lesser decay.

2.15.21 Turbulent Air Flow in the Air Jet Nozzle

The air flow in the air jet nozzle is turbulent and unsteady. When the Reynolds number of a flow exceeds a defined critical value, the laminar flow passes through a transition (which is a combination of several complicated steps) and changes into turbulent flow. Turbulent flow can be roughly described as disorderly, randomly unsteady, rotational, and three dimensional. It is characterized by high levels of fluctuating vorticity. Turbulent flows are always dissipative. Turbulence needs a continuous supply of energy to make up for viscous losses. If no energy is supplied, it decays rapidly. Turbulence is a property of the flow, not the fluid.

In a turbulent flow, any variable can be resolved into a mean plus a fluctuating value [Reynolds decomposition], thus, for example, the longitudinal velocity component $u$ in a flow can be divided up

$$u = \bar{u} \pm u' \quad (2.9)$$

in which
\[ \bar{u} = \frac{1}{t_f - t_i} \int_{t_0}^{t_f + t_i} u dt \]  

(2.10)

where an over bar denotes a time mean value and prime denotes a fluctuation or deviation from the mean. The integration interval \( t_i \) is selected to be larger than the period of fluctuation \( u' \). By definition, \( u' = 0 \), i.e., it is a deviation from the mean. Its magnitude is given by

\[ \bar{u}^2 = \frac{1}{t_f - t_i} \int_{t_0}^{t_f + t_i} u'^2 dt \]  

(2.11)

The fluctuation can be as high as 10% of the free stream speed. The longitudinal fluctuation \( u' \) is the longest. The mean value itself may vary with time and this is called unsteady, turbulent flow which is the sort of flow in air jets.

Since turbulence has been impossible to analyse exactly, turbulent flow analysing is usually semi-empirical in nature.

There are two ways to measures a quantity in turbulent flow; the first is by averaging the random fluctuating velocity component over a long period of time and obtaining a time average quantity which is given by equation.

\[ \bar{u} = \frac{1}{t_f - t_i} \int_{t_0}^{t_f + t_i} u dt \]  

(2.11a)

The second is setting up N identical experiments and taking all N measurements at the same time, then averaging these to get
\[ < u(t) > = \frac{1}{N} \sum_{n=1}^{N} u_n(t) \]  

where for many measurements, a definite quantity called “ensemble average” is obtained. If \(< u(t) >\) is independent of time, the time average equals the ensemble average and the process is said to be stationary. At a certain point and range of Reynolds numbers around the critical number, the flow in air jet can be turbulent or laminar alternatively. The percentage of time that the flow is turbulent is characterised by the “intermittency factor \(I\)”. Thus, for continuous turbulent flow \(I = 1\), and for continuous laminar flow \(I = 0\).

The dimensionless Mach number \((M)\) of a flow is defined as \(M = \frac{u}{c}\), where \(u\) is the flow velocity and \(c\) is the velocity of sound in the fluid. \(M = 1\) represents a sonic flow. For subsonic flows \(M < 1\) and for supersonic flows \(M > 1\). Under small Mach number conditions, changes in fluid density are negligible. Therefore, density is considered constant, and such a flow is called an incompressible flow. When the Mach number is between 0.3 to 1, the flow becomes a compressible subsonic flow. A compressible turbulent flow is complicated by the addition of density as a variable and density fluctuations. For air, with the velocity of sound of about \(C = 1100 \text{ ft/sec} [335 \text{ m/s}]\), a flow velocity of 330 ft/sec [100 m/s] is considered the outside limit for assuming incompressibility.

Therefore, for air velocities higher than 100m/s, compressibility should be taken into account.

Rwei et al (2001) have conducted studies on fluid simulation of the air flow in interlacing nozzle.

A considerable amount of work on air flow in the nozzles has been made by Wray and Entwistle (1968), Sivakumar (1975), Bock and
Lunenschloss (1981), Acar et al (1986) and Demir (1987). Wray and Entwistle (1968) have reported on the extension of turbulent-flow theory to the bulking jet. They have made a significant observation that it is the rotational nature of the turbulent air stream which is responsible for giving rise to a false twisting action such as would untwist the yarn temporarily during its passage through the jet and thereby cause an opening of the multifilament of the overfeed to take effect. It has been found that the filaments are first convoluted into U-shaped waves which in turn snarl into looped coils owing to the twist liveliness of the slackened filaments.

Mathematical models for texturing nozzles both converging – diverging and cylindrical have been developed by research workers.

2.16 STRUCTURAL STUDIES OF AIR JET YARNS

Basu and Oxenham (1992) have reported that in the case of 100% polyester, polyester/cotton blended yarn and 100% cotton yarn, the relative frequency of class 1 structure is around 50%. The frequency of other classes was not very much different for different materials. The average length of wrapped structure was found different for yarns made of different materials which the highest core twist and polyester yarn the lowest. The explanation advanced by these authors is that due to higher efficiency of twist transference (i.e., conversion of twist into wrapper fibres) in the case of polyester, the residual twist was minimum in polyester yarns.

Kato (1986) observed that the structure of air jet spun yarn was not uniform but includes ‘smooth parts’ with balanced tension between the core fibres bundle and wrapping fibres. “Kinky” parts and wrapping parts with fibres wound irregularly around the bundle. Also, there are some yarn sections which fall between these three divisions.
Chasmawala (1987) felt that the yarn structure was essentially that of a comparatively straight central core of fibres held together by taut surface fibres wound onto the central core helically. The straight fibres are termed as “core fibres” while the taut helically wound fibres are called “wrapper fibres”. Another class of fibres which follow random, intermittent paths are termed as “wild fibres”. Two additional categories “core wild” and wrapped were added to these three easily distinguishable type to cover the entire range of fibre configuration. The proportions of different classes vary with the change in process parameters. The microscopic observation made by them revealed that a prominent feature of polyester air jet spun yarns is the predominance of leading hooks. According to them, these hooks could have originated in the carding process or due to either air currents into the nozzles. A protruding leading end is likely to be bent back and get caught in the fibres behind it to form a leading hook; a protruding trailing hook can be to be straightened out at the point of entry into the nozzle. Further analysis showed that hooks might have predominantly formed at the nozzle.

Punj et al (1997) observed that while using polyester viscose blended yarn that there is a majority of trailing hooks, as compared to leading and both sides hooks. Viscose fibre has more hooking tendency as well as more hook extent than polyester fibre. They have classified the yarn structure as belts, short wrappers, long wrappers migrated core fibres and core fibres. The percentage of belts and short wrappers is very low and there is no significant difference between the percentage of belts made of polyester and viscose fibres. The percentage of tight short wrappers made by viscose fibres is more than that of polyester fibres and in the case of tight long wrappers the trend is vice versa. The percentage of tight long wrappers is significantly higher than those of loose long wrappers in both the fibres.
Uematsu (1986) and Nakahara (1988) also classified the yarn structures into different categories. According to the former, the yarn structure can be controlled by optimizing various process parameters. According to Lord (1984), yarn core has very little twist and the wrapper fibres apply lateral forces to the yarn which give it coherence. The wrapper fibres are under tension in the spun yarn and this not only causes a substantial coherence between the core fibres but also causes the core to contract as it takes up the shape of a small radius helix.

Ishtiaque and Khare (1993) reported a study on the internal structures of ring, rotor and air jet spun polyester/cotton -50/50 blended yarns. The centre of gravity of the cross-section was calculated with the help of an image analyzer. Taking that as the centre, they divided the area of cross section into class intervals of five equal width zones. The fibre packing density is not uniform across the yarn cross-section. It is observed that the radial packing density is maximum irrespective of the spinning system. Of all the three yarns, rotor spun yarn in the first zone (from centre) of the yarn cross-section, at other end, air jet spun yarn shows the least packing density followed by rotor and ring spun yarns in the fifth zone of the yarn cross-section. For air jet spun yarns, fibres are mostly packed in the first three zones, the last two zones giving lower packing density in comparison with the other two. Total packing density, calculated as the ratio of total area of fibres in yarn cross section to the yarn cross section is maximum for air jet spun yarn followed by ring and rotor yarns. The rotor yarn has the lowest migration index followed by ring and air jet spun yarns.

Punj et al (1997) have noticed that the extent of short wrappers, long wrappers and migrated core fibres is more in viscose fibre as compared to that of polyester fibre. Viscose core fibres show less fibre extent than polyester fibres due to more hooks in the case of viscose. The average fibre extent of
viscose is more hooking tendency. The fibre extent varies with change in process parameters such as second nozzle pressure and spinning speed, Punj and his colleagues have also studied the effect of process variables on the internal structure of polyester/viscose 42/58 blended yarn of 14.76 tex. Packing density first increases when the first nozzle pressure is further increased to 2.5 kg/cm² and then decreases when the pressure is further increased. Packing density increases with the increase in second nozzle pressure. Spinning speed above 190 mpm decreases the packing density of fibers in yarn cross-section.

In an investigation on the structure of polyester and cotton wrappers in a polyester/cotton air jet yarn, Bhortakke et al (1999) have found that polyester fibers contribute more to the total number of wrappers; Cotton seems to have better wrapper forming tendencies when the number of polyester and cotton wrappers are expressed in percent of the respective number of fibers in the yarn cross section. Cotton forms more loose wrappers than polyester. The wrapping angle for cotton is also greater.

2.17 YARN STRUCTURE ANALYSIS

To study the yarn structure two different experimental techniques have been developed by research workers such as Morton and Yen (1952).

2.17.1 Tracer Fibre Technique

This technique involves immersing a yarn which contains a very small percentage of dyed fibres in a liquid whose refractive index is the same as that of the original undyed fibres. This causes the undyed fibres to almost disappear from view and enables the observation of the path of a black dyed traced fibre under a microscope. Dyed fibres are added to the raw stock before
spinning to act as tracers. This technique was introduced by Morton and Yen (1952).

2.17.2 Fibre Migration

Fibre migration can be defined as the position occupied by a fibre in a yarn which is traced out point by point along its length. It will be seen that it traverses back and forth across imaginary cylindrical zones of the yarn body being in part at or near the core and in part at or near the surface. Chasmawala, Hansen and Jayaraman (1990) used tracer fibres to determine the effects of yarn structure and properties of front zone and back zone draft ratios and compressed air pressures applied to the first of the two jets on a Murata air jet spinning system. Increases in these variables increased the wrapping fibre frequency and improved the yarn tensile properties, but increased the yarn regularity. Fibre migration ensures that some parts of all fibres were blocked in the structure.

Peirce (1947) recognized that there is a need for the interchange of the fibre position inside a yarn since if a yarn consisted of a core fibre surrounded by the coaxial cylindrical layers of other fibres, each performing a perfect helix of constant radius, discrete layers of the yarn could be easily separate.

2.17.3 Mechanism Causing Fibre Migration

Morton (1956) proposed that one of the mechanisms which causes fibre migration is the tension difference between fibres at a different radial positions in a twisted yarn. During the twist insertion, fibres are subjected to different tensions depending on their radial positions. Fibres at the core will be under minimum tension due to shorter fibre path while the fibres on the surface will be exposed to the maximum tension. According to the principle
of minimum energy of deformation, fibres lying near the yarn surface will try to migrate into inner zones where the energy is lower. This is the so called tension mechanism. Later Hearle and Bose (1965) came out with another mechanism which caused migration. They suggested that when the ribbon-like fibre bundle is turned into the yarn the fibres of one side of the bundle will go to the centre of a yarn while those on the other side will appear on the yarn surface. From this geometric mechanism, they determined the length of the migration period.

Hearle et al (1965) suggested a combined mechanism to explain fibre migration. This is based on the premise that the fibre migration due to tension differences and the geometrical mechanism are not mutually exclusive. In fact, fibre migration results from the combination of these two mechanisms. While the former mechanism gives rapid migration, the latter one depending on the initial twist causes a slower migration. The rapid migration is laid over on the slower migration and it is predominant.

Factors affecting fibre migration include fibre type, fibre length, fibre fineness, fibre initial modulus, fibre bending and torsion rigidities, fibre surface properties, yarn related factors such as yarn twist and processing factor such as twisting tension, drafting system and number of doubling.

2.17.4 Methods for Assessing Fibre Migration

The tracer fibre technique was used to study the migration behaviour. A small proportion of tracer fibre added to the fibres stock and the path of the single tracer fibre under a microscope. With a view to drawing the paths of the tracer fibres in the horizontal plane, Morton and Yen (1952) made measurement at successive peak and troughs of the tracer images. Each peak and trough was in turn brought to register with the hairline of a micrometer eye piece and scale reading were taken a, b and c as seen in the Figure 2.7.
Figure 2.7 Measured parameters on path of a tracer fibre

The yarn diameter in scale unit was given by

\[ r_i = b_i - \frac{a_i + c_i}{2} \]  \hspace{1cm} (2.13)

The distance between the adjacent peaks and trough was denoted by \( d \). The overall extent of the tracer fibre was obtained from the images. Morton and Yen concluded that in one complete cycle of migration the fibre rarely crosses through all zones of the structure, from the surface of the yarn to the core and back again, which was considered as ideal migration.

Morton characterized migration by means of a coefficient which is called “the coefficient of migration”. He proposed that the intensity of migration, i.e., completeness of the migration, or otherwise, of any migratory traverse could be evaluated by the change in helix radius between successive inflections of the helix, envelope expressed as a fraction of yarn radius. For example, intensity of migration in Figure 2.8 from A to B was stated as

\[ \frac{r_A - r_B}{R} = \frac{1}{R} \]  \hspace{1cm} (2.14)

where \( r_A \) and \( r_B \) are helix radius at A and B respectively and \( R \) is yarn radius. In order to express the intensity of migration for a whole fibre, Morton used the coefficient of migration was given by
\[ C = \frac{\Sigma i s}{R L} \]  

(2.15)

where \( i \) is the radical distance that the fibres traverse in each migration.

\( s \) is the yarn length between two traversing points.

\( R \) is the yarn radius.

\( L \) is the yarn length.

The coefficient of migration \( C \), was equal to 1 if the migration is perfectly complete throughout the length of the tracer fibre while \( C \) was zero if no migration takes place. Figure 2.8 shows the actual path of fibre migration.

![Helix Envelope Profile](image)

**Figure 2.8  Actual path of fibre migration**

Due to irregularities in yarn diameter, Merchant (1962) modified the helix envelope by expressing the radial position in terms of \((r/R)\) in order to avoid any effects. The plot of \((r/R)\) along the yarn axis gives a cylindrical envelope of varying radius around which fibre follows a helical path. This plot is called a helix envelope profile. Expression of the radial position in terms of \((r/R)\) involves the division of yarn cross section into zones of equal radial spacing which means fibres present longer lengths in the outer zones. Hearle et al (1965) suggested that it is more convenient to divide the cross
sections into zones of equal area so that the fibres are equally distributed between all zones. This was achieved by expressing the radial position in terms of \( \left( \frac{r}{R} \right)^2 \) and the plot of \( \left( \frac{r}{R} \right)^2 \) against the length along the yarn is called a correlated helix envelope profile which presents a linear envelope for the ideal migration if the fibre packing density is uniform (Figure 2.9). The corrected helix envelope profile is much easier to manage analytically.

![Corrected helix envelope profile](image)

**Figure 2.9** Corrected helix envelope profile of an ideal pattern of migration (Z is length along the yarn)

Riding (1964) made some changes in the expression relating to \( r/R \) as a result of making some ingenious experimental changes. He put a mirror near the yarn in the liquid with the plane of the mirror at 45° to the direction of observation to observe the fibre from two different directions at right angles. The radial position of the tracer fibre along the yarn was calculated by the following equation:

\[
\frac{r}{R} = 2 \left[ \left( \frac{x}{dx} \right)^2 + \left( \frac{y}{dy} \right)^2 \right]^1_2
\]

(2.16)
where \( x \) and \( y \) are coordinates (referred to the yarn axis, which is taken as the point midway between the edges of yarn); and \( dx \) and \( dy \) are the corresponding diameter measurements. The yarn is viewed from two directions at right angles simultaneously.

Riding (1964) also made some changes in the manner of studying migration in that he used correlogram analysis. Hearle and Goswami (1968) had some reservations about his technique of studying migration, namely, correlogram analysis.

2.18 SUMMARY

From the foregoing it is clear that a considerable amount of work related to air jet spun yarns has been done. What appears to be less emphasized in the literature is the study of the structures and properties of yarns spun on rotor frames with the air jet nozzle and this thesis addresses these aspects.