CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter deals with the literature of air-jet spinning and the ring spinning frame incorporating the air-jet nozzle. Earlier work on the yarn characteristics produced has been reviewed.

2.2 AIR-JET SPINNING

A description of the air-jet spinning process is found in the patents filed by the inventors of the process, Nakahara\textsuperscript{[113]}. In the air-jet spinning process, Fig. 2.1, 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, \( N_1 \) and \( N_2 \) respectively. Air is introduced at high pressures through fluid jets \( J_1 \) and \( J_2 \) drilled in the nozzles to produce swirling air currents in mutually opposite directions \( A \) and \( B \), as shown in Fig. 2.2.

Referring to Fig. 2.3, the drafted strand is vibrated violently by an unstable secondary balloon \( B_2 \), formed between the front roller with \( Q \) and the inlet 5 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 the nozzle \( N_1 \), come under the influence of the swirling air currents, and are wound positively in the \( Z \) direction around the undetached fibres \( S_1 \).
Fig. 2.1 Air jet spinning system
Fig. 2.2 Action of the Nozzles on the fibre strand

Fig. 2.3 Formation of detached fibres
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 \( N_2 \). 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 \( N_2 \). 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 Z twisted fibres to give cohesion and strength to the yarn.

Fluid vortices have been used before by Lord et al\(^{(101)}\). These served the dual purpose of assembling and consolidating (by twisting) the fibres. But, as explained before, in the air-jet spinning process, the fluid nozzles are used only for the purpose of consolidation.

Recently, Murata has come out 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.

### 2.3 TWIN SPINNER

In ATME, Murata exhibited a Twin Spinner (MTS-881) which uses the concepts of jet spinning (twin-jet) and the yarns from two spinning positions are wound together on one package (isaacs)\(^{(75)}\). Following formation in the air-nozzles, the yarns pass through yarn clearer, waxing device and are then taken up (two parallel ends) on the finished package. These packages are fed directly to two-for-one twisting for twisting.

One of the salient features in Murata Twin Spinner is that the width of the cots and the active part of the bottom rollers are increased to accommodate the drafting of two slivers, simultaneously without touching each other. Sliver guides are provided 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 that the productivity of two spinners is 17 to 37 times higher than that of ring spinners depending on yarn count (Gobbel)\(^{(54)}\). 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 knottersplicer is used for joining. Recently Nergis and Ozipek\(^{(116)}\) have reported on the properties of two ply air jet spun yarns produced on the PLY-fil 1000 system.

### 2.4 ROLLER JET SPINNER

M/s. Murata Machinery Limited, Japan, during ITMA 95 at Milan, Italy have exhibited their Roller Jet Spinner (RJS-804)\(^{(6)}\). In conventional MJS machines, two air-jets are used for yarn formation. In the new model, the first air-jet is replaced by a crossed rubber roller unit for producing false twist. It is claimed that this helps noise reduction and energy conservation. At the ITMA'95 Fair, the RJS machine was shown running with 100 percent polyester at a speed of 400 mpm to spin 12\textsuperscript{s} Ne yarn. Roller jet spinner produces weaving yarns of very low hairiness. Automated piecing can be accommodated in the place of knotting. In that case, the yarn end from the yarn package is placed on the raised front roller and being pieced up at full speed.

### 2.5 VORTEX SPINNER 85%

Murata Vortex Spinner (MVS-851) by M/s. Murata Machinery Limited, Japan was exhibited at ITMA 99, Paris. The system uses four line drafting with vortex system to impart the twist (Ishtiaque)\(^{(78)}\). The feed material is 100\% cotton sliver. The drafting system is claimed to be capable enough to give draft range from 50 to 230 for count range of 10\textsuperscript{o} to 50\textsuperscript{o} 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. Although some other firms like Toyoto Automatic Looms Works Limited, Japan, Howa of Japan, Schuber and Salzer Maschinen fabrik, AG, Germany, NPK Tekstino Mashinostroene, Bulgaria, Maschinen fabrik Rieter AG, Germany and Toyota Chuo Kinkyusho, Japan have attempted in developing air-jet spinning systems, they are yet to become commercially successful.

2.6 JET-RING SPINNING SYSTEM

Attempts have been made to combine the mechanism of air-jet spinning with that of ring spinning; this system consists of a single air-jet below the yarn-forming zone of a conventional ring spinning system by Wang, Miao and How (196). 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 (0.5 bar) 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 yarn.

Sawhney et al (153) 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. Those yarns could be used for knitting and weaving without stripping. Mahmoudi and Oxenham (104) have used an air-jet nozzle to improve the bulkiness of worsted yarns. Sawhney and Kimmel (154) 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 ring spinning productivity.

It was Kalyanaraman (81) 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 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.

Wang and Miao have used an air-jet nozzle on a winding machine to control the hairiness of wound ring and rotor spun yarns. It is claimed that there is some reduction in the increase of hairiness during the winding process by using the air-jet nozzle. Chellamani, Chattopadhyay and Kumarasamy have reported that by using an air-jet nozzle in core winding machine, the hairs in ring yarn show a decrease by 50-75%.

It may be stated that the mechanism of air-jet application in winding machine is similar to that N, 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 some of gyrating air-jet, the yarn is detwisted for a short while and then retwisted the following action may logically be expected to occur:

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

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

Table 2.1 shows the details of the research carried out on ring and winding machines by many research workers using air-jet nozzle.
<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Author(s)</th>
<th>Details of year nozzle used and machine</th>
<th>Materials/ Details of count, speed</th>
<th>Conclusions</th>
</tr>
</thead>
</table>
| 1.     | Kalyanaraman(82) | 1992 unspecified ring frame | Cotton yarns, produced 20s, 30s, 40s, 60s and 80s | 1. Hairiness was less in yarns  
2. Hairiness is minimal for a nominal value of pressure rise and hairiness increases at low and high pressures |
| 2.     | Wang, Miao and How(190) | 1997 Unspecified ring frame S type nozzle | 56 Tex Woollen yarn | Hairiness reduces by 40% |
| 3.     | Wang and Miao(191) | 1997 Unspecified Winding S type nozzle | Rotor spun yarn of 18.5 tex combed 7 experiments performed. Also ring spun yarn was used. | Experiments (3) and (7) have led to highest reduction (cone winding) |
| 4.     | Sawhney and Kimmel(154) | 1997 Unspecified Ring Frame Z type nozzle | 29.5, 39.5 and 59 tex cotton and 39 tex 67/33 cotton, polyester | Higher productivity to the extent of 50% is possible. |
| 5.     | Chellamani Chattopadhyay and Kumarasamy(27) | 2000 Details of air jet nozzle are provided. Air pressure 0.5, 1.0 and 1.5 kg/cm², jet winding orifice angle 30, 45 and 60° | 20° and 40° carded cotton 40°, 80° and 100° from 100% cotton. | Hairs show a reduction of 50-75% (used in cone winding) |
| 6.     | Jeon Boong(80) | 2000 Some details such as sub hole dia of nozzle, nozzle length slant angle, nozzle shape are provided suction nozzle has been used in ring spinning. | 30°, 14,000 | Number of hairs longer than or equal to 3 mm decreases by more than 50% strength elongation and appearance show an improvement. |
2.7 STRUCTURE OF AIR-JET SPUN YARNS

The structure of air-jet yarn has been derived by Grosberg et al\(^{(55)}\) into four classes and by Chasmawala et al\(^{(31)}\) and Lawrence and Baqui\(^{(94)}\) into three classes.

Oxenham\(^{(121)}\) opines that the air-jet spun yarn is a fasciated type of yarn consisting of two parts; a core of parallel fibres held together by wrapper fibres. Lawrence and Baqui\(^{(94)}\) have reported that the acrylic air-jet spun yarn consisted of an untwisted core of fibres and a surface layer of fibres wrapped around the greater part of the core. According to them, the yarn can be classified into three types of structure Class I structure consists of a twistless core, which at times crimped but wrapped uniformly by a thin fine ribbon with an uniform helix angle and direction. Class II consists of a twistless 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, Cheng and Wong\(^{(71)}\) 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 fibres and outside wrapping fibres. In the bundle fibres, a majority of the 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 "Corkscrew-like" wrapping, irregular wrapping, kinked wrapping, even wrapping featuring the edge free end fibres wrapped evenly on the bundles, loose wrapping and non wrapped portions.

Miao\(^{(105)}\) and Basu\(^{(15)}\) have used the following classification 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 crimpiness 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 a geometry similar to a ring spun 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, this wrapping fibres are less tight.

Class 4: This type of structure has a straight yarn core with wrappers of irregular twist.

Basu and Oxenham\textsuperscript{(18)} 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 may be due to differences in fibre type and fibre length. The cotton yarn had the highest core twist and polyester yarns the lowest. The explanation advanced by these authors is that due to higher efficiency of twist transferency (i.e., conversion of twist into wrapper fibres) in the case of polyester, the residual twist was minimum in polyester yarns.

Kato\textsuperscript{(85)} observed that the structure of air-jet spun yarn was not uniform but includes 'smooth parts' with balanced tension between the core fibre 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\textsuperscript{(30)} 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 "wrapper wild" were added to these three easily distinguishable types to cover the entire range of fibre configurations. The proportions of different classes vary with the change in process parameters. The microscopic observations 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 or the frictional resistance encountered by fibres at the point of entry 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 expected to be straightened out at the point of entry into the nozzle. Further analysis showed that hooks might have predominantly formed at the first nozzle.

Punj, Ishtiaque and Dhingra\textsuperscript{131} 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\textsuperscript{182} and Nakahara\textsuperscript{114} also classified the yarn structures into different categories. According to the former, the yarn structure can be controlled by optimising various process parameters. According to Lord\textsuperscript{101}, 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\textsuperscript{(76)} 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 yarn cross-section was calculated with the help of an image analyser. 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 yarns give maximum packing density, followed by ring and air-jet 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 yarn, 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 and Debnath\textsuperscript{(132)} have reported that the packing density is maximum at core for the polyester/viscose - 42/58 blended MJS yarn. Wrappers are most loosely packed.

Punj, Ishtiaque and Dhingra\textsuperscript{(131)} 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 in polyester/viscose blended yarns despite viscose fibre having more hooking tendency. The fibre extent varies with change in process parameters such as second nozzle pressure.

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 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 fibres in yarn cross-section.

In an investigation on the structure of polyester and cotton wrappers in a polyester/cotton air-jet yarn, Bhortakke, Nishumura and Matsuo(24) have found that polyester fibres 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 fibres in the yarn cross section. Cotton forms more loose wrappers than polyester. The wrapping angle for cotton is also greater.

2.8 GENERAL QUALITY ATTRIBUTES OF AIR-JET YARNS.

2.8.1 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(165)). Similar observations were reported by Kato(85), Nierhaus(117) and Lunenschloss, Brockmann and Phoa(103). It is observed by Sreenivasamurthy, Chattopadhyay, Parthasarathy and Srinathan(164) 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 blended yarns, it is about 7-19% lower and the difference widens with decrease in yarn fineness. The work of rupture for air-jet yarns is lower by 55-64% compared to ring spun yarns of cotton and by 34-60% for polyester blended material. Contrary to many researcher’s observation, the tensile properties of polyester/cotton (65/35) air-jet spun yarns is not inferior as compared to ring spun yarn but loop strength is little lower owing to difference in single yarn structure (Murata)(111). Kaushik, Salhotra and Tyagi(86) have found that polyester/viscose blended air-jet spun
yarn is 14-18% weaker than that of ring spun yarn. 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, Kaushik and Salhotra)\textsuperscript{(176)}.

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, 
Mukhopadhyay and (Chakraborty)\textsuperscript{(133)}. 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 than 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, 
Mukhopadhyay and Maiti)\textsuperscript{(130)}.

2.8.2 Evenness and imperfections

Air-jet spun yarn is more even than equivalent ring spun yarn 
(Deussen\textsuperscript{(46)}, Kaushik, Salhotra and Tyagi\textsuperscript{(86)}, Lunenschloss, Brockmanns and 
Phoa\textsuperscript{(103)}, Nierhaus\textsuperscript{(117)}, Punj, Mukhopadhyay and Maiti\textsuperscript{(130)} and Stalder\textsuperscript{(166)}). 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, Chattoadhyay, Parthasarathy and
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 fibres in the cross section. Yarn imperfections, in terms of thin places, thick places and reps are lower for air-jet yarn as compared to 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).

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 yarns is better than the upper quartile values i.e., the results obtained by the best 25% of all spinning mills in the world for ring spun yarns. Artzt and Conzelmann have reported the advantages of air-jet yarns in that in thin places, they 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).

After doubling, the unevenness and imperfections of air-jet yarns decrease 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, Mukhopadhyay and Maiti).

The number of yarn defects (slubs) of air-jet yarn is far less as compared to that of ring spun yarn (Basu and Oxenham). In the case of ring spun carded cotton (polyester/cotton - 40/60), there are large quantity of trash and nep 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 stated that it might be insensitive to changes in folding twist. On the other hand, the strength of cotton air-jet spun yarns increases significant by with increased doubling twist, but these yarns are
substantially weaker than equivalent ring spun yarns. Punj et al.\(^{(129)}\) 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 concluded 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\(^{(33)}\) investigated the influence of ply twist and its direction on the properties of air-jet spun yarns. He concluded that an optimum level of ply twist in the opposite direction of the wrapping fibres increases the strength and reduces the hard feel of air-jet spun yarn.

2.8.3 Bending rigidity of air-jet spun yarns

Air-jet spun yarns have higher bending stiffness when compared with ring spun yarns (Basu)\(^{(19)}\), Kaushik, Salhotra and Tyagi\(^{(186)}\), Punj, Mukhopadhyay and Saha\(^{(129)}\), Vohs, Barker and Mohamed\(^{(186)}\), and are found to be less compressible than that of ring spun yarns.

Flexural rigidity of air-jet, spun acrylic/cotton blended yarn is 15-20% higher than that of rotor spun yarn (Tyagi, Kaushik and Salhotra)\(^{(179)}\). 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)\(^{(188)}\). 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, Mukhopadhyay and Maiti)\(^{(130)}\). If ring yarn diameter is taken as 100% the diameter of air-jet spun yarn of same linear density is 75-100%. Recently, Mukhopadhyay, Sharma and Saha\(^{(110)}\) have discussed the low stress behaviour of air-jet yarns by using Box-Behnken design of
experiments. They have 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.

2.8.4 Abrasion resistance

Nikolic, Cerkvenik and Stijepanovic(118) have reported that the abrasion resistance of air-jet spun yarn is higher than that of ring spun yarn. In acrylic/cotton blended yarn (70/30), air-jet yarn exhibited lower abrasion resistance than those of rotor spun yarns (Tyagi, Kaushik and Salhotra)(179). 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, Mukhopadhyay and Maiti)(130).

2.8.5 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 (101), Vohs Barker and Mohamed(186), Wang and Jordan)(188).
In general, the range in values of hairiness are 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\(^{177}\) 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, Mukhopadhyay and Maiti\(^{130}\) have observed that the hairiness of air-jet yarns decreases after doubling process by 62-89%.

2.8.6 Frictional properties

Kalyanaraman\(^{81}\), who undertook studies on the static and dynamic frictional behaviour of cotton and acrylic air-jet spun yarns, found that air-jet yarn was characterised by higher coefficient of friction compared to ring spun yarn. Acrylic yarns show 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)\(^{112}\).

2.8.7 Structure - Properties relationship

Yarn properties are affected by their structure Chasmawalla\(^{30}\), Chasmawala, Hansen and Jayaraman\(^{31}\) derived the following regression equations for polyester yarns.

- Breaking load (g) = 515 - 3.12 x \# core
- Evenness (CV%) = 15.6 + 0.191 \# Wr - 0.230 \# Wr - W,
- Hairiness = 4561 - 42.8 \# Wr - Wi - 92.4 \# W, - 35.1 \# core.
where

\[
\begin{align*}
\# \text{Core} & \quad - \quad \text{number of core fibres} \\
\# W_r & \quad - \quad \text{number of wrapper fibres} \\
\# W_r - W_i & \quad - \quad \text{number of wrapper wild fibres and} \\
\# W_i & \quad - \quad \text{number of wild fibres}.
\end{align*}
\]

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)\(^{(20)}\). How, Cheng and Wong\(^{(71)}\) have found that the type of wrapper fibres determines the strength of yarns produced. Grosberg, Oxenham and Miao\(^{(55)}\) reported that of the three jet arrangement (single jet, two jets in one direction and two jets in opposite directions), the two jets imparting twist in opposite directions produced the strongest yarn. Measurements made on the polyester structure indicate that this is due to a reduction in the proportion of unwrapped structure.

With changes in various process 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\(^{(94)}\) for acrylic yarns and How, Cheng and Wong\(^{(71)}\) for polyester cotton 65/35 blended yarns.

Krause and Soliman\(^{(62,63)}\) have shown that yarn strain is related to wrapper fibre strain by the equation

\[
e_y = (2 \sin^2 \alpha_o - 1) + [(2 \sin^2 \alpha_o - 1)^2 + e_w (2 + e_w)]^{1/2} \quad \ldots \ (2.1)
\]

where \(e_y\) is the yarn strain, \(e_w\) is the wrapper fibre strain and \(\alpha_o\) 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 fibres with the lowest wrapping angle break 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 $f$, and these stresses can be calculated from the above equation and the fibre modulus.

Rajamanickam\textsuperscript{(140)} attempted predicting the yarn strength from various parameters including the number of wrapper fibres, the wrapping angle of the different wrapper fibres 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 variations 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\textsuperscript{(94)} 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 (randomly 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 but did not correlate significantly with 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 ripeness. The registered neps were identified as the class II structures.

Basu\(^{15}\) has carried out a study on the structure - properties relationship using a microscope. The parameters studied were incidence of wrappers per unit length (\(X\)) 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 belts. Within each category, the major three parameters (1, AN and AL) were studied. These parameters are found to be well correlated with the yarn physical properties \((r = 0.41 \text{ to } 0.74)\). 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 \((r = 0.63 \text{ to } 0.91)\).

Punj, Debnath and Chowdhury\(^{136}\) 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’.

2.8.8 Influence of fibre 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 yarns.
2.8.9 Fibre length and fineness

Kato\textsuperscript{(85)} and Santjer\textsuperscript{(152)} have emphasised 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\textsuperscript{(152)}, the shorter the fibre, the lower the chance and this results in sharply increasing fibre loss. Longer fibre can be wound more number of times with same angle of twist and thus can securely hold the fibre bundle. At the same twist angle, shorter fibres 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\textsuperscript{(97)} observed that the use of 50\% fibres 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; 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 maximise 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 (Deussenn\textsuperscript{(46)}, Lord\textsuperscript{(101)}, Punj, Moitra and Behera\textsuperscript{(134)}, Puttachiyong\textsuperscript{(139)}). The effect of fibre length on evenness of air-jet spun yarn is far higher than for ring spun yarn (Sreenivasamurthy, Sreenivasamurthy, Chattopadhyay, Parthasarathy and Srinathan\textsuperscript{(164)}).

Krause and Soliman\textsuperscript{(92,93)} have shown by theoretical analysis of wrapping twist in single jet false twist spinning that this technique requires relatively long fibres of an even length distribution. Longer fibre length and minimal short fibre content contribute to improved quality in 100\% cotton air-jet spun yarns as reported by Kametches\textsuperscript{(83)}.
Artzt and Dallman\(^{(7)}\) 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\(^{(53)}\). An increase in short fibre has 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, Sanjter\(^{(152)}\) 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\(^{(96)}\) has pointed out that for polyester yarns, the fibre length does not influence unevenness of the yarns.

It is a well known fact that the number of fibres per cross section increases the tenacity of the yarns. Lord\(^{(101)}\) and Kaushik, Salhotra and Tyagi\(^{(87)}\) have observed a similar trend. The long coarse fibre tends to create more imperfections and machine stops than finer fibres (Lord\(^{(101)}\)). Air-jet spun viscose yarn produced from fine fibres has shown considerably lower flexural rigidity and higher elastic recovery. 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.

In contrast, it has been commented by Miao\(^{(105)}\), Puttachiyong\(^{(139)}\) and Basu and Oxenham\(^{(18)}\) that the ratio of wrapper to core fibre decreases when the fine fibres are used resulting in decrease in yarn strength. Gilbert\(^{(53)}\) 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\(^{(145)}\). For a given count, however, the number of fibres in a cross section decreases as the fibre denier increases. The resultant yarn strength is the function of two opposing factors - (a) the tendency of the increased number of fibres in the yarn 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\textsuperscript{(23,24)} 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\textsuperscript{(9)} opined that fibre fineness has no effect on yarn strength as long as sufficient number of fibres 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\textsuperscript{(9)}.

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\textsuperscript{(121)} 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\textsuperscript{(8)} have shown that the optimum length of polyester during air-jet spinning of polyester / cotton yarns lies in the region of 38 mm. Special lengths such as the 32 mm used for rotor spinning are found to be disadvantageous for false twist spinning. With increasing fibre count, there is a 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\textsuperscript{(112)} 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.
2.8.10 Fibre strength and elongation

The fibre strength and elongation have maximum influence on the tensile properties of air-jet spun yarn\(^{10,17}\). 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 0.85 - 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\(^{(176)}\) on the characteristics 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/tex offers no additional advantage in yarn strength due to reduced fibre elongation 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\(^ {152}\).

2.8.11 Frictional and other properties

Santjer\(^ {152}\) 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 wettable 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 problem 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, Hansen and Jayaraman\cite{142} 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 ($\mu = 0.05$, 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 ($\mu = 0.05$, 0.1 and 0.15) and fibre length (30, 45 and 65 min) 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 nepes hinder the rotation of the yarn in the narrow air path of the air-jets\cite{152}. 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, Kanthimathinathan and Gnanasekar\cite{36} 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\cite{47}. 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\(^{(47)}\). 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.

2.8.12 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 of these structures on the yarn response to tensile loading (Chasmawala, Hansen and Jayaraman, Krause and Soliman, Vohs).

2.8.13 Delivery speed

Punj et al. 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 increases 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. High spinning speed also influences the ballooning action which causes more edge fibres to move away from the fibre bundle and thus increases wrapper fibre percentage.

The tenacity of the acrylic yarn improves with increased delivery speed but the thick places and neps become higher. 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 increase in delivery speed up to a certain limit after which there is a deterioration. Tenacity of polyester/cotton increases with spinning speed up to 180 mpm and afterwards it starts deteriorating with further increase in speed. 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. have reported that the unevenness of polyester / viscose MJS yarns increases with increase in spinning speed. A study by Punj et al. showed that the average fibre extent in air-jet spun polyester / viscose blended yarns increases with increase in spinning speed.
Tyagi et al\(^{(178)}\) 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\(^{(179)}\), in another study, have reported that acrylic rich acrylic/ cotton MJS yarns 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\(^{(47)}\) 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\(^{(6)}\) have reported that the 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 places and neps show an increase after 180 mpm but the number of thin places are independent of delivery speed. Miao\(^{(105)}\) has concluded that, for cotton yarns the optimum speed in air-jet spinning is around 150 mpm.

2.8.14 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\(^{(31)}\).
An increase in main draft increases the abrasion resistance and flexural rigidity in an acrylic rich MJS yarn\textsuperscript{(179)}; 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\textsuperscript{(87)}. 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 imperfection. 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\textsuperscript{(176)}. Fibres with different levels of fibre finish exhibit levels of behaviour at different drafts showing significant interaction.

Overall drafts of upto 170 can be used to produce yarns with very good regularity indices using a three roller drafting system\textsuperscript{(5)}. 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 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 upto 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 upto specific preliminary and main draft levels. In particular, there are no differences regarding yarn tenacity and elongation of 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.

2.8.15 Air pressure

It was Miao(105) 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(139) reached the same conclusion for polyester cotton blends.

Lawrence and Baqui(94) have found that, while using long staple acrylic fibres in their experiments that 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(130) 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(131,134). 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 flexural rigidity\(^{(179)}\).

Rajamanickam and coworkers\(^{(142)}\) have reported a regression equation between yarn tenacity and nozzle pressure.

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

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

Rajamanickam et al\(^{(142)}\) 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 I 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 structure 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\(^{(145)}\). This is because the total number of wrapper fibres in a given yarn section and the 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.

2.8.16 Design of the Air-jet nozzle

Basu and Oxenham\(^{(20)}\) and Miao\(^{(105)}\) have described design features of the nozzle used in the ring frame.

Grosberg, Oxenham and Miao\(^{(55,56)}\), 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, Oxenham and Miao\(^{(55,56)}\) 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\(^{(91)}\). The yarn rotates at a much slower speed during false twisting. This speed lies between 1,50,000 and 2,50,000 rpm.

The air-flow in the twist insertion channel has been studied by Wang\(^{(189)}\). High speed cinematography revealed that the flow 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\textsuperscript{(20,123)} and Chen\textsuperscript{(38)}. These parameters have significant influence on yarn properties\textsuperscript{(20)}. For cotton or polyester / cotton yarn, the yarn quality improves with the increase of axial orifice angle up to 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.

2.8.17 First nozzle to front roll distance

Wang and Jordan\textsuperscript{(188)} 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\textsuperscript{(175)} with increase in \(N_1\) - 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\textsuperscript{(64)}.

2.8.18 Feed ratio

The tenacity of acrylic air-jet yarn increases marginally with feed ratio but then passes through a maximum value. The elongation at break...
follows a similar trend\textsuperscript{(94)}. The yarn uniformity is improved with increased feed ratio. Optimum value 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 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\textsuperscript{(188)}. 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 repression 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\textsuperscript{(129)}. 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\textsuperscript{(67)}. 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 is increased from 0.96 to 0.98 while spinning polyester/viscose yarns\textsuperscript{(175)}. This apparent increase is ascribed to the improved propagation of strain arising from improved alignment of fibres in the yarn.

\textbf{2.8.19 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 10 mm, the strongest polyester yarn could be produced with maximum number of wrappers\(^{(15)}\).

The effect of condenser width on yarn properties for polyester / viscose MJS yarns has been investigated by Punj et al\(^{(134)}\). They showed that the condenser width had a significant influence on yarn imperfections and hairiness. A narrower condenser width offers better guide to the sliver approaching to injector nozzle and therefore helps to produce yarns with lower imperfections and hairiness.

Tyagi et al\(^{(177,179)}\) 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 increases 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\(^{(84)}\) have reported that for model viscose fibres only minor improvement of the yarn tensile properties can be achieved by using a narrower condenser.

2.8.20 Heat Treatment of Air-jet yarns

Tyagi, Kaushik and Salhotra\(^{(178)}\) 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, an increase in diameter of about 26% due to heat treatment was seen over the untreated yarns, whereas the diameter increase 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 9.8 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 air-jet and ring yarns. Tension annealing reduces the 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.
2.8.21 Turbulent air flow in the air-jet nozzle

Figure 2.4 shows the air flow in the air-jet nozzle as 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

\[
 u = \bar{u} \pm u' 
\]

in which

\[
 \bar{u} = \frac{1}{t_1} \int_{t_0}^{t_1} u dt 
\]

where an over bar denotes a time mean value and prime denotes a fluctuation or deviation from the mean. The integration interval \( t_1 \) is selected to be larger than the period of fluctuation \( u' \). By definition, \( \bar{u}' = 0 \), i.e., it is a deviation from the mean. Its magnitude is given by

\[
 \bar{u}'^2 = \frac{1}{t_1} \int_{t_0}^{t_1} u'^2 dt 
\]

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.
Fig. 2.4 Turbulent air flow in the Air jet nozzle
Since turbulence has been impossible to analyse exactly, turbulent flow analysing is usually semi-empirical in nature. There are two ways to measure 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

\[
\bar{u} = \frac{1}{t_1 - t_0} \int_{t_0}^{t_1} u dt.
\]

The second is setting up \( N \) identical experiments and taking all \( N \) measurements at the same time, then averaging these to get

\[
< u(t) > = \frac{1}{N} \sum_{n=1}^{N} u_n(t) \quad \ldots \quad (2.5)
\]

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 \( M = u/c \), 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 \( C = 1100 \) ft/sec (335 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 100 m/s, compressibility should be taken into account.

Rwei, Pai and Wang\textsuperscript{(149)} 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\textsuperscript{(196)}; Sen\textsuperscript{(156)}; Sivakumar\textsuperscript{(143)}; Bock and Lunenschloss\textsuperscript{(25)}; Acar, Turton and Wray\textsuperscript{(1)} and Demir\textsuperscript{(43)}. Wray and Entwistle\textsuperscript{(196)} 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.

2.9 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 structure and properties of yarns spun on ring frames with the air-jet nozzle. The extension of the use of air-jet nozzle in cone winding and rotor has been examined.