CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Air-jet texturing is one of the several processes used to convert synthetic filament yarns to textured yarns and is the most versatile of all known texturing methods. The air-jet texturing process is widely known for its ability to produce spun like synthetic continuous filament yarns. The characteristics of air-jet textured yarn are important for its processing and end use. From the announcement of the first nozzle patent in 1952 to the present day, the air-jet texturing process has gone through many developments and improvements. The texturing speed has increased from 10 m/min to 900 m/min and the compressed air consumption per nozzle has reduced considerably, whilst the yarn properties have been improved. A large number of publications in this area highlight the research on characterization of textured yarn structure and properties in relation with process variable, jet parameters and raw material parameters. In the present review, in addition to general information regarding air-jet texturing, existing methods of measurement of bulk and instability, the factors affecting bulk and instability and a comparative study of air-jet textured yarn fabrics vis-à-vis spun yarn fabrics have also been reviewed.

2.2 The air-jet texturing process

The air-jet texturing process converts flat synthetic filament yarn into bulky spun like yarn. Fig. 2.1 shows the process sequence of air-jet texturing. The process involves overfeeding of multifilament supply yarns from a creel into an air-jet via an optional yarn wetting device. Action of the compressed turbulent cold air stream causes overfed individual filaments to entangle with each other and form loops. The yarn is withdrawn at right angles to nozzle axis by delivery rollers. Normally the supply yarn is wetted prior to texturing to improve the yarn quality. Presence of an impact element such as baffle ball at the nozzle exit also improves the yarn properties.
If partially oriented yarns are used as feeder yarns, a drawing zone is used prior to feed rollers with hot pins, where draw ratio and temperature can be controlled. After texturing, the yarn passes through a mechanical stabilizing zone where the textured yarn is stretched (usually 2-6% tension) between two pairs of rollers for removing unstable loops, tightening the entanglements and making the yarn more compact and stable. The stabilizing zone, therefore, improves subsequent process performance and quality of the end product. After the mechanical stabilizing zone, textured yarn passes through thermal stabilizing zone to impart further loop stability and thermal stability to the yarn by a pre-shrinking process and reduce the fabric shrinkage.

Fig. 2.1 Process flow sequence of air-jet texturing
The basic air-jet texturing process does not require either mechanical stabilization or heating; the inclusion of the above zones is simply to improve the yarn properties and performance. The textured yarn finally goes to the winding zone where suitably wound package is produced.

### 2.2.1 Mechanism of air-jet texturing

A number of hypotheses have been put forward regarding the mechanism of air-jet texturing by different researchers from time to time [1, 2, 18-21]. All the earlier hypothesis, which were based on the assumption that the supply yarn need to be pre-twisted are no longer valid to current processing technology where zero twist supply yarn is used. Further there appears to be no consensus among the research workers regarding any particular hypotheses.

The two basic requirements for texturing are overfeed of feed yarns and turbulent air flow. Overfeed of filament yarns helps in the availability of excess filament length for forming loops, floats and arcs, while the air turbulence must be sufficient to disarrange and entangle the filament bundle so that the looped filaments possess sufficient interfilament friction and the yarn is stable at working tensions. The hypotheses presented by different researchers are different in their finer details. Some of these are presented below.

#### 2.2.1.1 Mechanism according to Bock and Lunenschloss [18,19]

Bock [18] and Bock and Lunenschloss [19] showed that the velocity gradients and turbulence within the air-stream are helpful for texturing as they alter the forces acting on opened individual filaments which, in turn, cause longitudinal displacements of the filaments relative to each other. The bending of filaments is due to pressure barrier caused by the shock waves. The opened filament bundle places itself in a stream of high kinetic energy below the nozzle axis. With right-angled draw-off after the nozzle, an interlacing point forms above the nozzle axis, at the interface between two zones of different flow states. The filaments blown through below this interlacing point pass through a zone of high air turbulence, and are decelerated by the subsequent drop of
dynamic pressure. When the filaments interlace, loops projecting from the yarn are formed by the differently sized filament bends.

2.2.1.2 Mechanism according to Acar, Turton and Wray [1,2]

Acar et al.[1,2] suggested that though shock waves exist in free, undisturbed flows, they are destroyed by the presence of filaments in the actual texturing process. They also suggested that shock waves, their strength varying according to the particular nozzle type, are at least partially destroyed by the presence of filaments in the nozzle during the texturing process. Therefore any loop formation mechanism based on the presence of such waves is probably invalid. The flow characteristics from texturing jet are supersonic, turbulent, slightly asymmetric and non uniform. They illustrated the loop formation mechanism with the help of Fig. 2.2 in which only five filaments have been shown. At stage (a), filament 1 is the fastest moving filament, having the greatest longitudinal displacement relative to the others. The degree of the longitudinal displacements of filaments is affected by local drag and frictional forces instantaneously acting on the filaments and also by the overfeed. During texturing the textured yarn is withdrawn from the nozzle at right angles to the nozzle axis at the texturing speed. The emerging filaments are blown out of the nozzle along the direction of the air stream at much greater speeds than the yarn texturing speed, and, therefore filament 1 is forcibly bent into bows and arcs by the fluid forces acting on them.

Fig. 2.2 Mechanism of loop formation according to Acar et al. [1]

An instant later, at stage (b), it is bound into a fixed loop L1 within the textured yarn as a result of mutual entanglement of the filaments under the action of air stream. This newly formed fixed loop L1 increases the tension in the filament 1, which thereby
causes a change in its position and also contributes to the total yarn tension that is pulling the yarn down close to the nozzle. Meanwhile filament 2 comes under the action of a greater drag force as a result of the changes in the position of the filament across the nozzle and at stage (c) while filament 2 is being similarly entangled into a fixed loop L2, a further filament 3 commences a similar loop formation process.

Since there are many filaments in the actual supply yarn, several loops are formed at any particular instant, and these help each other to be fixed and locked within the yarn structure by mutual entanglement.

2.2.1.3 Mechanism according to Sengupta, Kothari and Shrinivasan [20]

Sengupta et al. [20], while working with zero twist and twisted feed material, proposed that compression-decompression shock waves in addition to the turbulent and asymmetric fluid forces are responsible for intermittent filament separation inside the nozzle. On the basis of their observations, they put forward the mechanism of air-jet texturing as follows: “Turbulent, asymmetric fluid forces in association with intermittent compression shock waves open up the filament and blow the overfed length out of the texturing nozzle at speed much greater than the delivery speed of the yarn. The differences in the speed between the leading and trailing end of the sections of filament under the action fluid forces causes bending of the filaments in the form of loops and arcs. In case of pre-twisted feed yarn, the compression shock waves cause momentary reduction in tension of the yarn inside the nozzle. This enables the yarn to rotate on its own axis in the direction opposite to the twist applied. When the yarn starts rotating, the swirl of the air inside the chamber helps in further freeing the filaments from each other. The overfed lengths of the freed filaments are individually blown out from the jet at speeds dependent on their position inside the jet. The filaments then bend to form loops in similar fashion as for the no twist yarn. On removal from the jet, the twist reasserts itself and enhances the binding force between the filaments".
2.2.1.4 Mechanism according to Dani [21]

According to Dani [21] along with producing a supersonic and turbulent airflow field inside the nozzle, a further function of the nozzle is to push the yarn out of the nozzle channel at high speeds. Due to this the yarn is under tension right up to the plane of air inlet as shown in Fig. 2.3, where it is believed that the effect of overfeed takes place.

![Mechanism if loop formation showing behaviour of filaments inside the nozzle channel. The image also shows the plane of air inlet [21].](image)

There is a sudden expansion of the airflow at the plane of air inlets and this leads to a turbulent, supersonic regime being created in and around that region. There are six circulation zones and a central zone where there is little or no circulation component. It may be hypothesized that as the filaments enter the primary airflow of the nozzle channel, they are not stable, but are being blown around randomly across the cross-section of the channel (Fig. 2.4). This may lead to some of them encountering one of the six circulation zones and be reoriented three dimensionally around axis of the yarn from their initial position, while the others may remain in the central non-circulation zone. Due to this random re-distribution of the filament across the yarn channel, and the large magnitude of forces involved in the airflow, some of the filaments may be bent and formed into loops which get stabilized due to the obstruction created by the other reoriented or intermixed filaments that don’t allow the bent lengths to be straightened-out again. As the filaments speed away from the plane of air inlet, the geometry of the nozzle dictates that they converge back together around the central core. This mechanism may also point towards the reason, why most of the loops observed in air-textured yarns are horseshoe type loops, which are formed by pure bending forces.
2.2.2 Properties of air-jet textured yarns

Air textured yarns have surface features unlike any other textile yarn structure. Though closely resembling and performing essentially the same function as the hairs on the surface of a spun yarn, the surface elements of an air textured yarn are “closed arcs” or as they are popularly called - “loops”. These yarns have a subdued luster, warmer hand, good uniformity, better covering power and good resistance to pilling which is equal to or greater than that of spun yarns. From the viewpoint of end use, the main aspects of interest in air-textured yarns are its bulk (yarn diameter) and instability, which means the retention of the texture (loops) under applied load such as those encountered during further processing of the yarns. The bulk may be considered a characteristic of the number, type and frequency of loops on the yarn surface, while the instability, may be dependent on the integrity of the core structure, which in turn may be dependent on the level of intermixing of the yarn, fibre-to-fibre frictional relationship and the extent of removal of the surface finish. Higher bulk and lower instability values have traditionally been used as indicators of the quality of air textured yarns. However, there is no agreement about the definition of quality in the published literature. A further complication is that, what may be considered good quality for one end use may not be acceptable quality for another end use. In spite of this disagreement, the term “improvement in quality” is being used consistently when trying to understand the influence of processing parameters on air textured yarns. The textured yarn bulk which is one of the important properties, is influenced by loop characteristics. Although air-jet
Textured yarns are in general not prone to lose their bulk, even under the high tensions encountered in further processing and during wear, some of the loops may be pulled out under working tensions. Loops that can be pulled out easily would be a disadvantage in fabric forming process, since bulk of the yarn could be reduced and the possibility of fabric irregularity increased. Therefore, instability of air-jet textured yarn is an important characteristic. A poorly textured yarn will have high instability and low level of bulk. Bulk and instability should therefore be judged simultaneously in characterizing the textured yarn.

Air-jet texturing causes longer lengths of synthetic filaments to be compacted into shorter lengths of textured yarn with an entangled loopy structure. This shortening of length, entanglements and loops causes the volume and linear density of the yarn to increase. The increase in linear density however depends not only on the amount of overfeed, but also on structural characteristics of textured yarn and its behaviour during on-line stabilizing and winding process. Since a well textured yarn will resist the stabilizing and winding-up tensions, the loops will stay intact within the well entangled core, and consequently its linear density will be higher than that of poorly textured yarn. Rozmarynowska and Godek [22] observed that the air-jet texturing process, however severe it may be, causes no damage in the form of cracks, local cross-sectional shrinkage, even chip formation on the filament surface. Any decrease in strength after texturing results solely from the entanglement of the originally parallel arrangement of the constituent filaments due to loop formation.

Textured yarns exhibit different load elongation characteristics as compared to flat filament yarn. The nature, size and frequency of loops, degree of entanglement among the filaments and interfilament friction are the decisive factors in controlling the tensile strength. A good quality textured yarn with many small, compact entangled loops will exhibit a large decrease in tenacity [23]. However a balance between bulk and strength as needed in the final product, can easily be achieved [24].

The air-jet textured yarn is also expected to have lower initial modulus but higher breaking elongation as compared to supply yarn. Stress-strain curve of an air-jet textured yarn is similar to that of spun yarn rather than filament yarn.
Hot water shrinkage is also a very important property of the air-jet textured yams as it determines dimensional stability of yams during subsequent processing stages and in fabrics. Also, the shrinkage process in the heater zone causes the yarn core to be compressed and long loops to be drawn into the yarn axis whereby the stability of the yarn improves and 'velcro' effect is reduced [25-28].

Apart from the above mentioned properties, size, form and frequency of loops are also important properties of air-jet textured yams. Smaller size and large frequency of loops yield a better covering power in the fabric and reduced 'velcro' effect. A well textured yarn must possess lower surface irregularity owing to uniformly distributed loops. The configurations of loops also play an important role in the warmth and comfort properties of the final product.

2.2.3 Test methods for air-jet textured yams

The characterization of the yarn is important from the point of view of its processing and end uses. Some of the important properties which characterize the textured yams are yarn instability, physical bulk, boiling water shrinkage, the size, form and frequency of loops and tensile properties. Various test methods available for evaluation of physical bulk and instability have been reviewed here as focus of the present work is the assessment of these properties.

2.2.3.1 Bulk measurement

Bulkiness in the conventional sense is the volume of a given mass. Since the outer boundary of air-jet textured yams is not well defined and is characterized by compressible surface loops of various configurations, it is difficult to obtain yarn volume. Therefore textured yarn bulk is evaluated indirectly. Bulkiness of air-jet textured yarn is often expressed in relative terms by the degree of voluminosity of the textured yarn in relation to that of the parent flat filament yarn. There are numerous methods for measuring bulk, out of which measurement through package density method is most widely used.
2.2.3.1.1 Package density method

Package density method is extensively used with a number of variations. One of the methods for measuring bulk as suggested by the DuPont company, is based on package densities of yarn packages before and after texturing. A length of parent yarn weighing 3 oz (85 g) is wound onto a package, and a volumetrically similar package of textured yarn is then wound at the same tension. The ratio of their net weights is an assessment of physical bulk.

Later Wray and Sen [29] reported a refined version of the DuPont method, which incorporates a more accurate measurement of the various diameters as shown in Eq. 2.1.

\[
\text{Physical bulk (\%)} = \frac{W_p}{(D_f^2 - D_i^2)_p} \times \frac{(D_f^2 - D_i^2)_b}{W_b} \times 100
\]  

(2.1)

Where, \( W \) is the net weight of yarn wound on the package in grams; \( D_f \), the outside diameter of the final package in inches; \( D_i \), the diameter of empty package in inches; and the subscripts \( p \) and \( b \) indicate the parent and bulked yarns respectively.

It is fairly difficult to wind packages of exactly the same volume. Kothari et al. [30] put forward a slightly modified approach using the same principle. They suggested winding the parent and corresponding textured yarns on a package (cheese) for 20 minutes at a constant tension level of 3 gf (2.94 cN) on the winding unit of the texturing machine operating at a linear speed of 300 m/min. The package density was calculated as the ratio of the net weight of the yarn and the volume occupied by the yarn.

The physical bulk of the textured yarn is given by the ratio of the package densities of the parent and the textured yarn measured in g/cm\(^3\).

Winding tension influences the measured bulk value as it affects the yarn compression. Therefore, controlling the winding tension is very important. Further, the pressure in different layers of a package increases progressively along the radius towards the centre. As a result density of the inner layers will be different for packages of different sizes.
due to the change of the pressure applied. Degree of flattening of parent yams inside the package also influences the physical bulk of textured yarn.

### 2.2.3.1.2 Textured yarn bulk evaluated through fabrics

Wray [31] reported the method of measurement of physical bulk of textured yarn based on woven fabric made with them. With parent and textured yarn as weft, woven fabric samples of similar construction are prepared. The percentage physical bulk is expressed as:

\[
\text{Physical bulk (\%)} = \frac{\text{Density of parent yam fabrics}}{\text{Density of bulked yam fabrics}} \times 100
\]

\[
= \frac{W_p}{T_p} \times \frac{T_t}{W_t} \times 100
\]

Where, \(W_t\) and \(T_t\) are the weight per unit area and thickness respectively of fabrics woven with textured yarn as weft and \(W_p\) and \(T_p\) are the corresponding measures of the fabrics woven with the parent yams as weft.

The bulk of textured yarn was also evaluated through measuring thickness of plain knitted fabric [32]. As the thickness of the fabrics largely depends on the bulkiness of the constituent threads, measurement of fabric thickness for a given construction was used for the evaluation of bulk. However, the use of this method was restricted for comparison of textured yarn of same final denier only.

### 2.2.3.1.3 Water uptake method

Wray and Sen [29] devised a water absorption test method for the measurement of physical bulk of air-jet type bulked yarn. In this method, unlike package density method, characteristic loops are not compressed during the bulk measurement. The procedure for test is as follows:

- **a)** A water bath is weighed when it is filled with water.
b) A length of 400 yd (366 m) of yarn is allowed to pass through the bath at a speed of 40 yd/min (36.6 m/min) under a 0.1 gf/den (0.9 gf/tex) tension measured at the output.

c) The bath is again weighed to ascertain the amount of water absorbed by the yarn.

The same procedure is used for both parent and textured yarns and the percentage increase in water absorption by the textured yarn in comparison to the parent yarn is given in Eq.2.4,

\[
\text{Increase in water absorption (\%)} = \frac{W_b - W_p}{W_p} \times 100
\]  

(2.4)

Where, \(W_b\) = Weight of water absorbed by the bulked yarn (g), and

\(W_p\) = Weight of water absorbed by the parent yarn (g)

Since this method was developed in the early stages of the development of the air-jet texturing process, a pre-twisted yarn is used here, which is no more used now-a-days. In the experiment [33] it was noticed that water absorption method gives assessment of yarn bulk comparable to those obtained by DuPont package density method. The above method was criticized [32] as wet textured yarn transport less amount of water in spite of its higher physical bulk. The reason for this is the compact core diameter of wet textured yarns and their poor wettability owing to partial removal of spin finishes during wet texturing. The above work highlighted that percentage increase in water uptake of textured yarn is quite dependant on spin finish types and levels and on the characteristics of core.

2.2.3.1.4 Image analysis method

Mukhopadhyay [34] used image analysis to evaluate the physical bulk of yarn by using projected image of yarn to obtain core and total projected area of air textured yarn. The specific volume of the textured yarn was derived from the projected area of air-textured yarn and its linear density. They used standard deviation of the textured yarn as a measure of physical irregularity of the yarn.
2.2.3.1.5 Method based on optical system

Earlier optical system was used mainly for characterization of surface properties of textured yarns [18, 31, 35-36], and in the process yarn core and overall yarn diameter were measured. Bock [18] described an optoelectronic instrument, Acar et al. [36] devised a micro-computer based instrument consisting of a line scan sensor and SLR camera to analyze textured yarn mean diameter, loop size and frequency. A few recent papers highlight direct measurement of bulk of air-jet textured yarn based on optical scanning of running yarn [37, 38].

2.2.3.2 Instability measurement

Instability refers to the behaviour of the textured yarn under applied load. In other words instability refers to the retention of texture (loops) under the application of load such as those encountered in processing the yarns into fabric. Several methods have been suggested for assessing or, more specifically, lack of it. These methods can be broadly divided into two groups depending on the characteristics used for assessing structural integrity of air-jet textured yarns. The two different concepts for measuring instability of air-jet textured yarns vary in their method of approach to the problem. One characterizes the instability by measuring the permanent elongation of the yarn after removing a specific load applied for a constant time, and other measures the extension upon application of a constant load. Though most of the methods of measuring instability fall broadly under these two approaches, there are wide variation in the amount of load used, the time of applying the load, the specimen length and its form, and mode of applying the load either by hanging it freely or by using a tensile tester. Yet another approach is based on the principle of repeated loading. There is no commonly agreed test procedure of instability and often a lack of agreement between the results is observed. Description of various methods of measurement of instability is given below.
2.2.3.2.1 Weight hanging methods

A) DuPont’s method

This method is based on the principle of permanent extension [39]. A basic load $W_1$ of approximately 0.01 gf/den (0.088 cN/tex) is hung at the end of the yarn and left on the specimen throughout the test. A 100 cm section on the thus tensioned specimen is marked. The specimen is then subjected to a higher load $W_2$ of 0.33 gf/den (2.91 cN/tex) for 30s. Using the 100 cm mark as datum, the permanent elongation in the length of the specimen is measured 30s after the load $W_2$ has been removed. The measured elongation $(L_2 - L_1)$ expressed as a percentage of initial length $L_1$ is a measure of stability. The procedure is illustrated in Fig. 2.5 DuPont suggested that for a satisfactory textured yarn, the stability value should be less than 5%. Since initial recommendation about the method by DuPont, there was very significant development of texturing nozzle for producing better textured yarn quality with much lower yarn instability. Later, DuPont has modified the above method by specifying higher load 0.5 gf/denier (4.41 cN/tex) with the goal instability below 4%. It was reported [9] that DuPont’s method shows higher sensitivity particularly when the yarns are unstable and lower sensitivity in case of stable yarn. Regarding the limiting value of instability, it should be mentioned that the use of the word ‘stability’ in DuPont test is often criticized [31]; therefore the term instability is used.

![Image of DuPont's stability test method](image)

Fig. 2.5 DuPont’s stability test method [39]
B) Heberlein’s method

Heberlein used hank of textured yarn instead of a single yarn specimen. The yarn is wrapped on a reel of 1 m circumference to form a small hank of approximately 2500 dtex, the number of wraps (to the nearest whole number) being

\[
\text{Number of wraps} = \frac{2500 \text{ dtex}}{2 \times \text{supply yarn linear density (dtex)}}
\] (2.5)

The hank is first tensioned for 60 seconds with a basic load of 0.01 cN/dtex and length \(a\) is measured. Then a higher load of 0.5 cN/dtex is substituted for the above basic load and applied for 60 seconds and the length \(b\) is measured. After 60 seconds the higher load is removed and the basic load is again applied to the hank and after 60 seconds the length \(c\) is measured. Two instability values are calculated. Instability I is the extension (\%) after 60 s at the load of 0.5 cN/tex; whereas the instability II is the permanent extension measured 60s after the removal of the higher load. One of the demerits of the method is that the instability values are influenced by the yarn-to-yarn friction which in turn is influenced by the surface geometry of the yarn. According to Demir et al. [3] the single yarn method of measurement of instability is more suitable than skeins and bundles, because they are easier to handle and the question of non-uniformly distributed load through the skeins or bundles do not arise.

2.2.3.2.2 Measurement using a tensile tester

A) Wray’s method

Wray [30] suggested a method for measuring instability of textured yarns (with pre-twisted supply yarns) by using a constant rate of extension tensile tester. The above method has been criticized as the extent of contribution of the pulling out of loops and the elastic deformation of the load bearing filaments to the total elongation of the textured yarn is unknown [40]. This is also due to the assumption that the extensibility of the textured yarn is a measure of its structural integrity [9, 41].
B) Acar’s method

Acar et al. [40] suggested the use of load elongation curves from a tensile testing machine for the instability measurement. They measured the instability as the percent extension between a high and a basic load. The method was criticized [9, 42] as the instability values obtained by this method were influenced by the extension behaviour of the parent yams. It was claimed [9] that the Acar’s method tends to overestimate the instability values for high parent yarn extensibility and underestimate it for unstable textured yarns.

C) Demir’s method

Demir et al. [3] proposed that the measurement of textured yarn extension is more important than measuring permanent extension of the yarn. As regards the loads they suggested the measurement of percentage elongation at the basic and higher load of 0.01 cN/dtex and 0.5 cN/dtex respectively on the textured yarn of 30 cm length using a tensile tester of Instron type.

2.2.3.2.3 Method based on running yarn

Instability can also be measured by measuring tensile force upon constant extension of a yarn in the running state. Wray [30] devised a quick method using a strainometer for measuring instability. Bock [18] suggested that with constant mechanical stretch, firmer the loops are tied to the yarn, the higher is the resulting tensile force. He proposed the measurement of thread tensile force in the stabilizing zone to measure the instability in the running yarn. Sengupta et al. [42] observed similar trend between stabilizing tension and instability values measured by Acar [40] and also by the % decay method evolved by them under similar loading condition.

Acar et al. [4] claimed that the stabilizing tension is the measure of the stability of the textured yarn. Acar and Wray [5] observed that at higher air pressure the instability values (Acar’s method) were higher. This was commented upon by Sengupta et al. [43]
stating that a higher stabilizing tension for the same level of stabilization stretch should indicate a more stable yarn. Acar and Wray [44] however suggested that it is obviously possible to obtain both increased stabilization zone tensions and instability values for yarns with a greater degree of entanglement and loop formation. As the tension levels involved in the instability measurement were very large compared to the low tension levels involved in stabilizing the yarn; consequently stable loops could be pulled out during instability measurement resulting in higher instability values. Acar and Versteeg [45] claimed that it may be possible to have higher instability in a well textured yarn with high level of loops than the instability in a poorly textured yarn with few loops. As the load level is different, therefore, it is also possible for a yarn that shows high stabilizing zone tension during texturing to show high instability after texturing.

A ‘on-line’ instability measuring instrument consisting a tension sensor has been reported by Demir [46].

2.23.2.4 Method based on repeated loading

Sengupta et al. [42] proposed the measurement of structural integrity of air-jet textured yarn based on repeated loading. According to them method based on cyclic loading provide a more realistic assessment of yarn instability because it simulates the practical situation use of a textured yarn. They used Instron tensile tester for measuring the % decay from the load elongation curve obtained there from. In another work, Sengupta et al. [9] criticized that the %decay method is sensitive to the changes in the structural stability of the yarns, and is independent of the parent yarn extensibility as Wray’s [30] and Acar’s method [40].

2.23.2.5 Method based on optical scanning

Fischer [47] proposed a method based on optical scanning of the yarn using photodiode cells before and after the tensile stressing of the textured yarn. Studying the loop size and configuration before and after tensile stressing, stability of the textured yarn can be predicted.
2.2.4 Factors influencing air-jet textured yarn properties

It is widely known that the physical, mechanical and aesthetic characteristics of an air-jet textured yarn are governed by the type, frequency and size of loops projecting from the surface of the yarn. The variables influencing the properties of air-jet textured yarns are discussed with respect to feed material characteristics, machine parameters and processing parameters. The various variables can be listed as follows:

2.2.4.1 Effect of feed material characteristics

2.2.4.1.1 Effect of polymer type

Structure and properties of air-jet textured yarns are influenced by the type of material. Roy [10] examined the properties of air-jet textured yarns produced from nylon, polyester, viscose and their blends. The yarns were produced under similar conditions using a modified DuPont XIV nozzle and all the yarns except viscose yarns were heat-set prior to testing. It was observed that tenacity and breaking extension were higher for polyester than nylon or viscose textured yarns. Initial modulus was highest for polyester yarn. Boiling water shrinkage and physical bulk was higher for viscose than for nylon or polyester yarn. Viscose yarn also showed the greater changes in linear density.

In a study on filament migration in air-jet textured yarns using different feed material, Kothari et al. [48] observed that migration is highest in polyester yarns followed by polypropylene and nylon yarns. They also stated that physical bulk, loop frequency and initial modulus increase with increasing migration parameters. Polyester feed material showed better properties. However, all the three materials showed similar trend of the above properties with changes in air pressure. Demir et al. [23] compared polyester and polyamide yarns and found that polyamide exhibited lower instability, slightly lower linear density increase, and lower percentage tenacity decrease and thus concluded that polyamide textured poorly compared to polyester.
2.2.4.1.2 Effect of filament linear density and number of filaments

It was found in a study [6] that total drag force on the filaments is dependent on the surface and projected areas of the filaments in the air flow, and greater drag force acts on the filaments with increased area. Further, as bending and torsional stiffness are directly proportional to the second moment of area about a diameter and to the polar second moment of inertia, therefore for an equal total yarn linear density, yarn of finer filaments require smaller fluid forces to displace and entangle them. This in turn lead to better texturisability for finer filament yarns [23]. The current trends of using filaments of lower linear densities which are suitable for air-jet texturing are reported in the literature [49, 50]. However, better texturing is possible for a certain range of number of filaments for a given yarn fineness. When this optimum range was exceeded, deterioration in yarn quality was observed [23, 49]. According to Mukhopadyay et al. [34] yarns having finer filaments, possess greater physical bulk upon being textured along with higher structural irregularity than coarser filament yarn. Rengasamy et al. [51] observed that texturing of finer filament yarn lead to a greater number of loops of lower height and length, and less floats and arcs. Finer filament textured yarn possess some good properties such as greater bulk, lower instability but it also possess lower tensile strength, higher mass variation, thick places and nepes. Demir et al. [23] suggested that the most suitable supply yarn for air-jet texturing should comprise filaments finer than 2 dtex. They claimed that with an increase in the number of filaments there is an improvement in texturing quality up to a certain maximum, but that further increase in filament number results in lowering the yarn quality due to two reasons:

- More disturbed airflow due to increased number of filaments (same as increase in overfeed).
- Increased number of filaments means that there is more number of loops and consequently an increase in the chance of the loops being pulled out.

Bose and Govindarajulu [52] showed that with increase in the number of feeder filaments, tenacity and loop frequency increases. For the same yarn linear density, textured yarn made from finer filament possesses smaller loop size. The reduction in
tenacity after texturing is more in finer filaments. Low bending rigidity of finer filaments will allow increased number of small loops to be formed [51].

Demir et al. [23] observed that as the number of filaments (total yarn denier density) increases, there is an enhancement in yarn quality as yarn instability decrease and percentage retention of tenacity after texturing is higher. However, a particular nozzle can texture yarn up to a certain number of filaments effectively at given process conditions. When this optimum number of filaments is exceeded deterioration in yarn quality occurs.

2.2.4.1.3 Effect of filament cross-sectional shape

The fluid forces acting on filaments will also vary owing to different surface and projected areas arising from non-circular cross-sectional shapes. Acar et al. [6] showed that drag forces acting on an elliptical filament is higher than those of acting on a circular filament of equal fineness, due to a larger projected surface areas of an elliptical filament. However, Acar [53] stated that hollow filaments have a greater surface area and projected area but are also stiffer in both torsional and bending modes. Rengasamy et al. [54] showed that texturisability of trilobal filaments is better than that of circular filaments, resulting in a higher delivery tension at the nozzle exit. Textured yarns with trilobal filaments have more loops of smaller height and length, fewer floats and arcs, more protrudes, closed and crossed loops. In comparison to the circular filament textured yarn, trilobal filament textured yarn possess lower instability, higher bulk, lower tenacity and extension values, lower number of thick places and nep. Sengupta et al. [55] observed that trilobal filament textured arcs have better wicking properties (both in equilibrium and dynamic condition) than circular filament textured yarns. It should be noted that wicking behaviour of air-jet textured yarn is dependent on surface structure, core diameter, spin finish and yarn tension in addition to fibre cross-sectional shape.

2.2.4.1.4 Effect of interfilament friction

Inter-filament friction is affected by the characteristics of filament (polymer type, filament fineness and cross-sectional shape etc.), spin finish and presence of water. Acar
et al. [4, 56-57] found improved texturisability with the reduction of filament to solid friction as well as filament to filament friction. However, in later work Kothari et al. [58] stated that the reduction in friction through lubrication by water plays a relatively less important role in the development of structure and properties of textured yarn. Higher interfilament friction results in higher instability, lower physical bulk, lower loop frequency and loop height, fewer protrudes, closed and crossed loop, reduction in tenacity and extension for both dry and wet textured yams.

Simmen [59] reported that the same type of supply yarn with different types of spin finishes applied to them behave differently during air-jet texturing. It is also well known in the industry that some types of spin finishes reduce the efficiency of the process within a very short time by contaminating the texturing nozzle.

Though the spin finish is not removed from the surface of the yarn while dry texturing, the level of spin finish is reduced by 67 to 85% of the original level after wet texturing. Experiments have shown [21] that variations in process parameters, amount of water used, nozzle type and temperature do not make any significant difference to the level of spin finish removal. The only factor which affects the amount of spin finish removal is the type of spin finish itself [49].

2.2.4.1.5 Effect of filament modulus

In air-jet texturing, the initial modulus plays an important role. Loop formation and interlocking depends on flexural rigidity, which in turn depends on initial modulus. It was observed [60] that an increased initial modulus leads to inferior textured yarn properties with poor bulk and stability, lower loop frequency, and higher nep level.

2.2.4.1.6 Effect of twist

Pre-twisted supply yarns were used with the earlier versions of jet designs to impart the stability needed for these textured structures. However, with the evolution of improved jet designs, the process became suitable for zero twist supply yarn. Chirmade et al. [61] reported the influence of pre-twisting and post-twisting on the structure and properties
of air-jet textured yarn. Breaking elongation, bulk, instability and loop size decrease with the increase in pre-twist level. The post-twisting produces more stable textured yarns with reduced loop size and loop frequency. Post-twisting was found to produce more stable, less bulky, and stronger textured yarns than pre-twisting.

Air texturing jets have an untwisting action on the yarn [20, 29]. Sengupta et al. [62] reported that the effectiveness of air texturing jets (HemaJet T100 and Taslan XX) in opening up and bulking twisted filament yarns show that these jets are able to texture continuous filament yarn twisted in both Z and S directions. While the physical bulk of the textured yarn made from pre-twisted feeder yarn is lower than that of the textured yarn made from zero twist feeder yarn, the former has a more stable structure with reduced core diameter, loop size and loop frequency. An increase in twist density in the feeder yarn reduces bulk but enhance stability and tenacity of the textured yarns. The direction of twist in the feeder yarn has no effect on texturizability.

2.2.4.1.7 Effect of blend

Blending of staple fibres in spinning is quite common in yarn manufacture. Blending of filament yarn also offers an equal potential [63]. Among the methods available for filament blending [64], air-jet texturing is becoming more and more popular because of its technological and economic advantage. Continuous filament yarns of both thermoplastic and non-thermoplastic types can be fed into the jet simultaneously and textured together. Structure and properties of textured yarn are influenced by blend constituents and blend homogeneity. The scope for producing yarns of diverse characteristics using this method is virtually unlimited.

Kothari and Rabindranath [11] studied the effect of various blend proportions of polyester and viscose filament yarns and heat setting on textured yarn properties. They showed that polyester rich blends have higher tenacity, elongation, modulus and hot water shrinkage but lower instability when compared to that of viscose-rich blends. The heat-setting effect is much stronger on polyester-rich air-jet textured yarn and post-heat-setting can substantially reduce the hot water shrinkage of these yarns.
Further the increase in tenacity and reduction in extension depend on the heat-setting temperature. Their investigation showed that although there is substantial reduction in the modulus due to air-jet texturing, the modulus can be partly increased through the subsequent heat-setting of polyester and polyester rich blended air-jet textured yarns. Viscose rich blended yarns were found to have a larger loop size and lower loop frequency.

Sengupta et al. [12] examined the blend inhomogeneity in air-jet textured yarns of nylon/nylon, nylon/PET and PET/PET parallel fed multifilament strands textured under dry and pre-wetted conditions using cylindrical and convergent-divergent nozzle. Their results showed that random blend irregularity is achievable under optimum condition of texturing and uses of filaments of dissimilar characteristics or disproportionate blend ratios can result in poor blend homogeneity. Texturing parameters and designs of nozzles have considerable influence on blend irregularity. Wet texturing was found to produce better blend uniformity and structural stability than dry texturing.

Apart from the blending of parallel-end yarns made out of different polymer, filaments combining the yarns of same polymer but of different shrinkage potential are also practiced. Pillar [65, 66] used parallel end air-jet texturing of different shrinkage potential yarns and reported higher loop frequency, greater cover, and warm and full hand in the resultant yarns after shrinkage. Pillar [66, 67] has also reported that it is not only the shrinkage value of feed yarn which decides the shrinkage properties of resultant textured yarns but also the shrinkage force and shrinkage work. He produced different shrinkage in the modified yarns by varying the draw ratio and drawing temperature and obtained a direct relationship between physical bulk and shrinkage force multiplied by the shrinkage.

Kothari and Yadav [68, 69] studied the textured yarns produced from feed yarns of different shrinkage potential under conditions of constant overfeed in the heater zone and constant winding tension. They observed that increase in the shrinkage difference between the feed yarns, increases the physical bulk and instability initially in case of yarn produced with constant overfeed in heat-setting zone but after a certain level of shrinkage difference, further increase in shrinkage difference leads to decrease in
physical bulk and instability. The opposite trend was observed in physical bulk and
instability in case of yams produced at constant winding tension on Eltex AT/HS air-jet
texturing machine. The shrinkage potential of drawn yams decreases as the drawing
temperature increases. Textured yams produced from high number of lower denier
filaments (total linear density remaining same) produce yarn with lower bulk, instability
and tenacity, and higher breaking elongation at all level of shrinkage difference in feed
materials, the shrinkage difference in the feeder yarns is not an effective way to increase
the bulk of air-et textured yarn.

2.2.4.2 Effect of jet parameters
2.2.4.2.1 Effect of nozzle

Type of nozzles (converging-diverging nozzle and cylindrical nozzle), their construction
details in each type (primary flow length, cross sectional area and shape, number of air
holes air inlet angles etc.) and setting (feed nozzle to venture) have very significant
influence on fluid flow characteristics through nozzle which affect the structure and
properties of air-jet textured yarn. Kim [70] reported that the inlet pore diameter of the
guide needle and the throat diameter of the outlet passage of the nozzle used in air-jet
texturing are critical. Simmen [59] compared the Hemajet core T100 and T311 for
texturing filaments with different linear densities. Demir et al. [23] showed that T100
and T341 Hemajets produce textured yams with similar instability but different linear
densities and yarn tenacity. The standard core Hemajet produces yams with reduced
instability, whereas the yams textured by the Taslan type XIV nozzle has higher
instability. Yarn textured by the T341 Hemajet attains the highest linear density but
display the lowest tenacity. The distinctive nature of the yarn textured by the Taslan
XIV nozzle is that the large loops and arcs are dominant on the surface of the yarn,
while the yams textured by the Hemajets appear to possess greater number of smaller
sized loops.

According to the relative texturing effectiveness, Demir et al. [23] ranked the four
different jets in the following order. T341 Hemajet, Taslan XIV, T100 Hemajet and
standard-core Hemajet. The T100 Hemajet is more effective than the standard core
Hemajet, despite its reduced air consumption and lower air velocity. Kothari and Timble
[71] showed that yarns produced using Hemajet T100, Hemajet T310 and Taslan XX jets possess lower instability, higher bulk, lower tenacity and breaking extension, lower Uster CV% and lower neps/1000m than the yarns produced using Taslan X, XI, XIV and XV jets.

Versteeg et al. [72] reported a preliminary investigation of the effect of nozzle geometry on air flow properties and texturing quality for a range of cylindrical nozzles. Bilgin et al. [73] found that the best texturing comes from nozzles with a slightly diverging main channel and a single air inlet hole located far from the nozzle exit. A curved diverging exit profile is observed to be essential for successful texturing. The results of their tests to determine the effect of air inlet angle are inconclusive and require further investigation.

2.2.4.2.2 Effect of impact element

The presence of baffle plate diverts the flow and produces high turbulence which gives better entanglement. With the increase in the baffle distance from jet exit, the number of large loops increases. There is an optimum distance of the baffle plate which lies near the intersections of the lines in Schlieren picture.

Impact elements have insignificant effect on the flow inside texturing nozzles, since any such element is usually situated at a distance of about one nozzle diameter from the exit. One possible minor role of an impact element is to act as a physical barrier to those filaments that are well away from the nozzle [74].

Bock [18] studied the effect of cylindrical baffle as well as flat baffle on the textured yarn properties. The use of baffle resulted in decrease in instability of yarn. Cylindrical baffle affected the free jet only negligibly whereas flat baffle altered the flow at the nozzle exit. Nep frequencies were found to increase with distance and angle of the baffle plate from the vertical plane of the nozzle exit.

Acar and Wray [5] observed that the introduction of an impact ball has a significant effect on breaking elongation particularly at high overfeed with wet texturing. In
contrast, the tenacity of the yarn is not affected significantly by using an impact ball except at high overfeed. The linear density and instability of the textured yarn are only slightly increased by using an impact element, but they are both considerably reduced in dry texturing because of less effective loop formation. Demir et al. [23] stated that the use of impact elements in the form of cylindrical bars, spherical elements, or flat plates placed at the exit of the nozzle can only be recommended for particular applications such as low linear density yarns or high speed operations. Instability and linear density increase while tenacity decreases with the use of a spherical impact element. The deployment of an impact element was not found to make any significant improvement in wet textured yarn. It is also observed [75] that using a baffle in front of the jet exit help to reduce nep frequency to a greater extent. Lower curvature flat baffles are especially more effective in this purpose. A closer baffle setting is also suggested to be a pre-requisite for reduction of nep.

2.2.4.3 Effect of process parameters

The main processing variables in air texturing are overfeed, stretch, operating condition (i.e., dry or wet texturing), production speed, and air pressure. The variation of these parameters is believed to influence the final air textured yarn structure to varying degrees.

2.2.4.3.1 Effect of air pressure

It was found that as air pressure increases, the degree of non-uniformity in air flow and turbulence increases [1, 5]. The filament separation and longitudinal displacement of filaments with respect to each other become more effective and filament travel and change their position at a higher rate. Hence better texturing can be achieved.

Acar and Wray [5] observed that although excess lengths of filaments are unchanged for a constant overfeed, the linear density of the textured yarn increases with the increase in air pressure. They concluded that “with increasing air pressure, the flow velocity and hence the ability of the nozzle to open and entangle the structure increases because of increase in the turbulence of the airflow, which in turn results in better texturing”. With
the increase in air pressure, yarn linear density and instability increase while tenacity decreases [76]. Sengupta et al. [42] and Kothari and Timble [71] reported that as air pressure increases, instability decreases. The air velocity increases at the jet exit and the degree of non-uniformity in velocity distribution increases with increase in air pressure. Due to better filament separation and longitudinal displacements, entanglement of filaments becomes better thus decreasing yarn instability.

Kothari and Timble [71] found that as the air pressure increases, physical bulk and loop frequency increase while the instability and loop size reduce. The increase in bulk with the increase in air pressure in air pressure is due to the formation of higher number of smaller loops which are more rigid. The effect of air pressure on physical bulk and instability can be seen figures. However, with the increase in air pressure the tenacity reduces and the yarn becomes stiffer as indicated by the higher value of modulus. In a work on neps in air-jet textured yarn, Sengupta et al. [77] reported that with increase in air pressure, nep level increases and yarn tenacity and extension at hpeak load decrease. Formation of neps at higher air pressure along with higher overfeeds and higher texturing speed values were much greater [78]. Mukhopadyay [34] used image analysis and values of standard deviation to claim that as the air pressure increases, the core of the textured yarn becomes more regular, initially with formation of loops of variable size, and higher air pressure leads to formation of greater number of loops with less variability.

2.2.4.3.2 Effect of overfeed

Experimental work carried out by Acar and Wray [5] showed that with the increase in overfeed, yarn linear density and instability increase whereas tenacity and breaking elongation decrease. At higher overfeed, the number of loops formed and loop size increases [1, 5]. The increase in linear density of textured yarn with higher overfeed is expected. With the increase in overfeed not all the loops are firmly fixed in the yarn core and at the same time number of loops increase, which in turn increases the probability that some of these loops will be removed on elongating the yarn and thereby result in greater yarn instability.
Demir et al. [10] observed that at lower overfeed (10%), the excess length of filament available to form loops and arcs are small. Hence texturing is poor with few loops on the surface. Instability is low due to the presence of more straight, unlooped load bearing filaments. As overfeed is increased, more length of filament is available to form loops. They claimed that “As the overfeed increases up to 20% there is an enhancement of texturing quality as indicated by the lower tenacity values, but above 25% there is no such improvement in quality.”

Kothari and Timble [71] and Sengupta et al. [42] have also reported higher instability for yarns produced at higher overfeeds. They observed that as the overfeed increases, core diameter, loop size and loop frequency increase which in turn increase yarn physical bulk. However, there is also significant reduction in tenacity and modulus, hot water shrinkage and increase in breaking extension with the increase in overfeed [71]. Mukhopadhyay [34] has stated that at higher levels of overfeed, the physical bulk of textured yarn and yarn structural irregularity are higher.

### 2.2.4.3.3 Effect of texturing speed

Acar et al. [1] proposed that with the increase in texturing speed, a given length of filament will be exposed to the air flow for a shorter time which in turn results in formation of unstable loops. Yarn instability increases slightly with the increase in speed [5]. With increase in texturing speed, yarn structure becomes less compact and consequently interfilament friction is expected to reduce resulting lower tenacity.

Demir et al. [23] stated that with the increase in texturing speed relative velocity between the filaments and the surrounding airflow changes resulting lower forces and torque exerted on the individual filament. They observed that at speed greater than 400 m/min, the texturing quality is markedly reduced due to large and unstable loop formation. However, instability and tenacity are affected only marginally with the increase in texturing speed. It was observed [78] that at higher air pressure and at higher overfeed, neps in textured yarn increase substantially with the increase in texturing speed. Mukhopadhyay [34] has claimed that with increase in texturing speed, the
textured yarn physical bulk increases up to a certain extent, but the yarn structural irregularity increases steadily at higher texturing speeds.

2.2.4.3.4 Effect of stabilizing tension

The purpose of the stabilizing tension subsequent to the texturing zone is to pull out those loops that are not firmly fixed to the core of the yarn. The level of this extension usually varies from 2% to 6%, because at higher levels, permanent yarn damage or even breakage can occur. With the increase in stabilizing tension from 0 to 10%, instability decreases due to the removal of unstable section in the yarn. With increase in stabilizing tension, linear density of the yarn decreases, while tenacity changes marginally [23].

In another study [78], it was observed that stabilizing tension up to 8.8% failed to bring down the nep count significantly. Therefore, it was concluded that the above parameter has little and no effect on neps in textured yarn.

2.2.4.3.5 Effect of heat stabilizing

Sengupta et al. [42] found that heat stabilizing of the air-jet textured yarns improve the stability of the loops. According to them this may be attributed to shrinkage of the filaments which straightens arcs and reduces the sizes of loops, thus increasing the overall frictional contact between filaments. Further as the filaments are heat set in their distorted state, their ability to return to their original configuration after removal would be better than the unset yarns. Heat-stabilization step after the jet produces stable yarn with significantly higher bulk than that obtained with conventional air-jet texturing process. Fabrics containing these yarns have a more spun like hand, higher bulk, and less shine. Kothari and Rabindranath [11] reported that polyester and blends with high polyester content respond more favourably to heat setting.

Sengupta et al. [79] stated that the shrinkage property of air-jet textured yarn is influenced by the drawing conditions. A post heat setting process reduces the shrinkage potential of the textured yarn and, hence reduces the influence of feeder yarn characteristics on the shrinkage behaviour of textured yarn. The heat setting process
improves bulk to some extent. Instability has a direct correlation with the shrinkage values of relaxed yarns. There is a decrease in tenacity and breaking extension on post heat setting after texturing. Texturing filament yarns with different shrinkage potentials was found to produce textured yarn with considerably higher bulk though with reduced tenacity values.

In another study Kothari and Timble [71] observed that as the heater temperature increases from 150°C to 210°C, instability and hot water shrinkage reduces. It was further observed that with the increase of heater temperature, tenacity and initial modulus increases, and breaking extension decreases. Further with the increase in stabilizing temperature, air-jet textured yarn structure is also changed as reflected by decrease in core diameter, loop size and loop frequency.

Kothari and Yadav [68, 69] studied the effect of heat-setting of parallel-end air-jet textured yarns produced from filament feed yarns with different shrinkage potential under conditions of constant overfeed in the heater zone and constant winding tension. Shrinkage potential in drawn yarns was found to decrease with an increase in drawing temperature.

2.2.4.3.6 Effect of water

The wetting of the filaments prior to texturing, which has been practiced since 1969, improves the effectiveness of the texturing process and result in better quality textured yarn. Water plays an important role in air-jet texturing [80, 81]. Improvement in texturisability with wetting has been attributed to the change in the fluid behaviour inside the jet in the presence of water [18-19, 47] as well as a reduction in friction force [4, 56-57] in the presence of water.

Artunc [82] observed that minimum amount of water required for texturing is 0.2 lire/hr. Water consumption rates higher than this did not affect the properties of textured yarn. Acar and Wray [5] showed that wet textured yarns have higher linear density but a lower tenacity and breaking elongation compared to dry textured yarns. Demir et al. [23] found that texturing is enhanced by the water application and higher numbers of smaller loops
are formed. In contradiction to the earlier findings [5] regarding the effect of wet texturing on instability, it was found [29, 42, 58, 80] that wet texturing always results in lower instability. Later, Acar and Demir [83] also reported increased loop stability on wet texturing.

It has been reported [29, 58, 76] that wet texturing results in lower core diameter, smaller loop height, higher loop frequency, more protrudes and more closed loops. The properties of wet textured polyester and nylon yarns are better owing to their lower instability, higher physical bulk, better evenness and lower yarn faults (thick places and neps).

Kothari et al. [80] found that the differences between properties of dry and wet textured nylon yarns exist at the same level of friction and better texturisability in the wet mode even at higher friction level is apparent. In another study, Kothari et al. [48] observed that textured yarn produced under wet condition show higher migration. Increasing values of migration parameters result in higher loop frequency, higher physical bulk, higher initial modulus and smaller loop size, lower tenacity, lower breaking extension and lower instability.

Chand [81] observed that the main factor causing improvements in texturing with wetting is probably not the reduction in friction but the change in fluid behaviour inside the jet, based on the assumption that condensation shock plays a role in texturing. Acar et al. [84] in a recent study claimed that water plays a dual role in loop formation and loop fixing/anchoring in air-jet texturing process. According to them water acts as a lubricant to generate a reduction in inter-filament and filament-to-solid surface kinetic friction prior to and during the loop and entanglement formation stage when the filament yarn traveled through the nozzle enabling easier relative motion of the filaments resulting in enhanced entanglement. It also acts as an agent for the removal of spin finish from the surface of the filaments leading to an increase in static friction between the constituent filaments of the textured yarn. This resulted in better fixing of the loops and consequently production of superior yarns.
2.2.4.4 Process economy

The process economy of any product should be viewed not from the initial cost-structure, based on capital expenditure, but from the long term perspective based on the objective assessment of long term benefits. The production of spun blended yarns involves several steps as compared to that of textured filaments yarns it can therefore be observed that the production of spun yarns involves more steps, while the production of textured yarns involves only a few number of steps.

PROCESSING SEQUENCES FOR BOTH YARNS

<table>
<thead>
<tr>
<th>SPUN YARN</th>
<th>AIR-JET TEXTURED YARN</th>
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<tbody>
<tr>
<td>Raw material (staple fibres)</td>
<td>Raw material (continuous filament yarn)</td>
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<td></td>
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<tr>
<td>↓ Blowroom</td>
<td>↓ Air-jet texturing</td>
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<td>↓ Carding</td>
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<td>↓ Lap formation</td>
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<td>↓ Flyframe</td>
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<td></td>
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<tr>
<td>↓ Yarn spinning</td>
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</table>

For making spun-blended yarns, synthetic filament yarns are cut into staple fibres, which is a questionable exercise from the point of view of production economy. Textured yarns are directly produced from synthetic yarns and besides this, the developments in melt-spinning with the advent of partially oriented yarn (POY)
technology and simultaneous draw texturing technology and even the spin-drawing technology, have rendered the production of textured yarn more and more economical. Therefore, spun blended yarn production is costlier than that of textured yarn [85]. The overall cost of spun-blended yarn should have been still higher than that of textured yarns.

2.3 Air-jet textured yarn fabrics

2.3.1 Air-jet textured yarn vis-à-vis spun yarn fabrics

At one time spun-blended yarn textiles were thought to be the only ones which combined the comfort characteristics of natural fibres, the durability of synthetics and aesthetics of spun-yarns. However with the rapid strides made in yarn engineering, by developments in texturing of synthetic filament yarn, textured yarn fabrics have started penetrating the traditional markets of spun blended textiles. Thus we now have these two, i.e., spun yarns and textured yarns, especially air-jet textured yarns (which have all the aesthetic, comfort and durability characteristics of spun yarns), competing with each other.

2.3.2 Processing of fabric from air-jet textured yarns

It has been observed [85] that end breakage rate during weaving is comparatively lesser with textured filament yarn than spun yarns with more or less comparable construction. Weavability of finer denier textured yarns is much better than spun blended yarns. The requirement of sizing is less or nil with textured yarns vis-à-vis spun yarn. There is no need of mixing to avoid barre, no problems with fly, no necessity of singeing or cropping with textured yarn fabrics. Although air-jet textured yarns can be used both in the warp and weft direction some difficulties have been experienced on the high speed shuttleless looms like uneven shed formation due to the anchoring behaviour of the air-jet textured yarns. The simplest way to construct a fabric is to take an existing spun yarn warp and weave in air-jet textured wefts. Finishing techniques (particularly relaxation and overfeed) for air-jet textured yarn fabrics are most important to maximize the spun-like aesthetics. High temperature jet dyeing helps in developing desired softness and handle [86].
2.3.3 Consumer acceptance

When it comes to the consumer, his/her choice is more likely to favor those fabrics which are lighter, softer, easy-care, and most importantly durable. Textured filament yarns, while retaining almost all the advantageous properties of flat filament yarns, also possess some of the important properties of spun yarns. Although the initial cost of textured yarn fabrics is more than the spun blended yarn fabrics, in the long run textured filament would turn out to be more economical to possess than spun yarn fabrics because [85]:

- Spun yarn fabrics tend to soil more, needing frequent washing which also reduces the serviceability.
- Spun yarn fabrics have poor crease recovery and dimensional stability, and therefore need more frequent pressing, which is not the case with textured filament yarn fabrics.
- The service life of textured yarn fabrics would be about twice as long as that of spun yarn fabrics because the latter are more prone to pilling and abrasion and are less durable.

2.4 Blended yarn fabrics

Modern day living conditions require clothing that is light weight, comfortable, safe, elegant, easy care and hard wearing. No single textile fibre has all the desirable attributes. Synthetic fibres have better wear and easy care properties but they lack many comfort related properties. Natural and regenerated cellulosic fibres have better feel and higher moisture absorbency leading to good comfort in wear and low static charges but have poor strength and abrasion resistance. The blended yarns composed of two or more fibre components of different types in intimate blend can produce yarns with desirable properties. For instance blending of polyester fibre with viscose has become popular because of the complementary nature of the properties as shown below:
<table>
<thead>
<tr>
<th>POLYESTER</th>
<th>VISCOSE</th>
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<tbody>
<tr>
<td>+ Good Tenacity</td>
<td>- Poor Tenacity</td>
</tr>
<tr>
<td>+ Good abrasion resistance</td>
<td>- Lower abrasion resistance</td>
</tr>
<tr>
<td>+ Easy to wash</td>
<td>- Difficult to wash</td>
</tr>
<tr>
<td>+ Good color fastness</td>
<td>- Lower color fastness</td>
</tr>
<tr>
<td>+ Good wrinkle recovery</td>
<td>- Poor wrinkle recovery</td>
</tr>
<tr>
<td>+ Good crease retention</td>
<td>- Poor crease retention</td>
</tr>
<tr>
<td>+ Low staining tendency</td>
<td>- Higher staining tendency</td>
</tr>
<tr>
<td>- Poor static dissipation</td>
<td>+ Good static dissipation</td>
</tr>
<tr>
<td>- Poor moisture vapor transmission</td>
<td>+ Good moisture vapor transmission</td>
</tr>
<tr>
<td>- Non bio-degradable</td>
<td>+ Bio-degradable</td>
</tr>
<tr>
<td>- Poor moisture absorption</td>
<td>+ Good moisture absorption</td>
</tr>
<tr>
<td>- Poor feel</td>
<td>+ Good feel</td>
</tr>
<tr>
<td>- Lower comfort</td>
<td>+ Better comfort</td>
</tr>
<tr>
<td>- Warm, crisp hand</td>
<td>+ Cool, silky hand</td>
</tr>
</tbody>
</table>

Knight, Hersh and Brown [87] stated that strength loss which occurs on addition of stronger synthetic fibres is a well known phenomenon usually ascribed to the differences in extensibility of the cotton and synthetic fibres being blended. The greater extensibility of the synthetic fibres allows them to simply elongate when stress is applied leaving most of the load to be absorbed by the cotton fibres in the blend. Since the addition of synthetic fibres in some small percentage means fewer cotton fibres, hence, lower breaking strength. In blends containing more than 50% synthetic fibre in which the synthetic fibre strength is greater than cotton, the strength of the synthetic fibre predominates and the strength of the fabric or yarn is enhanced. The effect of twist and blend levels on the initial modulus, dynamic modulus, tenacity and elongation of polyester/viscose blended spun yarns have been studied by El-Sheikh [88]. He concluded that the properties of blended yarns depend on their constituent fibres. Strength and elongation follows the mixture theory proposed by Hamburger [89] at extreme blend levels. It has also been shown that blended yarn tenacity decreases as the percentage of high tenacity fibre is increased, and then increase again at a critical blend.
level. The results also show that as twist is increased, the value of this critical blend level is decreased.

Dhingra et al. [90] stated that textile fabrics in garments rarely experience tensile loads anywhere near their breaking strength but are expected to adjust easily to the movement of human body. This elementary mechanical property of strength and elongation are generally believed to relate to such important fabric character as serviceability, handle, tailorability, creasing and shape retention property and also represents that tensile behaviour of woven fabrics is dependent on yarn linear density, ends/pick density, weave crimp and shear behaviour. They also stated that for different wool polyester blends there was a trend for initial relative tensile modulus to have a lower value with increasing wool content in the blend. Buck and McCord [91] conducted a broad survey of various aspect of crease-resistance. They found that the crease resistance of a textile fabric is affected by its construction and by the construction of yarn of which it is composed. However, the type of fibres which makes up the yarn and fabric has perhaps the greatest influence on the fabric’s crease resistance. The ability of fabrics that are made from wool and silk to resist the formation of wrinkles is well recognized, as is the tendency towards wrinkle formation in line with cotton and certain rayon textiles. Fibre characteristics responsible for these differences in crease resistance are related to the chemical and physical structure of fibre itself (chemical structure refers to the type of molecule, and physical structure to the manner in which the molecules are grouped together in the fibre). The physical dimensions of fibres undoubtedly affect the crease resistance of fabrics made from them. It is recognized that when fibres are too short, fibre to fibre cohesion in yarns is low and folding may displace fibres in the yarn so that their failure to return to their original position produces permanent deformations. On the other hand, continuous filament and exceptionally long staples appear to have little advantages over medium length fibres. McLaren et al. [92] studied the effect of moisture and temperature on crease recovery of blended fibre fabrics. They found that with low moisture contents, the materials would be expected to resist deformation more easily, hence high recovery. Looney and Handy [93] investigated the effect of blend ratio, yarn count, yarn twist, yarn ply, fabric tightness and fabric weave pattern of polyester/wool suiting on wear wrinkling. They concluded that the three major construction factors which improved wear wrinkling were greater population of polyester fibres, coarser yarn
count and longer float weave patterns. Interfibre friction, yarn twist and tightness for a given weave and yarn size had little effect on wrinkling property. Tyagi et al. [94] studied the relationships between low-stress mechanical properties of polyester-viscose and polyester-cotton ring and MJS yarn fabrics and yarn bulk and rigidity. It was observed that increased polyester component leads to a noticeable increase in bending and shear rigidities. They also concluded that polyester-cotton fabrics are preferable to a polyester-viscose fabric in respect of fabric handle. Bhargava and Yadav [95] found that reduction in the polyester component in square sett P/V fabrics results in a weaker, less extensible, and more flexible and permeable fabric with lower value of fabric assistance. They also observed that increase in fabric sett resulted in a strong, more extensible, less flexible and less permeable fabric with higher value of fabric assistance. Bhargava et al. [96] stated that the use of high tenacity polyester in a 67/33 P/V blended suiting fabric enable saving in cost through reduced requirement for the polyester component in the blend without compromising with the quality. But this require judicious selection of type of fibre, blend composition, type of weave, loom sett for fabric and appropriate heat-set and resin finishing treatments. Sunmonu et al. [97] studied some important physicomechanical properties of P/V blended yarn plain woven fabrics and found that increase in polyester component in the blend led to increase in fabric thickness, crease recovery angles, tear strength and abrasion resistance. Furthermore, an increase in the viscose component in the blend leads to increases in air permeability, drapeability, percentage shrinkage and extension at break. Nayak et al. [98] studied the handle and comfort properties of P/V blended suiting fabrics. They found that higher viscose content give better hand, higher air permeability and higher moisture vapor transfer but lower thermal insulation.

Tarafder et al. [99] found that the drapeability of P/V blended plain woven fabric is influenced by the linear density of the yarns, polyester content and bending length. Shearing deformations in the fabrics are highly related to its flexural rigidity and shear occurs easily with higher polyester content. They also mentioned that higher crimp in the yarns reduce drapability by attaining more shearing stiffness.
2.4.1 Blended yarn fabrics from air-jet textured yarn

Blended yarns produced from filament materials have not found the same market acceptance as those from staple fibres because of the unhybridisation of properties of filaments which may manifest itself in non-uniform appearance particularly after dyeing, also because of the inherent drawbacks of filament yarn fabrics such as metallic lustre, high rigidity, low bulk, unpleasant feel etc. Only through blending of filaments in air-jet texturing these drawbacks of the filament yarns can be removed.

Denton and Seth [13] reported about the computer simulation of the appearance of a variety of fabric structures, made from simulated blend yarns with defined levels of blend intimacy. They argued that in order to use blended air-jet textured yarns in the manufacture of suiting, the appearance of real worsted suiting has to be considered. As natural wool fibres are not uniform in their structure and properties, they have different levels of dye uptake and surface texture, thus conferring on the fabric an inherent degree of irregularity of appearance which may be described as 'speckliness' or 'scintillation'. It is therefore, essential that any attempt to simulate the fabric of this type should take this fact into account. If a good simulation is to be achieved with synthetic filament materials blended by air-jet texturing, a carefully controlled degree of non-homogeneity or imperfect blending is required. An inadequate blending will give a too high level of 'speckliness', too intimate blending will give a too uniform appearance to the fabric. They also reported [14] that the regularity of appearance of fabrics made from yarns consisting of two or more component is dependent on the blending efficiency of the component. Correlation between yarn and fabric reflectance, regression analysis of fabric reflectance and yarn indices, and mathematical modeling of yarn reflectance data were used to demonstrate the effect of yarn reflectance on fabric simulation.