Texturing and intermingling processes by using air-jets

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TEXTURING AND INTERMINGLING PROCESSES BY USING AIR-JETS

By

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BSc (U.U., Bursa)

A DOCTORAL THESIS
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SUMMARY

The air-jet texturing (AJT) and intermingling (INT) processes are two applications of air jets used to modify the structure of synthetic multifilament yarns. The modification is performed by high-speed jets, which are created by purpose designed nozzles.

The present work experimentally investigates the interrelation between properties of the yarn produced and air flow and the nozzle geometry in order to gain an improved understanding of the AJT process. Firstly, a number of industrial AJT nozzles were selected for detailed analysis. Undisturbed flows created by these nozzles are investigated by means of total pressure measurements and shadowgraphy.

The effect of nozzle geometry on the AJT process is investigated by using a series of systematically designed nozzles. A number of geometrical parameters of cylindrical type AJT nozzles are specified for successful texturing, after assessing performance of the nozzles by stabilising zone tension and the properties of yarns produced. It is found that large exit length and slightly diverging main duct are beneficial for texturing. Also the trumpet shaped exit profile is found to be necessary for adequate texturing. Low tilt angle of air inlet hole is recommended.

Effect of wetting on AJT is investigated with special reference to yarn-to-yarn and yarn-to-metal friction. It is found that when the supply yarn is treated with water interfilament friction prior to the nozzle is reduced, but increased slightly in the texturing area. The former may make relative movement of filaments easier. The latter is considered to be one of the ways through which wetting improves the process, since it assists anchoring the loops in the yarn.

Subsequently high-speed cine-photography is deployed to visualise the AJT process inside and around exit area of the nozzle. The nozzle used has rectangular cross-section and one glass wall, which allows to see inside the main channel. It is found that for successful texturing loop formation and fixing the loops are both necessary.

The INT process is investigated by using again several systematically designed nozzles with reference to correlation between nip frequency and nozzle geometry. Rectangular nozzles are found to be performing adequately, depending on their dimensions. The nozzles with area ratio smaller than unity perform adequate intermingling. It is also found that small aspect ratio is beneficial in terms of nip frequency.

A better understanding of the INT is achieved by means of SEM, high speed video and cine-photography and yarn tension measurements. The yarn is found to be necessary to run constantly against the incoming flow to reduce missing nips.
DECLARATION

This is to certify that I am responsible for the work submitted in this thesis and that the original work is my own except where due reference to previous work has been noted. I also certify that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

Sule Bilgin
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LIST OF SYMBOLS and ABBREVIATIONS

ABBREVIATIONS

AJT  Air-jet Texturing
BCF  Bulked Continuous Filament
dpf  denier per filament
dtex  decitex
FTT  False Twist Texturing
INT  Intermingling
PA  Polyamid
PET  Polyethylene Teraphthalate
POY  Partially Orientated Yarn
SEM  Scan Electron Microscope
tpi  twist per inch

SYMBOLS

\( \mu \)  friction coefficient
\( \gamma \)  specific heat ratio
\( p \)  pressure
\( \rho \)  density
\( A \)  area
\( M \)  Mach Number
\( \text{Re}_D \)  Reynolds Number based on diameter
\( \text{Re}_x \)  Reynolds Number based on length
\( u \)  velocity
\( V \)  velocity
\( \beta \)  helix angle
\( w \)  main channel width
\( d \)  main channel depth
\( s \)  width of air inlet hole
\( c_p \)  specific heat capacity at constant pressure
\( c_d \)  coefficient of pressure drag
\( c_t \)  coefficient of skin drag
\( c_D \)  coefficient of total drag
\( D \)  Main channel diameter

SUBSCRIPTS

\( t \)  values at minimum cross-sectional area
\( 0 \)  stagnation conditions

Symbols-1
CHAPTER 1
INTRODUCTION

Air-jet texturing, AJT, and intermingling, INT, are two of many applications of air flows utilised in the textile industry.

AJT is a process which takes continuous synthetic multi-filament yarn as the input and converts it into a more voluminous yarn by means of interaction with air flow, without requiring to heat set it. The process involves overfeeding the input yarn to a nozzle to which a high pressure air stream is fed. The interaction between the air and the filaments both inside and outside the nozzle causes the yarn to become voluminous. Although the AJT process has a very wide application range from carpet yarns to sewing threads, it has been mostly known, among the texturing techniques, by its capability of most closely simulating natural fibre yarns by using synthetic fibre yarns. This potential of AJT can make it a substantial alternative to the growing demand for apparel made from natural or mixed spun yarns. Taking all its applications into account, AJT yarns have attained a share of 10% by weight of all textured yarn below 500 dtex, constituting more than 0.6% of world total yarn production in 1988 [22].

INT is another pneumatic process, which creates alternating mingled and open sections along usually false-twist textured synthetic continuous filament yarns in order to keep the constituent filaments together throughout the subsequent textile processes. AJT is one of the texturing techniques, whose aim is to change the input yarn properties radically so as to obtain a very different yarn which can be formed into superior fabrics. In contrast, INT can be generally regarded as an alternative technique to other yarn preparation operations, such true twisting and sizing, prior to fabric forming processes. However in some
cases it is used to produce fabrics with superior quality.

Although AJT and INT are distinctly different in terms of process aims, nozzles designs, which create air flows, overfeed ratio, input and output yarn characteristics and processing conditions, they still are similar because in both operations air flows act on synthetic continuous filaments in order to change their original relative positions in a specified way. This commonality gives the reason to investigate the processes in conjunction. Table 1.1 gives a brief comparison of AJT and INT.

1.1. AIR-JET TEXTURING

Texturing techniques are mechanical or thermo-mechanical processes for further treatment of synthetic filament yarns with the objective of modifying yarn structure in order to enhance the properties of fabrics made from these yarns, such as warmth, handle, moisture absorbency and opacity. While all other texturing techniques are based on altering filaments' form and their relative positions in the yarn after making them amenable to reshaping by heating, AJT is an entirely mechanical process (which does not require thermoplastic filaments for structural modification). Therefore single and blend processing of PES, PP, PA, viscose, acetate and glass fibres is possible, making AJT a very versatile process. In its simplest form, an AJT system consists of a nozzle which brings the yarn into contact with high speed air flows and two sets of rollers which feed the yarn at a faster rate than the take-up speed (Figure 1.1). Drawing and heating zones can be added after the texturing zone.

Texturing is a result of opening, mixing and entangling of the continuous supply of excess length of filament yarns. The excess length is largely determined by the overfeed ratio, therefore overfeed ratio is one of the most crucial
parameters effecting the yarn characteristics. In general, sewing threads are attained with low overfeed, up to 20% approximately [41]; production of spun-like yarns for apparel requires higher overfeed between 20 and 80%, doubling or even quadrupling of linear density is necessary for carpet yarns, where yarn volume is the overriding yarn property. Feeding more than one yarn into the nozzle is one of the commonest and most versatile methods of manufacturing novel yarns. When these supply yarns are of different properties, such as colour, linear density, material, filament/spun yarn, linear density per filament, etc, and/or textured at different overfeed ratio the production range becomes almost limitless. In case of such multi-feed supply yarns, if overfeed is the same for all input yarns the process is termed parallel-end AJT, if it is unequal the process is known as core-effect AJT. Moreover overfeed can be made variable in time, widening the prospects even more; e.g. slub yarn production.

Post-texturing drawing and/or heating also enables the manufacture of various types of yarns; in fact post-texturing drawing is practised in virtually all texturing conditions, especially when yarn stability is of major concern because looser loops can be removed by pulling the yarn immediately after the texturing zone and it is therefore more commonly known as stabilising drawing.

To sum up, AJT processes can be generally categorised as follows:

i) **Single-end AJT**: The basic process in which there is one supply yarn and the overfeed is constant, for example for making fine spun-like yarn for apparel.

ii) **Parallel-end AJT**: more than one supply yarn fed at the same overfeed, used for production of coarser yarns.

iii) **Core-effect AJT**: more than one supply yarn fed at 1-3
different overfeeds; e.g. carpet yarns, yarns for knitting and upholstery, sewing threads.

iv) **Slub yarn production**: overfeed ratio varies with time; e.g. fancy yarns for knitting

v) **Sirospun yarn production**: bulking of spun staple yarns by AJT nozzles

An important aspect of AJT is wetting the input yarn, without which AJT process fails to produce adequately entangled, stable yarns with desired level of loop size and distribution. In the case of dry texturing loops are generally larger and distributed more irregularly along the yarn, resulting in an uneven yarn in appearance and yarn structure. With the addition of a small amount of water from 0.1 to 0.5 litre/h [3] depending on the volume of input yarn and spin finish, texturing process and yarn quality can be enhanced considerably.

As far as the economic aspects of AJT are concerned, AJT has become an economically viable process. This is contrary to the general perception, which prevailed in industry since the advent of the process, that it is a costly process due to the high consumption of compressed air. A comparison of energy consumed for the production of AJT yarns and ringspun yarns with similar count is given by Krenzer [42]. He reported that energy (kW per kg yarn) consumed by Ring Spinning is 2.4 times higher than that by AJT for yarns of 167 dtex and that AJT has become a significant competitor to conventional yarn production methods.

1.1.1. AIR-JET TEXTURED YARNS

Although AJT has a large range of production with diverse appearance and characteristics, AJT yarns can be distinguished by the loops protruding from the yarn surface, when examined closely. Shape, frequency and
overall distribution of loops along the yarn and yarn count determine yarn characteristics, and in turn, its application field. Some of the products made from AJT yarns are listed below:

* apparel, leisurewear, sportswear etc.
* upholstery, automobile upholstery and lining, luggage, tents
* sewing threads
* industrial fabrics; such as high tenacity yarns for automobile tyres, conveyor belts or filters
* carpet yarns

Major advantages of the AJT process can be summarised as follows:

* Having hairy appearance, low glittering, and low extensibility AJT yarns can simulate spun staple yarns.

* AJT yarns are generally bulkier than spun staple yarns of equal fineness, therefore, make lighter fabrics with equal or better covering power [24].

* No snagging can be obtained due to surface characteristics of AJT yarns in which there are protruding loops and arcs from the yarn core.

* Since the AJT process does not require heat-setting, non-thermoplastic yarns can also be texturised.

* Fabrics made from AJT yarns have good abrasion resistance and do not pill [29].

* AJT yarns are very stable; this enables their widespread use as sewing threads and in industrial fabrics.

* Yarns of very wide range can be texturised at relatively
high speeds, typically 400 m/min (Some machine manufacturers have claimed to produce 50-20000 denier yarns at speeds of 1200 m/min [46]). Parallel AJT and slub yarn technique even widen product range further.

* Yarns with small filament linear density can be textured to produce fabrics with low stiffness.

It is important to point out that since other texturing techniques mostly produce yarns with high extensibility, which have very different characteristics from AJT yarns, the latter should be categorised as "spun-like", but not merely "textured yarns".

1.2. INTERMINGLING

INT is one of the cohesion imparting techniques such as twisting and sizing, applied to synthetic filament yarns, usually to false-twist textured yarns. Its aim is to create intermingled-sections of filaments-at-regular-intervals. Main implement of INT (Figure 1.2) is a nozzle generating air flows which create the intermingled sections in the yarn. The nozzle usually has one air inlet which sends the compressed air at 90° with respect to the direction of yarn travelling.

Unlike AJT, considerably smaller overfeed is involved in INT, with a maximum of about 4%. Although negative overfeed, i.e. drawing, has been reported by Iemoto et al [33] the normal practice in the industry is slight overfeed.

Another difference between AJT and INT is that filament wetting is not required for INT process.

The main advantages of INT over other cohesion imparting techniques could be summarised as follows:
* Reduction of yarn preparation costs in comparison to twisting and sizing, which are nine and seven times more expensive than intermingling respectively [1].

* INT nozzles can be easily located on-line either POY (partially orientated yarn) spinning, false-twist texturing, warping or yarn package transfer operations. Therefore they do not require any additional specific machinery. Some possible locations of INT nozzles in various textile processes are given in Figure 1.3 and 1.4.

* Low air consumption per kg of yarn produced. Although the air consumption increases with increasing yarn count, such as carpet yarns, since the nozzle size must increase, cost of compressed air per kg of yarn produced is kept low, making this process an inexpensive yarn cohesion operation.

* Improved fabric quality compared with true twisting. Since there is no real twist in the yarn to compact the yarn, the fabric produced is softer and has better light reflection properties, which is desirable for certain applications.

* Production of large packages of fully cohesive multifilament yarns with very good off-take characteristics is possible, enabling successive layers of yarn to be unwound from the package at high speeds without tension variation or separation of the filaments [1].

* Decreased cost of fabric finishing processes. Since mingled sections mostly open up during and after fabric producing processes due to the tension exerted by usual subsequent operations no extra operation to remove the entanglement in the closed sections is necessary. This
compares favourably with sizing as a cohesion imparting technique, where it is necessary to remove the sizing chemical from the fabric.

INT can be used in many stages of yarn production simply by inserting the nozzle on-line in the existing yarn manufacturing (or preparation) system, such as spinning, texturing or warping. INT can also be utilised in elastic yarn production by feeding more than one yarn under different tensions, which is widely known as co-mingling. This process has proved itself to be an inexpensive alternative to twist covered yarns, 10-40 times cheaper depending on the twist level [35]. Product range vary between 20-2000 dtex [51].

1.3. TERMINOLOGY

AJT is sometimes termed as "cold-air texturing" or "cold-fluid texturing", especially when it is intended to be distinguished from BCF, where steam jet is involved, or "air- bulking". Some AJT yarns are called "spun-like", "spun-look" or "fibre-look" yarns in order to emphasise their resemblance to spun yarns.

INT process is also referred to as "tangling", "tanglelacing", "mingling", "entanglement", "air-mingling" or "interlacing". When more than one input yarn are fed to an INT nozzle then the operation is termed as "co-mingling", "core-mingling" or "air-covering". Closed sections in INT are called as "interlaced point", "tack point", "node", or "nip".

Throughout this thesis the terms "air-jet texturing" and "intermingling" are used, mostly by using their abbreviated forms of AJT and INT and mingled sections in INT yarns are referred as "nips".
1.4. SCOPE OF THE RESEARCH

In the previous sections AJT and INT processes have been briefly described. It has been stated that in both processes, yarn characteristics and cost of the processes are primarily determined by nozzle geometry, therefore purpose designed nozzles are essential to improve the processes qualitatively and economically. Despite the fact, however, that it has been approximately three and four decades since the introduction of INT and AJT respectively, factors governing the operations and, hence, how to control them, still require experiment based trial-and-error research. Therefore definite rules regarding nozzle design have not been clearly established yet. They can be established by investigating inter-block relations given in Figure 1.5. The figure expresses the fact that AJT yarn properties are governed by properties of the air flow, which in turn are determined by nozzle geometry.

The present research has been undertaken in order to improve our understanding of the processes involved and to design or set design rules for more effective industrial nozzles.

After a comprehensive survey of the literature (Chapter 2), this thesis reports an investigation of existing nozzles (Chapter 3) to generate a database of industrial AJT nozzle design and as a starting point for the remaining research. A number of AJT nozzles were selected for detailed analysis. Undisturbed flows created by the nozzles were investigated by means of total pressure measurements, yarn tension measurements and shadowgraphy techniques. Subsequently yarns produced by these nozzles were tested and yarn properties were related to flow properties and nozzle geometry.

Having noted that very similar yarns can be obtained by
distinctly different nozzle designs, it was concluded that fundamental principles underlying AJT mechanism should be investigated in more systematic way in Chapter 4. A generic nozzle with a rectangular cross-section was used to design a number of model nozzles in order to investigate the effect of nozzle geometry on AJT. The performance of the nozzles was assessed by determining the properties of the resulting AJT yarns. In doing so the relation between Box A and C (in Figure 1.5); i.e. effect of nozzle geometry on AJT yarn structure, has become more clear.

Effect of wetting on AJT is investigated with special reference to yarn-to-yarn friction and yarn-to-metal in Chapter 5.

In the subsequent chapter, high speed cinematography was deployed to visualise the AJT process. The basic design with rectangular cross-section developed in Chapter 4 enables us to see inside the main channel through its glass wall and was used in order to investigate the AJT process inside and outside the nozzle by means of high speed photography.

A very small amount of systematic work on intermingling is reported in the literature. In this study, the intermingling performance of several nozzles with rectangular cross-section was investigated. Chapter 7 reports the relation between yarn properties - more specifically nip frequency - and nozzle geometry. Subsequently the process was investigated in general by means of high speed video, high speed-cine photography and yarn tension measurements (Chapter 8).

The final chapter draws the findings of the work on AJT (Chapter 3,4,5,6) and INT (Chapter 7,8), together and general conclusions extracted from the whole work is summarised. Also suggestions for future work is given in
this chapter.

Layout of this work is presented in Figure 1.6.

1.5. TECHNIQUES USED IN THE RESEARCH

Undisturbed Flow Investigations:
a) Total pressure measurements in the free jet
b) Shadowgraphy technique to visualise the flow

Yarn Investigations
a) AJT Yarns
   * Increase in linear density
   * Scanning Electron Microscope (SEM) photography.
   * Tensile tests: instability, tenacity-breakage, elongation
b) INT Yarns
   * Nip frequency counts
   * SEM photography

Process Investigations
a) AJT Process
   * Cylindrical industrial nozzles
   * Nozzle design: Model nozzles with rectangular cross-section for photographic purpose and investigations of effect of nozzle geometry on the process
   * High speed cine photography inside and outside the model nozzles
   * Tension measurements in the stabilising zone
   * Yarn-to-yarn friction and yarn-to-metal friction measurements in investigations of effect of wetting on AJT process
   * Air consumption measurements

b) INT Process
   * High speed video
   * Yarn tension measurements
* Air consumption measurements
* High speed cine photography
<table>
<thead>
<tr>
<th>PROCESS OBJECTIVE</th>
<th>AJT</th>
<th>INT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produce more voluminous and spun-like yarns</td>
<td>Create tangled sections in yarn to impart inter-filament cohesion</td>
<td></td>
</tr>
<tr>
<td>PRESSURE (bar)</td>
<td>6-12</td>
<td>2-7</td>
</tr>
<tr>
<td>OVERFEED (%)</td>
<td>20-500</td>
<td>-1 - +4</td>
</tr>
<tr>
<td>WETTING</td>
<td>Necessary</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>AIR INTRODUCTION WITH RESPECT TO YARN PATH</td>
<td>Coaxial or 45° tilt angle</td>
<td>90° with Respect to Nozzle Axis</td>
</tr>
<tr>
<td>YARN DELIVERY WITH RESPECT TO YARN PATH</td>
<td>90°</td>
<td>Straight</td>
</tr>
</tbody>
</table>

TABLE 1.1 COMPARISON OF AJT AND INT
FIGURE 1.1 Schematic Illustration of Air-jet Texturing Process

AJT YARN

AJT NOZZLE

SUPPLY YARN(S)

process direction

compressed air

V$_1$ = (1.1-5) * V$_2$

V : Yarn transportation speed

stabilising draw zone

water

FIGURE 1.1 Schematic Illustration of Air-jet Texturing Process
V : Yarn transportation speed

\[ V_1 = (1-1.05) \times V_2 \]

PROCESS DIRECTION

OUTPUT YARN : INT yarn

INTERMINGLING NOZZLE

down

air-in

INPUT YARN (e.g. false twist textured yarn)

FIGURE 1.2 Schematic Illustration of Intermingling Process
FIGURE 1.3  Possible Deployment of INT Nozzles in False-Twist Texturing
FIGURE 1.4 Deployment of INT Nozzles in Various Processes
FIGURE 1.5 Interrelation between Nozzle Geometry, Air Flow Properties and AJT/INT Yarn Properties
FIGURE 1.6 Layout of the Thesis
Various aspects of AJT and INT processes have been reviewed by several researchers [18, 19, 30, 31 and 64]. In this chapter, an up-to-date survey of these processes is given with reference to the process mechanism, nozzle development, aerodynamics of the nozzles and associated machinery.

2.1. AIR-JET TEXTURING (AJT)

This section describes AJT in general in Section 2.1.1, AJT machinery in Section 2.1.2., AJT nozzles in Section 2.1.3, process mechanisms proposed for AJT, , in Section 2.1.4, aerodynamics of the process in Section 2.1.5, effect of wetting filaments on the process in Section 2.1.6 and finally gives a brief discussion in Section 2.1.7.

2.1.1. AJT GENERAL

AJT was introduced as a texturing method with the aim of imitating spun yarns in terms of bulk, handle, fabric covering factor and warmth. In time, the yarn quality and product range have seen considerable improvements. For instance, in the early years of AJT, the yarns required to be twisted after being textured in order to stabilise loosely grouped filaments, but in the modern AJT process such stabilisation is not required owing to the better entanglement of the filaments by means of drawing, which is considerably less costly than twisting. However the main factor preventing an increase of the market share of AJT has always been the production cost rather than yarn quality. Economising the process can be achieved in two ways: firstly, by reducing the compressed air consumption or by increasing yarn production speeds. Since the introduction of AJT four decades ago, air consumption has
been reduced typically by a factor of 3. Increase in texturing speed by a factor of 25 has also been achieved. There are AJT machines available running at 1200 m/min [45]. However the speed of the process is restricted by the processing conditions, rather than the machine capabilities.

At the early stages of the process, mostly pre-twisted yarns were used as the input yarn. If, however, the yarn had a smooth surface, such as Nylon, then twisting was not necessary [12]. Or, alternatively, yarns with as small producer twist as 3 tpi, could be used as the input yarn, but only after being coated with a water-sensitive size and after texturing, being treated in a warm humid atmosphere [13]. Improvements in the process have made it possible to use untwisted yarns as the input yarn, eliminating cost of twisting or sizing. Spun yarns have also been air-jet textured. Modern AJT can use pre-twisted, untwisted or spun staple yarns. Additionally, fibre industry has begun to make low dpf synthetic yarns which can easily be formed into loops, making them more suitable for AJT. Another advantage of using low dpf yarns is that when they are fed to the texturing nozzle some filaments are broken by the air creating free fibre ends, which simulate natural spun yarns [32]. The availability of such a wide range of supply yarns widens production range considerably.

2.1.2. AJT MACHINERY

At the early stages of AJT texturing trials used to be performed on conventional winding or spinning machines with some modifications. However availability of a wide range of input yarns and the demand for various types of yarns in modern yarn technology requires purpose-built machines which facilitate yarns to be pre-processed and which have equipment to enhance the textured yarn, by means of the following features:
* Drawing unit in the case of using POY yarns as the input yarn in order to acquire the final count.
* Pre-texturing heating unit for drawing POY yarns
* Wetting unit (Some nozzles are available with integrated wetting facilities.)
* Variable speed feeder for slub yarn production
* Stabilising drawing unit since majority of AJT yarns needs to be drawn after the nozzle in order to remove loose filaments and large loops.
* Post-texturing heating unit

Due to the essentials of modern texturing outlined above, AJT machine manufacturers have concentrated on special requirements of texturing with reference to increased yarn quality and variety, leaving nozzle development to the two major nozzle manufacturer; namely, DuPont of the U.S.A. and Heberlein of Switzerland. Some of the main AJT machine manufacturers are Guidici, RPR of Italy, Barmag, Stahle, Dietze & Schell and Eltex of Germany and Rieter-Scragg and Extrusion Systems of the U.K., Enterprise and H.J.Theiler of U.S.A. and ICBT of France.

It is also appropriate to record recent ventures of AJT to be combined with fabric making processes. In ITMA 91, Murata of Japan displayed a weaving machine integrated with an AJT unit which serves as the weft provider.

2.1.3. AJT NOZZLES

In this section a brief account of AJT nozzle development is presented. Further surveys of AJT nozzles are given by Demir et al [19, 20].

An AJT nozzle basically consists of a channel through which the yarn is fed and a passage to the main channel to introduce the compressed air. There are two main types of air introduction to the filaments:
i) through a number of holes (usually one, two or three) opening to the main channel, which meet(s) the filaments at an angle (usually 45°).

ii) through a chamber, which meets the filaments spatially

Modern AJT nozzles are of two types, according to the above feature. The first type, where the air is introduced through a number of hole(s), is cylindrical AJT nozzles (Figure 2.1) and the second type, where air introduction is spatial, is converging-diverging nozzles (Figure 2.2a-d, Figure 4a-b, Figure 2.9).

Today's world market of AJT nozzles has been dominated by products of two major nozzle manufacturer companies, E.I. DuPont de Nemours and Co. and Heberlein Maschinenfabrik A.G. The former had the first AJT nozzle patent in 1952 and led the market for almost two decades until Heberlein introduced its StandardCore HemaJet in late 1970's. Heberlein is mostly known for its cylindrical nozzles (Figure 2.1) while Du Pont's nozzles, whose trade name is Taslan, are of converging-diverging type.

As discussed earlier, AJT was initiated with the major objective of imparting bulk to synthetic continuous filaments. In the very first trials it was considered that this could be achieved by passing the yarn through a turbulent stream. The element of turbulence in the process was given so much emphasis that it was even stated that:

"it is only necessary for the yarn to be passed through a zone of sufficient turbulence for a sufficient distance to separate the filaments and form them into the described convolutions. The yarn need not be passed through an air jet or nozzle of the types described, but can be passed through a turbulent stream, however formed. Likewise, air need not be used as the turbulent medium; other gases or liquids can be used. Piezoelectric or magnetostrictive transducers might be employed to create turbulence in the treatment zone with an electrostatic field, but the fluid jet method is so inexpensive and easy to install." [10].
Due to this comprehension of the process, therefore, trials were mostly aimed at designing nozzles which could create turbulence.

The first nozzle, patented in 1952, simply consisted of a tube through which the yarn travelled and an air introduction pipe connected to the yarn tube at an angle (Figure 2.3) [10] (Interestingly, this simple approach was much later re-adopted by Heberlein and led to the design of cylindrical AJT nozzles.). Although it was reported to be adequate to accomplish effective yarn treatment, in the same patent two further designs were introduced: Taslan VII (Figure 2.4a) and Taslan VIII (Figure 2.4b). The former can automatically thread the yarn by means of a yarn guide element subsequently termed as the yarn feed needle. Another advantage of this design is that the distance between the yarn guide and the channel. Taslan VIII, still being adjustable, has a screw element with the aim of giving the air a swirling motion. Another feature of this nozzle is a flat plate, called baffle, fixed at the exit side of the nozzle, whose function is to break up and deflect the jetted stream of air. The baffle was reported to be optional but was used extensively in later designs. Average throughput speed for 300 denier PET was about 35 m/min. It should also be recorded that the yarn was required to be twisted after texturing, because the filaments were only loosely entangled and under tension bulkiness could be removed.

Necessity to use pre-twisted yarn, of post-twisting and low texturing speeds were the basic disadvantages of the early nozzle designs. The nozzle that succeeded these nozzles was Taslan IX, which was the first and last of its kind with its unique inclined yarn feed needle (Figure 2.2a).

In this design, turbulence (i.e, "requisite to convolution of the filaments", [11] is generated by means of inserting
an obstacle in the air stream. The obstacle is integral with the yarn tube.

Later on, in 1960, Taslan X was developed, returning to the original construction of straight yarn path through the nozzle (Figure 2.2b). The main improvement in this design was that there is only one adjustment necessary, keeping the rest of the geometrical parameters of the nozzle constant. Therefore, nozzle to nozzle inconsistency experienced in early designs has reduced. It was also claimed that the necessity of pre and/or post twisting was mostly eliminated. Texturing speeds as high as 90 m/min were achieved [13].

In 1969 Taslan XI (Figure 2.2c) succeeded the aforementioned nozzle. It represents the first of the modern converging-diverging AJT nozzles of this type. Another important feature of Taslan XI is its one-sided air introduction to the main channel, which creates asymmetric flow. Average texturing speed was increased up to 175 m/min. Taslan XI is also the first nozzle which can use staple yarn as the input yarn [14]. However variation in texturing performance from nozzle to nozzle, which was attributed to fixed baffle against the primary flow, remained to be a problem. Hence another nozzle, called Taslan XIV, was designed with a baffle which could move freely towards an equilibrium position responsive to variations in the force exerted by the yarn and fluid [15]. This was argued to be enabling more uniform texturing. Apart from this feature, the new nozzle; i.e. Taslan XIV (Figure 2.2d), has no significant difference in its internal structure from Taslan XI.

With the introduction of Taslan XV nozzle (not illustrated), the product range was enlarged further. While Taslan XIV nozzles are designed for yarns finer than 400 denier and single or parallel texturing, Taslan XV nozzles
are suitable for heavier yarns, by means of core and effect texturing [59]. The latest model of Du Pont's nozzle is Taslan XX (Figure 2.9), which essentially has the same structure as Taslan XI, Taslan XIV and Taslan XV but with considerably different dimensions, which results in substantial change in the flow characteristics.

Contribution of Heberlein in AJT nozzle begins with introduction of StandardCore HemaJet [61] in 1977 (Figure 2.5). This nozzle has a cylindrical main channel, which is a common feature of most Heberlein nozzles and three staggered air inlet holes. The successive Heberlein nozzles have kept this basic configuration, but had either one or three inlet holes and various channel diameters, depending on the yarn linear density to be textured. Their exit profile, a quarter of circle with 6.5 mm radius, is also different from that of StandardCore, whose radius is 3.0 mm. Heberlein has achieved considerable reductions in air consumption by designing aerodynamically efficient nozzles.

Cylindrical HemaJets are suitable for yarns finer than 200 denier, whereas the range of DuPont nozzles covers coarser yarns due to their ability to run at considerably high overfeed ratios [45]. However Heberlein has recently introduced HemaJet E0-52 (Figure 2.6), which is claimed to attain up to 500% overfeed, hence suitable for producing heavy yarns [28]. Cylindrical HemaJets also have the advantage of having no adjustable part and this eliminates differences in nozzle performance from one to another; but this also means to limit the yarn range that can be produced by a particular nozzle.

It is also important to record contributions by Enterprise Machine and Development Co. in 1976 by their EMAD nozzle, which is very similar to modern Taslan nozzles, with its convergent-divergent channel structure (Figure 2.7).
In addition to the nozzle development by industry, summarised above, researchers at Loughborough University of Technology [2, 19] have also worked on design of cylindrical AJT nozzles, especially with reference to lower air consumption.

The fundamental design strategy has been the creation of a high speed primary flow by reducing pressure losses as much as possible. To achieve this, the following geometry effects were determined accordingly (see Figure 2.1 for main features of a cylindrical AJT nozzle):

i) Ratio of cross-sectional area of the main channel to that of inlet hole(s) made smaller but very close to unity in order to avoid sudden enlargement of the incoming flow(s), hence, enabling conversion of the pressure energy into kinetic energy effectively.

ii) Primary flow channel: made divergent to be able to accelerate the supersonic flow.

iii) Length of the primary channel: increased to produce further acceleration

iv) The incoming flow(s) directed more to the primary flow side, either by tilting the inlet holes in the process direction or by reducing cross-sectional area of the secondary flow section at a step around the flow division zone (Figure 2.8).

A second design strategy was to promote asymmetry and swirl inside the nozzle, either by using the inlet holes of different diameters or by placing them in a staggered arrangement.
2.1.4. PREVIOUS RESEARCH INTO TEXTURING MECHANISM

Although AJT was introduced into the textile industry in the 1950's, the loop formation phenomenon is still not very well understood.

Wray's study

The behaviour of filaments during the "air-bulking" process was experimentally researched by Wray [65] with a view to understanding the bulked yarn's geometrical structure and physical properties. An introductory hypothesis of the mechanism of the bulking phenomenon was put forward and tested by observing the processing of yarn under various manufacturing conditions and by investigating the yarn structure. The yarn process observation techniques used were tracer filament technique, together with high speed-cine photography and flash photography techniques. Tests were carried out with experimental versions of Taslan Type IX nozzles, through which the compressed air was introduced and the parent yarn was fed by a feed needle at an angle to the air path (Figure 2.2a). However in later designs, e.g. Taslan X, XI, XIV, XV and XX, the input yarn follows a straight path axial through the nozzle (Figure 2.2c-d and Figure 2.9); so the flow created by Taslan Type IX nozzle and, therefore, the flow-filament interaction are quite different. The hypothesis of mechanism of AJT was summed up as follows:

"The pre-twisted yarn is fed into the venturi where it is temporarily untwisted by a complex vortex action so as to affect a loosening of the whole filament bundle."

"Individual filaments can snarl into loops when this untwisting occurs because they had been heat-set while the yarn was in its twisted state. However, the studies on tracer filaments have shown that when a loop forms in a particular filament some tensioning occurs in that part of the filament following it, and the interfilament friction effect gives rise to groups of U-shaped waves in neighbouring filaments. The U-shaped waves are also
assisted to form by bending of the yarn as it leaves the needle, causing a buckling of the filaments on the inside of the bend. These wave-like convolutions would in turn form loops due to the filament torsional energy and if no overfeed were provided these would be removed (or perhaps the filaments might even be broken). If on the other hand, overfeed is provided, these loops are not removed and can remain in the yarn in this form or in some modification of it."[65]

The "vortex action" mentioned, which played a significant role in Wray's hypothesis, was said to be caused by the presence of feed needle which bifurcates the flow, therefore makes the air highly turbulent. Again it is important to point out that there is no feed needle in modern texturing nozzles to guide the parent yarn into the air flow inside the main channel.

Sen's study
The mechanism of the air jet "bulking" was investigated by Sen [56], by using a scaled-up model of Taslan IX nozzle. High-speed cine photographs of the process in the perspex model showed that the pre-twisted parent yarn is untwisted and opened within the nozzle and then the actual bulking occurs immediately outside the nozzle, but not inside the nozzle as Wray argued in his earlier work. Sen stated that:

"The twist-free and overfed filaments snarl into a looped and entangled configuration and after leaving the nozzle, the previous twist reasserts itself and locks the already formed filament loops into position." [56]

Measurements of Reynolds Number based on the throat diameter of the nozzle under industrial operating conditions showed that it is not possible that any periodic shedding of vortices occurs in the wake of a cylindrical body, disproving Wray's hypothesis. Therefore Sen concluded that any hypothesis based on untwisting of the pre-twisted parent yarn within the nozzle due to a vortex action seems to be far from being valid. Instead he explained the phenomenon as follows:
"The highly turbulent air flow blows the overfed parent yarn out of the jet, and this causes the portion of yarn immediately following it (i.e. that just entering the jet) to be in high tension. As the variation in mean flow velocities is high, this occurrence continues intermittently. Thus there is an intermittent fluctuation of tension in the overfed yarn entering the jet. At the exit of the jet the yarn changes its path abruptly as it is withdrawn from the jet at a right angle to the jet axis. Due to the momentum of the blown out yarn, the end of yarn being withdrawn from the jet exit is subjected to an alternating force at right angles to its axis (i.e. an alternating torque). As a result of this a false-twisting effect is created such that it untwists the portion of the parent yarn inside the jet and thus its structure is opened. Then when the opened overfed yarn is blown out of the jet the extra available filament lengths snarl into a looped and entangled state at the jet exit under the extremely violent (turbulent) nature of the flow" [56].

Clearly Sen stressed the importance of right-angled deflection of yarn at the exit plane in the texturing phenomena and of turbulence.

**Sivakumar's study**

A theoretical analysis of the role of shock waves in AJT with Taslan IX and X nozzles was given by Sivakumar [57]. A postulation for the mechanism of yarn bulking was formed as follows:

"For commercially operating air pressures, there exist compression shock barriers (shock waves) in the jet... These compression shock waves form a "pressure barrier" at the place of their occurrence."

He continued that the highly pretwisted yarn is retarded by the "pressure barrier" and causes the yarn tension to decrease. This results in filaments snarling. The snarled filament are entangled by turbulence and stay that way because of interfilament friction as well as twist imparted after texturing.
**Price's study**

Price's explanation of texturing [49] is based on two main points: Presence of turbulence within the nozzle and its vigorous action on filaments.

"The turbulence from compressed air is like a tornado in the confined area where yarn and air meet, and the bundle is whipped around so violently individual filaments are separated from the bundle and exit as non ringlike loops. Since the jets have a torque stream from interference, baffles or angle of air entry, the incremental twist at the exit end relieves the stress of the unstable loops by turning them into ringlike kinks or crunodes. The trick in the operation is to collapse the remainder of the bundle around this loop before it can pull out since it is the source of bulk in the finished yarn." [49].

This description stress the interactions between yarn and a turbulent air stream and limits the place where texturing takes place to the area of the flow where turbulence is high.

**Bock et al**

Taslan type texturing nozzles, which succeeded the Taslan IX nozzle, were investigated experimentally in detail by Bock [6-9] by using actual nozzles as well as flat transparent models with rectangular cross-section. He took numerous Schlieren photographs of both undisturbed air flow and the actual texturing process and put forward an hypothesis of the loop formation mechanism for untwisted parent yarn, based on shock waves as follows:

"They (the filaments) are condensed into a compact yarn bundle at a discrete point, so called "interlacing point". Right-angled draw off after the nozzle produces an arcing of the filaments at that point to a varying degree, resulting in the production of loop in the compact yarn. The actual texturing process therefore includes the deflection of the opened mass of filaments at right angles, as a result of which filaments are intermingled and finally interlaced into a compact yarn above the point of deflection. This means that extra length of filaments resulting from the overfeed have to be taken up between the outlet of the duct, where the yarn is opened, and the
interlacing point." [8-9].

To establish a correlation between the flow and the loop formation process, the positions of the thread leaving the nozzle and the "interlacing point" were recorded with high speed photographs (Figure 2.10).

"About 70% to the interlacing points lie in the jet or at the edge of it. There is a clear tendency for the interlacing point to materialise at the boundary between the zones of different density and velocity, either at the edge of the jet or at the edge of the boundary of surfaces visible in the schlieren pictures, especially where two lines of the Schlieren picture meet at the edge, the points lie very close together. Shock waves produced in the free flow behind the nozzle evidently exert a force on the filaments. A deflection of a portion of the filaments in close groups developed after passing through a shock wave." [8-9].

Acar's study

In experimental work of Acar [2] both centre-line velocity measurements and shadowgraphs of some cylindrical AJT nozzles proved that shock waves are not as strong as those of Taslan nozzles, furthermore, during texturing they become even weaker due to the presence of the filament yarn. This and the fact that the textured yarns made by different cylindrical nozzles with varying shock wave strengths showed no substantial difference in quality, led Acar [2] to conclude that shock waves have no significant role in loop formation, so the hypothesis based on shock waves may not be relevant.

Acar also investigated filament behaviour during texturing by using high-speed still and cine photography. They clearly showed that the loops are being formed as the filaments emerge from the nozzle and they occupy the lower half of the nozzle outlet. Then he suggested that longitudinal displacement of the filaments relative to each other is caused by the variation in the local velocities since the forces acting on the filaments are determined by
local velocities. As the motion of filaments in the direction of the nozzle axis is explained so, the movement at the other axes; i.e. across the nozzle is attributed to turbulence forces.

In a further experiment, the yarn was not taken up by the delivery rollers at right angle but it emerged from the nozzle without changing its natural path; in this case deflection in the yarn path owing to the forces created by shock waves or any other forces was not observed.

Evaluating the experimental data with the aid of theory, Acar suggested a loop formation mechanism of untwisted parent yarns with a very analytical approach as follows:

"At any instant some of the filaments will be moving at faster speeds than others due to the relatively greater fluid forces acting on them. The free excess lengths provided by overfeeding the filaments enable the faster moving filaments to slip and be displaced longitudinally with respect to the relatively slower moving filaments. The amount of these longitudinal displacement is affected by local drag and frictional forces instantaneously acting on the filaments and also by the overfeed ratio." [2].

It should be noted that in Acar’s investigations untwisted supply yarns were used.

**Sengupta et al**

Sengupta et al [58] gave loop formation mechanism of AJT of spun staple yarns as follows, emphasising untwisting action of yarn inside the nozzle:

"In air-jet texturing, when filaments or spun yarns are subjected to the action of the air jet inside the nozzles, fibers move relative to each other. They form loops and arcs due to loosening of the restraining force through opening up of the twist and simultaneous availability of excess length through overfeed. The integrity of the strand is subsequently maintained by the reassertion of ply twist." [58]

The above description is related to AJT of spun filament
yarn only, which constitutes only a small fraction of normal practise.

2.1.5. DISCUSSIONS ON PREVIOUS WORKS ON AJT MECHANISM

Hitherto given explanations for mechanism of AJT process are limited to certain nozzle designs and process parameters, such as yarn types. In this section the limitations of the proposed mechanisms are reviewed:

Wray's [65] explanations of motion of filaments in AJT process are limited to those with pre-twisted parent yarns as the supply yarn and to Taslan IX type nozzles because he described an untwisting of the yarn and also in the turbulent air flow created specifically by the nozzle. Wray's theory is specific to AJT with untwisted parent yarns and Taslan IX and not sufficiently general to explain modern AJT process. It should be noted that in Taslan IX the supply yarn is fed through a needle opening to the main channel at an angle, whereas in the case of latest models of Taslan nozzles the yarn follows a straight path.

As Wray's hypothesis, Sen [56] and Sivakumar's [57] explanation of AJT also lack universality since it is limited to the use of pretwisted supply yarn and Taslan type nozzles.

As far as Price's explanation [49] is concerned, it overemphasised the interaction between filaments and the turbulent air stream. This limits the place where texturing takes place to the area of the flow where turbulence is high. Subsequently, however, it has been found by Acar [2] and also visualised in Chapter 6 that, in the case of cylindrical nozzles texturing does not occur in the section of main channel where the incoming air jet creates highly turbulent flow, but around the exit area, where the flow is much more settled and less turbulent. Similarly Bock et al
visualised texturing to take place outside the nozzle, which is a converging-diverging type nozzle [7-9].

With respect to Bock's studies [6-9], they are based on vast amounts of experimental results and revealed many aspects of the texturing phenomenon. However his hypothesis which attributes loop formation to the presence of shock waves in the outlet stream may not be universally valid, because subsequently Hemajet nozzles with very weak shock waves have also been found to be capable of texturing successfully by Acar [2] and Demir [19].

Acar's explanation [2] addresses the modern AJT process since in the investigations untwisted supply yarn was used. It should also be noted that filament motion given by Acar does not specify a certain type of flow created by a certain type of nozzle. However his explanations of the AJT process need more clarification with reference to air-filament interaction inside the nozzle.

2.1.6. WETTING IN AJT

The mechanism explaining how wetting improves AJT process has been investigated by several researchers, namely Fischer [25], Bock [7], Acar [2,3], Demir [19] and Kothari et al [39, 40].

a) Effect of wetting on air flows
Fischer basically attributed the improvement in the process due to wetting to changes in the air flow [25]. He stated that with the introduction of water a condensation shock is created and the shock is surmised to be assisting the interlacing of the filaments; i.e. texturing.

Bock et al [7] also studied the effects of presence of water in the flow created by Taslan nozzles. They stated, similar to Fischer, that if moist air is passed through a
de Laval nozzle condensation can occur in the jet as a result of the rapid temperature fall. A condensation pulse will occur after the narrowest cross-section of the jet in the case of spontaneous condensation which leads to a sudden increase in pressure and a decrease in the velocity. They assumed that the filaments are disturbed and diverted by the pressure increase caused by the pulse. This explanation is very much in line with their general explanation of air-jet texturing phenomena, which is basically about filaments being forced to be diverted by a field of pressure gradient (see section 2.1.4 for Bock et al's [7-8] explanation for texturing).

Demir's [19] experiments looked at the effect of water droplets in the flow the shock waves of AJT nozzles and found, by using shadowgraphy, no noticeable difference between air jets with and without water.

Effect of water on the air jet was also investigated by Acar [2,3] and he theoretically predicted by using the principles of two-phase flow that water droplets decelerates the flow in the order of 2-5%, depending on the amount of water used during texturing and the supply air pressure. Acar concluded that this small reduction in the velocity would have an adverse effect on the flow and cannot possibly explain the effect of filament wetting on the texturing process through a dramatic change in the flow properties as Fischer and Bock suggested. Therefore he deduced that wetting mechanism must be due to a change in the frictional behaviour of the filaments themselves.

b) Effect of wetting on frictional behaviour of filaments
Acar [2] reported, after yarn tension measurements at several points of the yarn path, that wetting reduces filament-to-metal friction and possibly filament-to-filament friction. Consequently, he concluded that reduced interfilament friction assists the relative motion of the
filaments to slide over each other more easily, resulting in enhanced loop formation. Investigations of Demir [19] also arrived at similar conclusions.

Subsequent research was carried out by Kothari et al [39, 40] by using various supply yarns with different interfilament friction properties. They tested two supply yarns one of which had the same friction level under dry condition as the other under wet condition. They found that the structure of the two yarns produced under these conditions were not similar but the yarn which textured under wet conditions produced better textured yarn. They also tested yarns, one with smaller interfilament friction at dry condition and another higher interfilament friction wet condition. The yarn with low interfilament friction had been expected to give better texturing but the reverse was found. From these findings they deduced that interfilament friction does not explain why wetting improves texturing. They concluded, in this case, that the way that wetting improves the texturing process must be through a change in the air flow. They speculated that the moisture within the jet affects the fluid dynamics in the turbulent zone in the jet, but this conclusion has yet to be proven.

Demir [19] measured coefficient of dynamic friction between yarn and metal in the cases of dry and wet yarns and found that wetting reduces yarn-to-metal friction. He also found that varying the yarn-to-solid friction between yarn and yarn guide prior to the nozzle does not significantly affect texturability of the yarn, after trying several yarn guides with different surface roughness.

2.1.7. AERODYNAMICS OF AIR FLOWS CREATED BY AJT NOZZLES

Investigation of air flows created by the AJT nozzles is of considerable interest as texturing is a result of air acting on filaments. Ideally, the air flow and filaments
should be taken into consideration concurrently in order to investigate the actual process since the air and filaments have an effect on each other. However it is currently not possible to measure the air flows when the filaments are present, therefore, most of the work reported on aerodynamics has neglected presence of yarn in the nozzle.

Sivakumar [57] conducted theoretical research into flow properties of Taslan IX and X. Assuming that the working section of the feed needle is a converging-diverging nozzle he used one-dimensional isentropic flow for perfect gases to calculate flow properties and the location and strength of shock waves produced by the corresponding converging-diverging nozzle.

Subsequently Bock et al (Ref.5-8) investigated flows created by Taslan XV nozzle by means of schlieren photography technique. In the photographs of the free jet there are periodic dark and bright area, which indicate density changes. In order to quantify the changes in the flow the dynamic pressure along the jet axis was measured. It was found that in bright areas the flow accelerates and in dark areas it decelerates. The alternating acceleration and deceleration in the flow was given to be the reason for yarns to be deflected and, hence, loop formation as discussed in detail in Section 2.1.4).

Acar [2], carried out both theoretical and experimental work on Cylindrical HemaJet type AJT nozzles by means of shadowgraphy, air velocity and static pressure measurements. He used both full-size and scaled-up models. Flow investigations led to the generalisation that the air flow created by these particular types of nozzles are supersonic, turbulent flows with non-uniform and asymmetric velocity distributions. This conclusion is mostly in agreement with that of Bock, suggesting that these are characteristics common to most, if not all texturing
nozzles.

Acar also developed a mathematical model based on one-dimensional compressible flow theory for predicting flow properties.

In an extension to Acar’s research, Demir [19] investigated the effects of geometrical parameters on flow properties. By changing one parameter at a time, he investigated the air flow experimentally and concluded that high-speed flow with minimum air consumption can be obtained by having a long and diverging primary flow channel, avoiding sudden area enlargements in the flow between the inlet holes and the main channel. The fact that a diverging passage accelerates a supersonic flow had already been theoretically shown and experimentally applied to cylindrical type HemaJet nozzles by Acar [2] and a nozzle with diverging main channel had been made and tested.

2.1.8. DISCUSSIONS ON PREVIOUS WORKS ON AJT

AJT was developed by industrial initiatives and attempts to reveal the process mechanism have been made later. Clearly theory is coming behind industrial practice. Proposed texturing mechanisms have been limited to explaining the existing conditions and need significant reconsideration with changes in the process parameters and nozzle geometry. The mechanisms proposed to-date are not universally valid. For example, the process mechanisms suggested for the pre-twisted yarns by pioneering researchers (Wray [65] and Sen [56]) cannot explain modern AJT, which predominantly uses untwisted input yarn.

These approaches have led workers to identify one feature of air flow as the requisite of the process and to guide the design of nozzles. An example of this approach is the development of the early Taslan nozzles, in whose patents
firstly turbulence was stated to be the requisite for texturing and then nozzles were designed accordingly. A similar approach can be seen in attempts of Demir and Acar, in which high speed air-jets were considered to be necessary for texturing and then nozzles were designed accordingly. The appearance of nozzles which satisfy these requisites but still do not texture adequately suggests that texturing phenomenon is too complicated to be explained by singling out one flow feature.

Consequently, it would be more helpful to work towards a comprehensive explanation of the texturing mechanism, otherwise nozzle design will remain a matter of trial and error, which is costly. In this research AJT process has been investigated with the aim to bring about an improved understanding of the texturing phenomenon. The nozzles in this research have been primarily designated to allow the process to be investigated most easily, rather than as alternatives to industrial nozzles.

Previous investigations of the effects of wetting also give conflicting explanations. As discussed above Acar [2,3] attributes the improvement owing to the wetting to interfiament friction whereas Kothari et al [39, 40] stresses the changes in the air flows. A further investigation, especially on frictional behaviour of the yarn, has been carried out in an attempt to improve understanding of the phenomenon (Chapter 6).

It should also be added that the necessary conditions for texturing stated by Acar [2] and Bock et al [7] are not universal. These conditions (namely a turbulent flow with non-uniform, asymmetric and supersonic velocity) are also necessary to be reviewed because there have been cases where, for example, texturing is possible with air flows with symmetric velocity profile [19].
**2.2. INTERMINGLE (INT)**

This section describes INT in general in Sec.2.2.1, INT machinery in Sec.2.2.2., INT nozzles in Sec.2.2.3, process mechanisms proposed for INT in Sec.2.2.4, aerodynamics of the process in 2.2.5 and finally a brief discussion is presented in Sec.2.2.6.

**2.2.1. INT GENERAL**

INT was initiated later than AJT (the earliest patent was taken out in 1961). Since it is a process which is usually integrated with yarn production/preparation processes, its evolution is mostly governed by them. Therefore process developments have been concentrated on aspects that are independent of the main production process, for example air consumption, rather than process speed or input yarn properties. Additionally the very purpose of INT, that it creates only temporary effect on the yarn, requires INT to comply with certain necessities; for example, filament breakage is not acceptable in INT whereas in AJT such yarns can be considered as new type of yarn.

**2.2.2. INT MACHINERY**

As pointed out earlier INT does not require separate machinery except in the case of co-mingling of yarns that are distinctly different from each other (e.g. staple yarn and elastane) where a machine needs to be able to feed the yarns at necessary different rates. Among the major manufacturers there are Fadis and Guidici of Italy, ICBT of France and Eltex of Germany [47].

**2.2.3. INDUSTRIAL INT NOZZLES**

Unlike the domination of AJT nozzle market by only a few specialist companies, INT nozzles have been developed by
many more manufacturers with contributions from a variety of textile companies, which do not specialise in nozzle making. The relatively simple structure of INT nozzles compared with AJT nozzles enables yarn producers to design and make their own nozzles according to their needs. Many nozzles are not offered to the market, but used in-house and, therefore, little is known about their evolution.

Basic requirements of an INT nozzle are a channel for the yarn to travel through and air inlet(s) opening to the channel, usually at right angle. Geometry of the main channel (cross-sectional and lengthwise) influences flow characteristics, and hence, yarn quality. It also governs noise production, which is an important factor in the industry, as well as compressed air consumption, which constitutes the main cost of the process. A classification of INT nozzles according to nozzle geometry is given in Figure 2.11 [18]. One of the important geometrical parameters is the cross-sectional shape of the main channel. Joint research by Fibreguide and the Shirley Institute, U.K., revealed that nozzles with triangular cross-section are more efficient than those with circular ones in terms of air requirement at lower pressure, lower noise level, less filament damage, higher nip frequency and more consistent nips. Triangular nozzles give an air flow pattern creating very high turbulence at low pressure, which results in high frequency regular nip counts in the yarn [1, 23]. As a result Fibreguide, which is one of main nozzle suppliers, changed its circular design into triangular one in 1984.

An important aspect of INT nozzles is the threading of the yarn into the main channel. As the speed of yarn production/preparation processes has increased the threading time needs to be kept to a minimum especially in the case of high speed operations such as spinning. This problem has been solved by designing nozzles with a narrow.
slit in the main channel, which enables the threading of the yarn without stopping the machine and the process. In this respect INT nozzles are divided into two groups: open and closed nozzles. The slitted construction results in higher air consumption due to escaping air and increased noise. As discussed in developments of AJT nozzles, lowering the supply air pressure reduces the compressed air consumption. Furthermore high pressure results in filament damage and/or yarn breakages, so designing nozzles which run at low pressure is of main concern. In industry the current practice is currently between 2-6 bar.

2.2.4. PREVIOUS RESEARCH INTO INT MECHANISM

The first patent of an INT nozzle was acquired by DuPont in 1961 [33]. Since then several researchers have dealt with the mechanism of the mingling process. The point mostly referred to, directly or indirectly, is the presence of a pair of vortices rotating in opposite directions across the channel, which are created by division of the incoming flow inside the nozzle, whose existence is deduced from flow visualisation of the undisturbed flow [36] or observations of yarn motion across the main channel [34, 63]. The importance of the vortices is expressed by Jammers [35] as "The heart of the process is an air mingling jet with counterrotating vortices."

A brief review of this research work is given below:

WEINSDORFER et al

Filament behaviour in INT was investigated [63] by photographic means in an industrial nozzle, whose threading plate was replaced with a glass one. The compressed air was introduced from underneath the nozzle. Entanglement of filaments was described as follows:

"Entanglement is a local twisting of some of the filaments. Several filaments wrap themselves around other filaments
like a false twist. The interlacing effect moves upwards and downwards until it meets resistance or until the interlacing strength has diminished so much that the twist transmission comes to a standstill. At this point partially twisted filaments stick up, an interlace node is formed. As the yarn is being transported constantly in the direction of its axis the top interlace node will pass the air inlet without the air stream having much effect. The thread remains closed. Only after the interlaced node has passed the air inlet can the air stream again open the following section of yarn."

The interlacing mechanism suggested by Weinsdorfer et al was finalised as follows:

"The sharp air stream tears the filaments apart, opening the thread like a bubble. If such an opened section is in front of the air inlet, then the individual filaments are caught up by the stream and accelerated. The effect differs depending on the position of the filament. A filament in the middle of the yarn channel is accelerated most of all. Filaments which are to the side of the primary stream are caught up in the weaker backstreams. Thus two whirl sections form. These twist the groups of filaments together. The two whirl sections thereby give each respective group of filaments an opposite twist. A kind of plaiting effect results [63]."

JIAN et al

A cylindrical transparent INT nozzle is used for investigation of behaviour of the filament by photographic means from two normal angles simultaneously. Additionally yarn motion is observed from tracks created by the filaments on nozzle surface coated by a special mixture of oil. It has been stated that the filaments are rotating in opposite directions under the effect of two opposite flows. Cross-sectional views of the subflows inside the nozzle used by Jian et al is shown in Figure 2.12, which are resulted from bifurcation of the incoming jet [36]. The division of the incoming jet is hypothesized to give the velocity distribution across the main channel as depicted in Figure 2.13. Filaments are said to rotate according to their location in the velocity field. If a filament or a bundle of filaments is at Point M, for instance, it is
under an effect of a force pair, which results in twisting of the filament(s). If the filament is at Point N, it is drawn downwards. As a result of these movements filaments interlace each other. Jian continues as follows:

"This process continues until a single filament or a bundle stopped to depart from the interlacing knot which is formed in the upstream zone when it passes through the entrance of compressed air. This process of interlacing phenomena will be repeated so that a periodic interlacing knots is formed." [36].

IEMOTO et al
Yarn motion in a cylindrical nozzle is photographed by a high speed camera and yarn position is analysed by a digitiser. As expected from a symmetrical air entrance which opens to a uniformly shaped main channel, two subflows rotating in opposite direction are created. The yarn has been found to be following an S-shaped path at the plane of the air jet nozzle by moving in one direction at one half of nozzle cross-section and then in the opposite direction at the other half and again coming back to the other half (Figure 2.14a-b).

It is recorded that the yarn motion occurring consecutively at each half of the cross-section takes place for a certain constant time, which is in the order of a few milliseconds and decreases with increasing supply pressure or yarn speed. Yarn motion becomes irregular near the exit plane just inside the nozzle. Outside the nozzle yarn motion remains irregular in character, but since it is unconstrained it covers a larger area. The irregularity has been reported to increase with increasing supply pressure, yarn speed or overfeed ratio.

2.2.5. AERODYNAMICS OF FLOWS CREATED BY INT NOZZLES

In contrast to the availability of only two major types of
AJT nozzles in the industry, there are a large number of different types of INT nozzles available therefore the flows delivered by INT nozzles are very difficult to be typified. Investigations by Demir et al [21] on free jets created by a number of INT nozzles revealed that the velocity profiles are of diverse shapes.

2.2.6. DISCUSSIONS ON PREVIOUS WORKS ON INT

As in the case of AJT, theory of INT process is coming behind its industrial practice. There have been a number of attempts to explain the INT process, but they lack identifying the elements which lead to successful or unsuccessful nip formation. Therefore in this research an improved understanding of the process itself has been attempted to be gained.

Previous researches on INT process and nozzles seem to be less systematic than those on AJT, because great deal of them have been carried out in industry, which are limited to their range of yarns and nozzles. Therefore the present research has used nozzles which are systematically generated from a basic design.
FIGURE 2.1 CYLINDRICAL AJT NOZZLE
FIGURE 2.2a-d A SELECTION OF TASLAN NOZZLE
FIGURE 2.3 AN EARLY AJT SYSTEM
SUPPLY YARN

FIGURE 2.4a TASLAN VII

FIGURE 2.4b TASLAN VIII
FIGURE 2.5 STANDARDCORE HEMAJET
FIGURE 2.6 EO-52

FIGURE 2.7 EMAD AJT NOZZLE
FIGURE 2.8 RESTRICTED SECONDARY FLOW INTO A CYLINDRICAL AJT NOZZLE BY MEANS OF A STEPPED MAIN CHANNEL
FIGURE 2.9 TASLAN XX

FIGURE 2.10 INTERLACING POINTS IN AJT
CLASSIFICATION OF INTERMINGLING NOZZLES

YARN THREADING FACILITY
- OPEN
- CLOSED

COMPRESSED AIR SUPPLY
- CONTINUOUS
- PULSED

AIR ENTRY
- SINGLE
- MULTIPLE

POSITIONING
- SINGLE
- TANDEM

AIR INPUT
- PERPENDICULAR
- INCLINED

LONGITUDINAL FORM OF THE YARN CHANNEL
- STRAIGHT
- HALF-DIVERGING
- CENTRAL ENLARGEMENT
- STEPPED
- IRREGULAR

YARN CHANNEL CROSS-SECTION
- CIRCULAR
- HALF-CIRCULAR
- SECTORAL
- TRIANGULAR
- RECTANGULAR
- PENTAGONAL
- IRREGULAR

FIGURE 2.11 CLASSIFICATION OF INT NOZZLES ACCORDING TO GEOMETRY
FIGURE 2.12 AIR FLOW IN A CYLINDRICAL INT NOZZLE
Hypothesised Velocity Profile

FIGURE 2.13 CROSSSTREAM VELOCITY PROFILE IN A CYLINDRICAL INT NOZZLE
FIGURE 2.14 a-b YARN LOCATION ACROSS A CYLINDRICAL INT NOZZLE
CHAPTER 3
A STUDY ON INDUSTRIAL AIR-JET TEXTURING NOZZLES

3.1. INTRODUCTION

In this chapter, aerodynamic and texturing performance of nine cylindrical type nozzles were investigated as a basis for an improved understanding of the effect of nozzle geometry on texturing by drawing together the following experimental data:

i) Total pressure measurements of jets
   a) Total pressure profiles along the jet axis (referred to throughout the work as centre-line total pressure distributions)
   b) Total pressure profiles of the free jets in planes normal to the jet axis (referred to throughout the work as cross-stream total pressure distributions)

ii) Compressed air consumption data

iii) Shadowgraphy

iv) Tension in the stabilising zone

v) Yarn Properties
   a) Visual inspections and scanning electron microscopy images (SEM)
   b) Tensile properties (instability, tenacity and breakage elongation)
   c) Increase in linear density

3.2. DESCRIPTION OF THE NOZZLES

The performance of six HemaJet type industrial nozzles from Heberlein Maschinenfabrik AG, which have widely been used in industry, and three experimental cylindrical nozzles
which were designed at Loughborough University of Technology by Acar [2] and Demir [19] were investigated. The investigation was aimed to cover nozzles which produce adequately textured yarns as well as those which do not, in order to get a grasp of the process.

Table 3.1 and Figure 3.1 present some geometrical features of the nozzles investigated. The industrial nozzles in Table 3.1 have either one or three inlet holes. The experimental nozzles L1 and L3 have two inlet holes of different diameter and L5 has three inlet holes of equal diameter.

All nozzles have a typical trumpet-shaped diverging exit geometry. The exit radii of Standard Core HemaJet and L5 are 3.0 and 3.75 mm respectively and the exit radius of all the other nozzles is 6.5 mm, typical of a Heberlein T-series trumpet exit shape.

All the nozzles investigated have uniform cylindrical channels with the exception of nozzles L3 and L5, which have a conical diverging section leading to the trumpet-shaped exit region, with a half cone angles of 1.5° and 1.15° respectively.

Among the nozzles with multiple air inlet holes Standard Core HemaJet is unique in its design having a staggered arrangement of inlet holes. The centre-lines of the inlet holes of other nozzles intersect on the centre-line of the main channel.

Guidance on the suitability of the applications of the industrial nozzle is available from the manufacturer [26, 27]. The experimental nozzles, L1, L3 and L5 were specifically designed to produce higher jet velocities at reduced air consumption rather than aiming to produce any particular type of yarn.
3.3. EXPERIMENTATION

3.3.1. TEXTURING TRIALS

Although the nozzles are designed for a varying range of yarns, in order to make a comparison, they were run by inputting the same supply yarn, PET 167/66, with the same process variables given below, which are a set of conditions typical of those used in industry:

- supply pressure = 8 bar (gauge)
- texturing speed = 200 m/min
- overfeed = 20%
- draw ratio at the stabilising zone = 4%
- water flow rate = 1 l/h (by a wetting head integrated with the nozzle housing.)

The results are presented according to the nozzles in Table 3.2 in order to present overall performance of each nozzle.

3.3.2. TOTAL PRESSURE MEASUREMENTS

A fine, purpose-made pitot tube is the most suitable technique for measuring total pressure of the high speed flows created by texturing nozzles in an efficient and accurate way [19]. Readings of the pitot tube have not been used for calculating velocity data, which would have provide extra information about the flow field, for the reason explained in Appendix A.

The system used for the present tests, which is sketched in Figure 3.2, consists of the following parts:

1. The nozzle which creates the air flow to be measured
2. Pitot tube (0.6 mm internal diameter)
3. Pressure transducer (Druck DP 1260 with pressure range of 0-200 kPa (gauge))
4. Drive board (PC 39 interface)
5. A microcomputer (Victor 286A PC)
6. XYZ manipulator with stepper motor drives
7. Compressor, air dryer, filters and regulators

A dedicated compressor supplied the compressed air to the nozzle via an air dryer, coarse and fine filters and pressure regulators. The pitot tube was mounted on an XYZ manipulator, which was driven by the microcomputer. Centre-line total pressure distributions were taken with 0.25 mm steps starting from a distance of 2 mm inside the nozzle up to 8 mm away from the nozzle exit plane, hence, tracing a distance of total 10 mm along the jet axis. The cross-stream total pressure measurements were taken by the pitot tube at various distances (0D, 1D, 2D, and 3D away from the nozzle exit, where D is main channel diameter) in planes normal to jet axis. Measurements were taken at 25 points along the perpendicular x and y directions in these planes. The x and y ranges were adjusted to probe those regions in which measurable data occur, so further downstream from the nozzle exit data are taken across a larger area due to spreading of the jet. Pressure was measured by a pressure transducer and the readings were transferred to the microcomputer.

3.3.3. SHADOWGRAPHY SYSTEM

Shadowgraphy is one of the flow visualisation techniques utilised in investigations of shock waves. The principle of the system (Figure 3.3) is based on the fact that when a light beam travels through a local change of refractive index, \( n \), it is deflected with a certain angle. The refractive index, \( n \), and density, \( \rho \), of a light transmitting medium are related as follows [44]:

\[
\rho = \frac{n^2}{c^2}
\]
any change in density results in a similar change in refractive index, hence a deviation of the light path. If there is an increase in density the light beams converge and therefore a light zone is created on a screen, and vice versa. Therefore any change in density can be mapped on a screen, creating light and dark area.

Since the method depends on the relative deflection of the rays (Eq.3.2) it is suitable for investigating shock waves, which consist of sharp changes of density [44].

A shadowgraphy test rig basically consists of the following components:

i) A point light source
ii) A lens or a mirror for collimating the light (optional)
iii) A mat screen
iv) An object to be visualised, positioned between the lens and the screen

In our experiments a Class 3B He-Ne laser with 15 mW power (including a microscope objective (x20) and a pin hole of 15 μm diameter was utilised as the light source and the light was collimated through a lens. The object, which is a jet created by an AJT nozzle, was located between the lens and a piece of tracing paper, which acted as the screen.

3.3.4. COMPRESSED AIR CONSUMPTION MEASUREMENTS

Compressed air consumption of each nozzle was measured at 8 bar inlet pressure by using a rotameter (Platon Flow Control).
3.3.5. YARN TESTS

The following properties of the textured yarns were investigated:

i) Tensile properties: At least twenty yarn samples from each package were prepared for determining the following tensile properties:

   a) Tenacity (cN/dtex, where dtex is linear density of the textured yarn) (For definition of tenacity see [60])

   b) Breakage elongation (For definition of breakage of elongation see [60])

   c) Instability (Calculation of the instability results from tensile tests is based on the definition that instability is the percentage elongation between 0.01 cN/dtex and 0.5 cN/dtex loads, where dtex is linear density of untextured yarn [19].)

The tensile tests were carried out by using an Instron machine under the following test conditions recommended by Demir [19]:

- distance between the jaws (i.e. specimen length) = 30 cm
- chart speed = 10 cm/min
- cross-head speed = 2 cm/min
- nominal load = 0.5cN * untextured yarn linear density in dtex

ii) Increase in linear density after texturing

iii) Tension in the stabilising zone; i.e. the drawing zone between the rollers immediately after the nozzle and the wind-up rollers. Absolute tension values were measured
on-line by a Rothschild tensiometer, whose sensor head was positioned between the rollers and normalised by dividing each values by the maximum.

In addition to the above-mentioned yarn properties the textured yarns were visually inspected and also photographed with SEM.

iv) Visual inspections: The criteria for this qualitative assessment are:

- overall appearance
- loop structure (size, shape, etc.)
- light reflection
- handling
- length ratio of textured and untextured sections

v) SEM images: After visual inspections and study of the SEM images, the yarns were categorised into three groups, namely; satisfactory, average, and poor quality textured yarns.

3.4. RESULTS AND DISCUSSIONS

3.4.1. TOTAL PRESSURE MEASUREMENTS

It would be ideal to probe the whole flow created by the nozzles, but the small size of the nozzles, with a main channel diameter varying between 1.5 and 2.4 mm, makes it very difficult to insert any measuring apparatus inside the nozzle without disturbing and, consequently, changing the characteristics of the flow to be investigated. Therefore, total pressure measurements can be performed only in the free jet in the nozzle exit region.

Centre-line total pressure distribution
Figures 3.4a-b show the centre-line total pressure
measurements. Centre-line distributions of five nozzles (T341W, Standard Core, L5, T350 and L1), which are given in Figure 3.4a, exhibit distinct oscillations. Those of the remaining four are presented in Figure 3.4b. Distributions of two, T100 and T110W, show almost no fluctuation and the other two (T311W, and L3) show some fluctuations near the exit plane.

Cross-stream total pressure distributions
Four typical cross-stream total pressure distributions in planes normal to the jet centre-line are given in Figures 3.5a-d. The distributions show total pressures at the exit plane and 3D away from the exit plane for the T100 and T341W nozzles. Figures 3.6a and 3.6b show single vertical y-direction sections of the total pressure distributions at the exit plane, 1D, 2D and 3D from the exit for the above mentioned nozzles.

Symmetry in the cross-stream total pressure distributions
All other nozzles have cross-stream total pressure distributions similar to those of T100 and T341W nozzles. It can be seen in the figures that the cross-stream distributions, do not show significant asymmetry. Although Acar [2] reported that cylindrical HemaJet nozzles create asymmetric jets, subsequently Demir [19] reported that jets delivered by L1, StandardCore and T341W do not exhibit significant asymmetry. It is interesting to note that although an initial asymmetry exists in nozzles with one inlet hole or staggered inlet holes at the exit plane the jets are almost symmetric. From this it can be concluded that the main channel length of these nozzles is sufficiently great for the flow to settle and redistribute flow downstream from the entrance in the main channel.

Central depression in the cross-stream total pressure distributions
There are two basic shapes of cross-stream total pressure
profiles:

i) Bell-shaped without depression at the centre
ii) With depression at the centre

Demir [19] also found similar trends in his measurements of other industrial nozzles.

Nozzles which have centre-line total pressure distributions without fluctuations and, hence, have no external shock waves have bell-shaped cross-stream total pressure distributions without depressions; i.e. pattern (i).

Nozzles with fluctuations in their centre-line distributions and, hence, have strong shock waves exhibit both types of cross-stream total pressure distributions shape. In this case, if the shock waves are of moderate strength then pattern (ii) is observed at the exit plane but at further downstream pattern (i) appears.

Divergence of the free jets
The cross-stream total pressure measurements are further processed in order to determine how much the free jets expand after leaving nozzle boundaries. If each free jet is roughly considered to be enlarging in the form of a half cone (Figure 3.7), a slice of the jet taken normal to the axis of the cone corresponds to a circle. If these slices are taken at the exit plane, 1D, 2D and 3D planes there are four circles for a given jet. Diameters of these circle can approximately be found from each set of cross-stream total pressure readings. Once the circles, which approximately represent jet boundaries at the given plane, are determined the cone is formed and its half angle gives enlargement of the particular jet. The calculated enlargement angle of primary jets delivered by the nozzles are given in Table 3.3 and vary between 5° and 12°.
3.4.2 SHADOWGRAPHY OF THE JETS

Shock waves in AJT
AJT nozzles generally create underexpanded jets [19], which expand into atmosphere since the exit pressure is greater than atmospheric pressure. The expansion continues until where the jet loses its pressure energy and its static pressure drops below the ambient pressure. Subsequently the flow is compressed again and the static pressure rises above ambient. Losses of energy take place in the shock waves and friction at the jet boundaries also causes the flow to lose energy. Hence the fluctuating total pressure pattern repeats itself a number of times before it is dissipated. The consecutive expansions and compressions are created by oblique shock waves.

Primary jets of all the nozzles were visualised at 8 bar supply pressure, except L5 at 7 bar, by deploying a shadowgraphy system (Figure 3.8a–i) and the following results were found.

1) The shadowgraphs show shock cells with convex boundaries, which are characteristic of underexpanded jets (Figure 3.8a–d).

2) The shock strength, assessed qualitatively by the photographic contrast between light and dark areas, varies strongly with nozzle type. StandardCore HemaJet seems to be producing the strongest shock waves (Figure 3.8b). T341W comes after it in this respect (Figure 3.8c).

3) The distance from the exit plane within which the shock cell pattern dissipates covers the visible shock cells is concerned the nozzles L5 (Figure 3.8a), StandardCore (Figure 3.8b) and T341W (Figure 3.8c) create jets with shock waves which are dissipated at the largest distance from the nozzle exit plane respectively. When the presence
of free jets inside the nozzles is considered the ranking becomes L5, T341W and StandardCore.

4) The shadowgraphs of the Standard Core nozzle showed that Mach disks formed in the first visible shock cell due to interaction between the shock fronts. This pattern is quite similar to Ramskill's work [50] for underexpanded jets. The conditions necessary for the formation of Mach disks were found to be \( \frac{P_{\text{exit}}}{P_{\text{inv}}} \geq 2 \). Therefore it seems reasonable to conclude that at 8 bar inlet pressure the Standard Core nozzle experiences an exit pressure around 2 bar, whereas the other nozzles operate with exit pressures between ambient and 2 bar.

6) The geometry of the shock cell pattern varies strongly with nozzle type. Under the conditions investigated it appears that nozzles which produce strong shock cells also show a large number of cells which dissipate over a large distance. This pattern is also characteristic of underexpanded nozzles operating at exit plane pressure to ambient pressure ratio around \( n=2 \) [16].

3.4.3. TENSION IN THE STABILISING ZONE

The normalised data for the tension of the yarn produced by each nozzle have been presented in Figure 3.9. The mean value was found to be 0.57 and its standard deviation 0.24 across the range of nozzles. It should be noted that the units are non-dimensional with respect to the highest tension value measured for yarn produced by T341W in the stabilising zone. Nozzles T341W, T110W and T350, have high stabilising tension.

3.4.4. COMPRESSED AIR CONSUMPTION DATA

Measured air consumption data are plotted against total inlet hole area in Figure 3.10 and, as expected, the larger
the inlet holes the greater the amount of air is consumed. Figure 3.10 shows that the experimental air consumption is linearly related to the total inlet area.

In Figure 3.10 theoretical mass flow rate which could be delivered at the same stagnation conditions from converging-diverging nozzles with throat area which is equal to total inlet hole area of the nozzles is also given along with air consumption data of the nozzles. In the calculation of the theoretical volume flow rate, the following expression (e.g. [44]) is used:

\[ m_{\text{max}} = A_t \rho_o \rho_o \gamma \left( \frac{2}{\gamma+1} \right)^{(\gamma+1)/(\gamma-1)} \left( \frac{2}{\gamma+1} \right)^{0.5} \]  \hspace{1cm} (3.1)

where
- \( m_{\text{max}} \) = maximum volume flow rate attainable over critical conditions (standard m \(^3\)/s)
- \( A_t \) = total inlet area (m\(^2\))
- \( \rho_o \) = stagnation pressure (Pa abs.)
- \( \rho_o \) = stagnation density (kg/m\(^3\))
- \( \gamma \) = specific heat ratio

Figure 3.10 shows that the theoretical values of the flow rate are in accordance with this formula. Therefore it can be stated that the nozzles at the given supply pressure behave as converging-diverging nozzles, which are choked due to the high supply pressure, and deliver only a certain amount of mass flow rate regardless of nozzle geometry.

Table 3.4 gives values of the flow coefficient C defined as the ratio between measured and theoretical flow rate. C is close to unity if the inlet area is small, but decreases as the inlet area increases suggesting that details of the inlet geometry begin to influence the flow rate through the nozzle.

This work clearly shows that the nozzle air consumption can
This work clearly shows that the nozzle air consumption can only be reduced by a decrease of the total inlet area or reduction of stagnation pressure. Since texturing is poor at low supply pressures, which was established by many researchers [2, 19], air consumption can be minimised by designing nozzles with small inlet area without deteriorating yarn quality.

3.4.5. YARN TESTS

Visual inspection and SEM images of the textured yarns
The textured yarns have been qualitatively categorised into three groups according to the criteria listed in Section 3.3.5. Three distinct examples which represent poor, average and satisfactory quality textured yarn are presented respectively in Figure 3.11a-c at magnification of 15x.

Satisfactory textured yarns such as those made by nozzles T311W, T341W and T110W, have small and frequent loops; no untextured sections, low light reflection and spun-like handling characteristics. The SEM image shown in Figure 3.11a is typical of such yarns. Unsatisfactory yarns, those produced in these tests by Standard Core, L3 and L5, have large untextured sections, which give rise to high light reflectivity and typical synthetic handling (Figure 3.11c). Average yarns have intermediate characteristics; i.e. some large loops and/or some untextured sections (Figure 3.11b).

When the results of the stabilising zone tension are compared with those of the SEM images of the yarn it can be seen that the nozzles which have been identified as adequate nozzles, namely, T341, T350 and T110, also have high stabilizing zone tension. Furthermore, the nozzles which produce inadequately textured yarn, namely, L1 and L3, have low stabilising zone tension. There are some cases that data stabilizing zone tension do not particularly
correlate with the categorisation of the visual inspections of the textured yarns. Nevertheless it is still possible to conclude that high stabilising zone tension is a reasonable indicator of adequate entanglement, therefore, good texturing.

**Increase in linear density after texturing**
The results of increase in linear density, given in Figure 3.12 for each nozzle, exhibit a distribution with small variation. The mean increase in linear density is 17.0% and its standard deviation is 0.8%.

**Tensile tests**
Instability, tenacity and breakage elongation values of yarns produced by the nozzles were presented in Figure 3.13, 14 and 15. The textured yarns, which were produced with very different nozzles in geometry, showed very close tensile properties.

The average instability was measured at 1.5% with standard deviation of 0.2%. Tenacity results for the supply and textured yarns presented in Figure 3.14 show that the texturing process causes the supply yarn to lose an average of 44% of its strength. For all yarns the average tenacity was measured to be 2.1 cN/dtex with a standard deviation of 0.1 cN/dtex across all nozzles tested. The average breakage elongation was found to be 15% with a standard deviation of 2%.

**3.5. CONCLUSIONS**

1. Cross-stream total pressure profiles do not exhibit very much different forms from nozzle to nozzle. Variation in shapes is basically governed by the relative position of the measuring plane with respect to shock cells, if any, and the distance of the measuring plane from the exit plane (2), rather than a specific geometrical parameter.

3-14
Nevertheless it must be pointed out that since the shape of total pressure distributions is determined by shock wave pattern and shock waves occur in supersonic flows, nozzles with high loss (small area ratio, straight main channel, short main channel) have a tendency to create jets without shock waves; therefore their total pressure profiles are bell-shaped.

2. There is no correlation between mean total pressure level in the exit region and texturing quality.

3. There is no significant asymmetry in cross-stream total pressure profiles.

4. Analysis of air consumption results with total inlet hole area has shown that all the nozzles are choked at the inlet hole(s). At a typical texturing conditions the nozzles behave as corresponding converging-diverging nozzles.

5. Well textured yarns can be produced with nozzles which have only modest strength shock waves at the exit and the nozzles with strongest shock waves (Standard Core and L5) produced yarns of lowest quality. It appears that although shock waves may sometimes play a part, they are certainly not essential for good texturing.

6. Tension in the stabilising zone has shown itself to be the best quantitative measurement of effectiveness of texturing in these tests.

7. Although the yarn properties mentioned in Section 3.4.5, especially instability, have previously been used as assessment tests for the effectiveness of the filament entanglement [19] the results from the present tests seem to suggest that this kind of approach only applies when yarns produced by one nozzle is under a range of different
Table 3.1 GEOMETRICAL FEATURES OF THE NOZZLES

<table>
<thead>
<tr>
<th>NOZZLE</th>
<th>No of Air Inlets</th>
<th>Main Duct Diameter (D) (mm)</th>
<th>Inlet Hole Diameter (mm)</th>
<th>Exit Duct Radius (mm)</th>
<th>Exit Duct Length (x/D)</th>
<th>Main Duct Div. Ang. (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T100</td>
<td>1</td>
<td>1.51</td>
<td>1.10</td>
<td>6.50</td>
<td>2.85</td>
<td>0</td>
</tr>
<tr>
<td>T110</td>
<td>1</td>
<td>1.70</td>
<td>1.25</td>
<td>6.50</td>
<td>2.92</td>
<td>0</td>
</tr>
<tr>
<td>T311</td>
<td>3</td>
<td>1.20</td>
<td>0.60</td>
<td>6.50</td>
<td>2.75</td>
<td>0</td>
</tr>
<tr>
<td>T341</td>
<td>3</td>
<td>2.00</td>
<td>1.00</td>
<td>6.50</td>
<td>2.89</td>
<td>0</td>
</tr>
<tr>
<td>T350</td>
<td>3</td>
<td>2.40</td>
<td>1.20</td>
<td>6.50</td>
<td>3.13</td>
<td>0</td>
</tr>
<tr>
<td>St.Core</td>
<td>3</td>
<td>2.00</td>
<td>0.90</td>
<td>3.00</td>
<td>3.25</td>
<td>0</td>
</tr>
<tr>
<td>L1</td>
<td>2</td>
<td>1.80</td>
<td>1.1/0.9</td>
<td>6.50</td>
<td>1.72</td>
<td>0</td>
</tr>
<tr>
<td>L3</td>
<td>2</td>
<td>1.50</td>
<td>1.0/0.8</td>
<td>6.50</td>
<td>2.01</td>
<td>1.50</td>
</tr>
<tr>
<td>L5</td>
<td>3</td>
<td>1.56</td>
<td>0.90</td>
<td>3.75</td>
<td>4.49</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Table 3.2 Properties of the Textured Yarn

<table>
<thead>
<tr>
<th>NOZZLES</th>
<th>Tenacity (cN/dtex)</th>
<th>Breakage Instability (%)</th>
<th>Elongat. in Lin. Zone (%)</th>
<th>Increase in Dens(%)</th>
<th>Stabilising Tens. (normalised)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T100</td>
<td>2.06</td>
<td>12.8</td>
<td>1.59</td>
<td>15.6</td>
<td>0.63</td>
</tr>
<tr>
<td>T110</td>
<td>2.08</td>
<td>14.0</td>
<td>1.29</td>
<td>17.4</td>
<td>0.50</td>
</tr>
<tr>
<td>T311</td>
<td>2.35</td>
<td>18.8</td>
<td>1.27</td>
<td>17.5</td>
<td>1.00</td>
</tr>
<tr>
<td>T341</td>
<td>2.14</td>
<td>14.5</td>
<td>1.62</td>
<td>17.3</td>
<td>0.53</td>
</tr>
<tr>
<td>T350</td>
<td>2.12</td>
<td>14.3</td>
<td>1.69</td>
<td>18.3</td>
<td>0.79</td>
</tr>
<tr>
<td>St.Core</td>
<td>2.26</td>
<td>16.3</td>
<td>1.37</td>
<td>16.8</td>
<td>0.18</td>
</tr>
<tr>
<td>L1</td>
<td>2.00</td>
<td>13.0</td>
<td>1.40</td>
<td>17.1</td>
<td>0.58</td>
</tr>
<tr>
<td>L3</td>
<td>2.08</td>
<td>15.1</td>
<td>1.80</td>
<td>15.9</td>
<td>0.34</td>
</tr>
<tr>
<td>L5</td>
<td>2.04</td>
<td>14.0</td>
<td>1.27</td>
<td>17.1</td>
<td>0.60</td>
</tr>
</tbody>
</table>
Table 3.3 DIVERGENCE ANGLE OF THE JETS CREATED BY THE AJT NOZZLES

<table>
<thead>
<tr>
<th>NOZZLE</th>
<th>JET DIVERGENCE ANGLE (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T100</td>
<td>6</td>
</tr>
<tr>
<td>T110</td>
<td>6</td>
</tr>
<tr>
<td>T311</td>
<td>12</td>
</tr>
<tr>
<td>T341</td>
<td>10</td>
</tr>
<tr>
<td>T350</td>
<td>10</td>
</tr>
<tr>
<td>St.Core</td>
<td>9</td>
</tr>
<tr>
<td>L1</td>
<td>9</td>
</tr>
<tr>
<td>L3</td>
<td>9</td>
</tr>
<tr>
<td>L5</td>
<td>5</td>
</tr>
</tbody>
</table>

* half cone angle of diverging jet (see Figure 3.7)

Table 3.4 COMPRESSED AIR CONSUMPTION DATA

<table>
<thead>
<tr>
<th>NOZZLE</th>
<th>AIR CONSUMPTION</th>
<th>MEASURED FLOW COEFFICIENT</th>
<th>TOTAL THROAT AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Theoretical</td>
<td></td>
</tr>
<tr>
<td>T100</td>
<td>5.7</td>
<td>5.4</td>
<td>1.05</td>
</tr>
<tr>
<td>T110</td>
<td>7.5</td>
<td>7.0</td>
<td>1.07</td>
</tr>
<tr>
<td>T311</td>
<td>5.0</td>
<td>4.8</td>
<td>1.03</td>
</tr>
<tr>
<td>T341</td>
<td>12.2</td>
<td>13.5</td>
<td>0.90</td>
</tr>
<tr>
<td>T350</td>
<td>17.0</td>
<td>19.4</td>
<td>0.88</td>
</tr>
<tr>
<td>St.Core</td>
<td>10.2</td>
<td>10.9</td>
<td>0.94</td>
</tr>
<tr>
<td>L1</td>
<td>8.7</td>
<td>9.1</td>
<td>0.86</td>
</tr>
<tr>
<td>L3</td>
<td>7.4</td>
<td>7.4</td>
<td>1.00</td>
</tr>
<tr>
<td>L5</td>
<td>10.3</td>
<td>10.9</td>
<td>0.95</td>
</tr>
</tbody>
</table>
D = main channel diameter
R = exit radius
α = divergence angle
x = primary channel length

FIGURE 3.1 GEOMETRICAL PARAMETERS OF A CYLINDRICAL AJT NOZZLE
FILTERS
REGULATORS
NOZZLE
PRESSURE TRANSUDER
DRYER
COMPRESSOR

FIGURE 3.2. TOTAL PRESSURE MEASUREMENT SYSTEM
FIGURE 3.3 SHADOWGRAPHY SET-UP
FIGURE 3.4a CENTRE-LINE TOTAL PRESSURE DISTRIBUTIONS OF L5, T341, STANDARDCORE, L1 AND T350
FIGURE 3.4b CENTRE-LINE TOTAL PRESSURE DISTRIBUTIONS OF T100, T110W, L3 AND T311W
FIGURE 3.5a
Cross-stream total pressure distribution for T100 at Exit Plane

FIGURE 3.5b
Cross-stream total pressure distribution for T100 at 3D plane
FIGURE 3.5c
Cross-stream total pressure distribution for T341 at Exit Plane

step = 0.238125 mm

FIGURE 3.5d
Cross-stream total pressure distribution for T341 at 3D plane

step = 0.28575 mm
FIGURE 3.6a AXIAL (y-AXIS) TOTAL PRESSURE DISTRIBUTION OF T100

FIGURE 3.6b AXIAL (y-AXIS) TOTAL PRESSURE DISTRIBUTION OF T341
$\alpha$: Divergence Angle of the air-jet

FIGURE 3.7 DIVERGENCE OF PRIMARY JETS CREATED BY AN AJT NOZZLE
FIGURE 3.8a-e SHADOWGRAPHS OF PRIMARY JETS CREATED BY THE AJT NOZZLES
FIGURE 3.8f-i SHADOWGRAPHS OF PRIMARY JETS CREATED BY THE AJT NOZZLES
FIGURE 3.9 DATA OF TENSION IN THE STABILISING ZONE OF THE NOZZLES
FIGURE 3.10 FLOW RATE vs TOTAL INLET AREA
Comparison of Theoretical and Experimental Results
FIGURE 3.11 a-c SEM Images of SATISFACTORY AVERAGE and POOR QUALITY TEXTURED YARNS
FIGURE 3.12 INCREASE IN LINEAR DENSITY DATA OF THE NOZZLES

FIGURE 3.13 INSTABILITY DATA OF THE NOZZLES
FIGURE 3.14 TENACITY DATA OF THE NOZZLES

FIGURE 3.15 BREAKAGE ELONGATION DATA OF THE NOZZLES
CHAPTER 4

SYSTEMATIC INVESTIGATION OF THE EFFECT OF NOZZLE GEOMETRY ON AIR-JET TEXTURING

4.1. INTRODUCTION

The air flow in an AJT nozzle is mainly governed by the geometry of the nozzle. To date, for a number of nozzles the influence of process parameters on the air flow distribution has been investigated by Acar [2] and Demir [19], but these findings have not actually been related to yarn entanglement. In other words, in Figure 1.5 inter-block relation between A (nozzle geometry) and B (air flow properties) has been established but the one between A (nozzle geometry) and C (yarn properties) still remains to be investigated.

In Chapter 3, an investigation of some existing industrial AJT nozzles was reported. Since those nozzles were not systematically related to each other in terms of their geometrical properties, a change in one parameter is likely to affect the other. It was obvious that the nozzle geometry influenced the flow properties, which in turn affected the texturing performance, but not clear which geometric parameter or combination of parameters was responsible for the differing yarn properties. In this chapter a report of investigations with a series of model texturing nozzles, designed and built in a systematic manner, on texturing is given.

4.2. EXPERIMENTATION

Texturing performance of the model nozzles is assessed by the following criteria, details of which were earlier defined in Section 3.3.5:

* Process observations
* Yarn quality assessment by visual inspection and SEM photographs
* Measurement of tension in the stabilising zone
* Yarn tests (increase in linear density and tensile tests; namely, instability, tenacity, breakage elongation)

4.2.1. DESCRIPTION OF THE NOZZLES

The most widely used AJT nozzles are of cylindrical HemaJet type, whose basic design consists of a uniform main channel of circular cross-section with a trumpet shaped exit section and an air inlet hole at an angle of approximately 45° to the main channel to introduce the compressed air into it (Figure 2.5).

The circular cross-section of the nozzle makes it very difficult to visualise the flow and filament-flow interaction inside the nozzle. Earlier attempts by other researchers to make model nozzles from optically clear materials, such as perspex, have failed to produce successful results. Moreover, the precision engineering and tight tolerances required in manufacturing of such nozzles forces us to consider an alternative solution. We needed easy to manufacture nozzles so that a number of geometrical features of the nozzle can systematically be altered and their effect can be investigated. We also required a nozzle which would facilitate visualisation of the air low-filament interaction inside the nozzle. On the other hand, such nozzles were required to simulate the industrial nozzles and textures yarns successfully.

The model nozzles used in this study were designed to simulate the cylindrical HemaJet nozzles, but rectangular cross-section was used instead of circular cross-section of the cylindrical nozzles for the two following reasons:
i) Manufacturing such nozzles is easier at the required high precision.

ii) Rectangular cross-section also facilitates the visualisation of the filaments-air flow interaction inside the nozzle by means of high speed-cine filming technique, by replacing one side of the nozzle with a glass plate (The visualisation investigations are carried out in Chapter 5).

In the design of the model nozzles, many features common to cylindrical nozzles were maintained. These include a straight main channel, into which the compressed air is introduced at 45° angle through an air inlet channel and a trumpet shaped exit. The area ratio (ratio of area of incoming air inlet to that of the main channel) of the model nozzles is chosen to be 0.67, which falls in the range of those of the industrial ones, which typically varies between 0.5 and 0.75.

To make the nozzles easy to manufacture they were designed in two pieces: The first is of brass and contains the nozzle profile; i.e. the air inlet hole, the main channel and the exit profile, cut into it as an open channel. The second is a flat clear glass plate. The glass is secured on the metal piece and, hence, the two pieces form a closed nozzle structure.

A prototype nozzle was developed to test whether this design was capable of simulating the AJT process. A preliminary assessment of the yarn made by this model nozzle, based on overall appearance, handling and light reflection, showed that the yarn is textured in a way similar to yarns made with industrial nozzles.

The other model nozzles have been systematically generated from the basic design with the specifications given in
Table 4.1. The basic design is Model Nozzle 5, its geometrical features are sketched in Figure 4.1. When one geometrical parameter is changed the others are kept the same and, hence, it has become possible to investigate the effect of nozzle geometry on AJT process. The following is a summary of the geometry of the model nozzle:

* Model Nozzles 1-9: Nozzles with nine different primary flow channel length, \( \bar{x} \), which determines the location of the air inlet with respect to nozzle exit (Figure 4.2a). \( \bar{x} \) is 10mm for the basic nozzle.

* Model Nozzle 10 and 11: The inclination position of the inlet hole to the main channel, \( \alpha \), at 30° and 60° respectively (Figure 4.2b). \( \alpha \) is 45° for the basic nozzle.

* Model Nozzle 12: No trumpet shaped exit-profile (Figure 4.2c). The basic nozzle has a trumpet shaped exit profile with the radius of 6mm.

* Model Nozzle 13: Two opposing inlet holes (Figure 4.2d). There is only one inlet hole in the basic nozzle.

* Model Nozzle 14: Diverging main channel on the primary flow side (Figure 4.2e). The main channel of the basic nozzle is straight.

4.2.2. TEXTURING TRIALS

The following set of processing conditions, which are of typical of industry, were used throughout the tests:
Supply pressure = 8 bar (gauge)
Yarn Speed = 200 m/min
Overfeed : 20%
Stabilising Draw : 4%
Water : 11/l

Stabilising draw ratio is 4% for texturing trials but for tension measurement only it was increased to 6% because in the former case the tension readings were very low. This increase in the stabilising draw also enabled to have measurements with very low fluctuations, 5% of maximum reading approximately.

A WIRA tensiometer was used to measure mean tension. The yarn is the same as the one used in the previous tests as detailed in Chapter 3.

4.2.3. YARN TESTS

The textured yarns were subjected to tensile and other tests, whose details are given in Chapter 3. The results are presented in Table 4.2, with those of T100 for comparison. These tests include tenacity, breakage elongation, instability, and increase in the linear density.

In addition to these results, load-elongation graphs are also evaluated and found to be revealing useful information about the degree of filament entanglement.

4.2.4. EVALUATION OF THE NOZZLE ASSESSMENT CRITERIA

Performance of a given nozzle can be assessed by several tests, which have been listed in Section 4.2. However it is necessary to establish, firstly, the conditions under which the tests can be used as an indicator of nozzle performance.
As far as process observations are concerned, their judgement should be given priority over the other criteria because any irregularity in the process; such as, an occasional pulsation in the primary jet or a departure of yarn from its usual path indicates an unevenly textured yarn, which may not be detected by other indicators. Process observations are necessary to determine whether the resultant yarn is evenly textured, but for more detailed information about yarn structure additional tests are required.

Once a nozzle is identified to be producing yarn with consistent quality by the judgement of process observations, SEM images and visual inspections of the yarn produced can be taken as the second major criteria for judging nozzle performance. Appearance of the yarn, especially under high magnification, reveals actual yarn structure, hence provides useful information about the effectiveness of texturing. Since an effectively-textured yarn is one with entangled core, small and frequent loops and more regularly distributed along it, visual inspections and SEM images can directly be used in judging the effectiveness of a nozzle.

In addition, a quantitative criterion for assessment nozzle performance has been shown in Chapter 3 to be the yarn tension in the stabilising zone because it measures the degree of resistance of loops to the pulling action applied in that zone, hence, giving a measure of the degree of filament entanglement.

Furthermore, increase in the linear density of the yarn after texturing can also be considered as one of the ways of measuring degree of effectiveness of texturing since it shows how much of the overfed yarn has been actually transformed to be a part of the textured yarn. Therefore the higher the increase in linear density the more
effective the texturing is. However, again, without the verdict of the first criterion; i.e. process observations, this can be misleading.

Chapter 3 indicates that the tensile tests cannot give direct and definite information about loop structure of a textured yarn as the first four criteria, just discussed, namely; process observations, visual yarn inspections, tension in the stabilising zone and increase in linear density after texturing. As far as the instability tests are concerned, the reason for this is that the tensile force used in the instability tests, 0.5 gram/dtex (by definition) causes the loops to be permanently removed. Demir [19] reported that a tensile force greater than 0.23 gram/dtex causes the loops to be pulled out, causing permanent changes in the yarn structure. Since the loop structure cannot be maintained due to the high pulling force in the instability tests, any increase recorded in the force during the tests is partly due to the resistance of the loops and partly due to the extension of individual filaments. As a result, unlike stabilising tension, high instability values cannot always be interpreted as an indicator of a good textured yarn. It should be noted that a 0.5 gram/dtex tensile force is well above the limit of 0.23 gram/dtex critical force reported by Demir. Typical tensions recorded in the stabilising zone are well below the limit of permanent loop removal (see Section 4.3.3). It should also be noted that the yarn is subjected to further higher tension due to the winding of the yarn, which further contributes to removal of loops prior to the instability tests.

As far as the tenacity and breakage elongation data are concerned, there appears to be no straightforward relation between them and textured yarn structure. Low tenacity and breakage elongation values have been considered to be indicating an effectively textured yarn by several
researchers [2, 38, 53], arguing that any decrease in strength from that of the supply yarn is due to the fact that there are considerably fewer load-bearing filaments in AJT yarns than the parent supply yarns. This approach is, however, somewhat oversimplified. It is correct to state that during tensile tests of textured yarns, only few filaments experience the pulling force at any instance while the others lie loose at an angle to the former, therefore the latter do not bear the load. As the pulling continues the loose filaments may become tensioned, creating a shear force on the filaments already carrying the pulling force since the former lie at an angle on the latter. In this case of multiple stress applied to the already tightened filaments, they break earlier that the case in which only pulling tension was present. The effect of the neighbouring filaments on the premature breakage depends on which section of the tightened filaments they apply the shear force. If the shear force comes on a weak section of the already pulled filaments then the breakage will occur early. It can be, therefore, argued that any drop in the total strength is not only because there are less filaments carrying the pulling tension but also because they are weakened by the neighbouring filaments applying shear forces, depending on the application point of the shear stress on the pulled filaments. Consequently small tenacity does not necessarily mean that there are only small number of load-bearing filaments, indicating more loops.

The tensile tests, namely; instability, tenacity and breakage elongation, however, can give information about how the yarn can behave during further processes under tensile forces, comparing with industrial yarns and can be used as complementary source of information.
4.3. RESULTS AND DISCUSSIONS

4.3.1. PROCESS OBSERVATIONS

All nozzles gave stable texturing conditions, with the exception of the two following model nozzles: the nozzle with the air inlet hole closest to the exit (Model Nozzle 1) and the nozzle with two inlet holes (Model Nozzle 13). With Model Nozzle 1, as soon as the process was started the yarn burst out of the nozzle and broke. Consequently no data is available for this nozzle in Table 4.2 and Table 4.3. The nozzles with air inlet holes further back, which do not exhibit such problems.

The nozzle with the two inlet holes, Model Nozzle 13, was another nozzle which gave an unstable process. The jet sometimes pulses at irregular intervals. Although it is possible to take-up the yarn on the bobbin without any breakage occurring, the yarn is occasionally blown away in the direction of the free jet due to the pulsation of the jet. This suggests that the nozzle is not capable of making yarn with even quality.

The remaining model nozzles did run steadily.

4.3.2. VISUAL INSPECTION AND SEM IMAGES OF THE YARNS

The yarns produced by the model nozzles were assessed according to their overall appearance, as detailed in Chapter 3. Additionally SEM images of the yarns were produced with 25x magnification and presented in Figure 4.3a-h. In order to illustrate the effect of primary flow channel length, x, on yarn properties, only three images from Nozzles 2-9 have been presented. These are the nozzles with the smallest, medium and largest values of x in Figure 4.3a-c respectively. The reason for including only three nozzles to represent the nine nozzles of different x is to
show the difference in yarn structure from nozzle to nozzle more distinctively. Images from all the other nozzles were included in the Figure 4.3d-h.

The yarns were classified as described in Section 3.4.5. According to this classification, Nozzles 9, 10 and 14 produce satisfactorily textured yarn. Nozzles 2, 11, and 13 produce poor quality yarns and Nozzles 5 and 12 produce yarns with average quality.

Figure 4.3a is of the yarn produced by Nozzle 2, which is the one with the smallest x distance that can texturise satisfactorily. This shows that the yarn made by this nozzle has large loops and a core with little entanglement, indicating not very successful texturing. Figure 4.3b is of Model 5, which shows smaller loops and more tangled core, indicating better texturing. Image of yarn textured by Nozzle 9, which has the greatest x, is presented in Figure 4.3c and shows smaller and more frequent loops and a well entangled core, indicating much more successful texturing. These results show that the further away the air inlet hole from the nozzle exit the more beneficial it becomes for texturing.

In Figure 4.3d and e, yarns produced by the Nozzles 10 and 11, with inlet hole inclination at 30° and 60° respectively, are presented. When the yarns made by model nozzles with different tilt angle of air inlet are compared it is clearly seen that the model nozzle with $a=30°$ does better texturing that the one with $b=60°$. Although Nozzle 10 ($b=30°$) has got smaller x than Nozzle 11 it still produces yarn with higher quality. When Nozzle 5 ($a=45°$) is included into the comparison it can be stated that quality of the made by Nozzle 5 falls between those of made by Nozzle 10 and 11. These results lead to the conclusion that low tilt angle of air introduction to the main channel improves
texturing quality.

Yarn made by the nozzle without a trumpet shaped exit, Model Nozzle 12, presented in Figure 4.3f, exhibits quite large loops and a loose core, indicating poor texturing. This highlights the importance of the nozzle exit profile of trumpet shape.

Figure 4.3g also shows inadequately textured yarn with a long untextured section and large loops. The yarn is produced by Nozzle 13, which has two inlet holes.

When all the images are compared Figure 4.3h shows the most successfully textured yarn with more regular, small and frequent loops. This yarn was textured by Nozzle 14, indicating that a slight divergence in the main channel significantly improves texturing.

4.3.3. STABILISING ZONE TENSION

Stabilising zone tension data of the model nozzles is presented in Table 4.3 and Figure 4.4. The data seem to be accumulated at two levels. The low values vary between 0 and 3.5 and the high values vary between 22.2 and 25.5 gram. Nozzle 2, 12 and 13 gave results in the low region, whereas the rest of the nozzles produced tension in the high region. The first group of nozzles which produced low stabilising zone tension have also been observed by the visual inspection and the SEM images to have produced inferior yarns. The rest of the nozzles produced high stabilising zone tension which indicates, which indicates more successful texturing.

A comparison of the stabilising zone tension of Nozzles 2, 5 and 9 shows that again the higher the tension correlates with high yarn quality and hence more effective yarn entanglement. With the correlation between entanglement and
the stabilising zone tension confirmed, both data sets indicate that long main channel is beneficial in texturing.

From the above argument it can be further concluded that the nozzles with no exit profile and the one with two inlet holes do not produce adequate texturing, whereas Nozzle 14 (diverging main channel) is successful in texturing. This confirms the findings of visual inspections and SEM image evaluations, in Section 4.3.2.

The fact that the correlation between yarn quality and stabilising zone tension is by no means perfect is stressed when considering Nozzle 11 (b=60°). The poor yarn quality, as demonstrated by the SEM image in Figure 4.3e, leads one to expect a low stabilising zone tension. Nevertheless the stabilising zone tension was measured to be 22.4 gram, which is in the high region.

4.3.4. INCREASE IN THE LINEAR DENSITY

The increase in linear density after texturing is presented in Table 4.2 and Figure 4.5. The figure shows that there is a consistent correlation between the primary channel length and the increase in linear density after texturing. The general trend of the graph indicates a steady increase in linear density after texturing with increasing x distance. Since high values of increase in the linear density indicates effective entanglement, it can be concluded that the nozzles with longer main channel perform considerably better. This conclusion has also reached by the results of the stabilising zone tension.

Interestingly, the poor yarn quality produced by Nozzle 11 does correlate with increase in linear density, which is seen to be as low as the values associated with yarns produced by Nozzles 2, 3, 12 and 13, which are not
successful in texturing.

In the figure the result of T100 is within the results of the other nozzles, indicating that they are capable of producing yarns with quality similar to those of industrial nozzles.

4.3.5. TENSILE TESTS

A) Quantitative analysis of the tensile tests
Quantitative results of the tensile tests are given in Table 4.2. Graphs of each individual test results; namely, instability, tenacity and breakage elongation versus the model nozzles have been presented in Figure 4.6, 4.7 and 4.8 respectively.

Instability test results of all the model nozzles are presented in Figure 4.6. They vary between 3.70 and 1.67%, which are greater than instability of T100, 1.59%.

Tenacity test results are presented in Figure 4.7. They vary between 3.13 and 1.60 cN/dtex and tenacity of T100 is 2.06 cN/dtex.

Breakage Elongation results are presented in Figure 4.8. The results vary between 16.9% and 11.6% and that of T100 is within this range, 12.8%.

The tensile test results of T100 are well comparable with those of the model nozzles, indicating that they can produce yarns with similar strength properties to those of industrial nozzles.

B) Qualitative analysis of the tensile tests
Sample load-elongation graphs of the supply yarn and the yarns made by the model nozzles are presented in Figure 4.9a–n. It can be seen that the supply yarn and the yarn
made by Nozzle 2 have similar breakage patterns after the maximum load and these two are distinctly different from the others. The load-elongation curves of the supply yarn and the yarn made by Nozzle 2 show that after the maximum force is experienced the filaments break individually at different times and the overall breakage is gradual. Demir [19] reported that the gradual breakage is typical of supply yarns, where the filaments are parallel, and the breakage of textured yarns is sudden. The relative similarity between the shapes of graph of Nozzle 2 and that of the supply yarn suggests that the nozzle does not change the structure of the supply yarn very much; i.e. Nozzle 2 does little texturing.

Graphs of the remaining nozzles; which can texture yarn, can be roughly divided into two categories according to their shape as follows:

* Curve 1: Continuous curve (Nozzle 4, 7, 8, 9, 14)
* Curve 2: Toothed curve (Nozzle 2, 3, 5, 6, 13, 10, 11, 12)

The following analogy can be used to illustrate a possible relation between shape of load-elongation graph of a yarn and relative position of the filaments of the yarn; i.e. degree of entanglement. It is known from experience that when an individual filament of a yarn with entangled structure is pulled, it cannot come off easily due to the friction created by the entangled structure of the neighbouring filaments. That is to say that the pulling force applied to a particular filament from its one end cannot be felt at the other end because the force cannot be transmitted along that filament due to the entangled structure. Similarly, this analogy can be applied to the case of yarn tensile tests, as illustrated in Figure 4.10. As the whole yarn is pulled in these tests, the pulling tension sensed by the load cell, T, steadily increases with
the elongation. In the figure, an individual filament is highlighted (Filament B) to represent orientation of a typical filament in an AJT yarn. This filament sometimes becomes a part of the core (invisible) and sometimes of the surfaces (visible). If this filament breaks during the course of the tensile test, the pulling stress in the yarn at the broken filament becomes zero. However this relief is not instantly felt at the other end of the filament, which is connected to the sensor of the tensile tester, if the filaments are all entangled, resulting considerably high inter-filament friction created by the entangled structure. Consequently the tensile tester still records the pulling tension increasing. From this argument it can be said that yarns with well entangled filaments have smooth load-elongation graphs (of type of Curve 1).

In some tests, as the yarn is pulled in the tensile tester the tensile force steadily increases but occasionally falls suddenly just a small fraction and then increases again, forming a tooth on the graph. This may be interpreted such that when a filament breaks it cannot, naturally, bear the load at that instant. Therefore the machine reads the force borne by the remaining filaments for a short time, which is the one that experienced by the filament before its breakage and, therefore, smaller than that of the whole yarn before the breakage. Soon after, tension in the yarn starts increasing. Therefore it can be concluded that curves with teeth indicate a yarn whose filaments are not very well entangled; i.e. ineffectively textured yarn. Obviously, it can be argued that the deeper and/or the more frequent the teeth on the graph the less effective texturing is.

According to the above discussion on the classification of the degree of yarn entanglement based on the shape of the load-elongation graphs it can be argued that the following nozzles are not very effective in texturing:
usage of individual tests of as an assessment criteria of nozzle performance in Section 4.3.1, effect of each geometrical parameter is evaluated as follows:

**EFFECT OF LOCATION OF INLET HOLE WITH RESPECT TO NOZZLE EXIT**: 
Model Nozzle 1 cannot texture at all. Additionally, Nozzle 2 (with the second shortest primary flow channel length) has been found not to be producing texturing at the desired level by all the indicators. These facts lead to the conclusion that there is a lower limit for the primary flow channel length for adequate texturing. This limit is approximately 7 mm for the particular type of nozzles. Many indicators (stabilising zone tension, visual inspections of the yarns, analysis of shape of load-elongation graph and increase in linear density) are also in agreement with the suggestion that nozzles with longer primary flow channel produce yarn with better quality. The reasons for longer nozzles performing better can be attributed to the fact, also confirmed by experiments by Demir [19], that they allow the primary flow to accelerate, which results in higher drag force acting on the filaments, consequently promoting filament entangling.

**EFFECT OF TILT ANGLE OF AIR INLET**: 
Three different nozzles with different angle of inclination of the air inlet hole; namely at 30°, 45° and 60°, were tried and the first two seem to make yarn similar in quality according to all the indicators. The latter is suggested to be ineffective in texturing by stabilising zone tension data and analysis of load-elongation graphs. The reason for the nozzles with 45° and 30° to produce adequately textured yarns may be that incoming air flow is introduced to the yarn path at relatively low angles, which increases the amount of air going into the primary flow which in turn results in higher momentum and drag force in

4-17
this direction. This applies greater force on the filaments and consequently causes better texturing.

**EFFECT OF ABSENCE OF TRUMPET SHAPED EXIT:**
Nozzle 12 is ineffective in texturing according to visual inspections and SEM images of the yarns, stabilising zone tension data and analysis of the load-elongation tests. The reason for this nozzle not performing at desired level may be that the trumpet shaped exit profile assists the right angle turn of the yarn as it leaves the nozzle.

**EFFECT OF NUMBER OF AIR INLETS:**
The nozzle with two opposing inlet holes did not a give stable process as indicated by the texturing trials, visual inspections of the yarn, stabilising zone tension and data of increase in linear density.

**EFFECT OF DIVERGENCE ANGLE OF MAIN CHANNEL:**
According to all indications Nozzle 14 does adequate texturing, if not superior to most of the nozzles tested. The reason for this may be the fact that divergence causes supersonic flows to further accelerate, hence, the filaments are carried at higher speeds. Although filaments moving at high speed does not guarantee effective texturing, for this particular case it appears to be beneficial when compared with an identical nozzle but without the divergence in its main channel; i.e. Nozzle 5. This is a further improvement on the already successful design of Nozzle 5.

**4.4. CONCLUSIONS**

1. Most of the model nozzles tested with rectangular cross-section are capable of producing textured yarns with qualities comparable to those obtained from industrial nozzles. It can be concluded that there is no reason to produce texturing nozzles of circular cross-sectional.
Rectangular cross-sectional nozzles have proved to be at least as effective, whereas manufacture of such nozzles is much easier than circular nozzles. This would give the rectangular nozzles the potential for commercial exploitation.

2. The following are the geometric parameters recommended for the design of rectangular nozzles for effective texturing:

i) Nozzles with air inlet hole located far from the nozzle exit, at least 7mm, are beneficial for satisfactory texturing.

ii) A divergence of 1° of main channel is also beneficial for texturing.

iii) The incoming air jet opening to the main channel should not impinge on the filaments at a high angle, but rather meet them in a way to assist their forward motion. The tilt angle of air inlet may be in the range of 30°-45°.

iv) Trumpet shaped exit profile assists texturing.

3. Shape of load-elongation graphs of textured yarns can give information about yarn structure, hence, effectiveness of texturing. The more and/or deeper the tooth in the graph the less effective texturing is.

4. Shock waves are not essential for texturing.
### TABLE 4.1 GEOMETRY OF THE MODEL NOZZLES

<table>
<thead>
<tr>
<th>MODEL NOZZLE</th>
<th>X (mm)</th>
<th>a (degree)</th>
<th>b (degree)</th>
<th>EXIT PROFILE</th>
<th>NUMBER OF INLETS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>5.5</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>8.5</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>10.0</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>11.5</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>13.0</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>14.5</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>16.0</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>6.3</td>
<td>30</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>12.1</td>
<td>60</td>
<td>0</td>
<td>T.E.</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>10.0</td>
<td>45</td>
<td>0</td>
<td>N.E.</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>10.0</td>
<td>45</td>
<td>0</td>
<td>T.E.</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>10.0</td>
<td>45</td>
<td>1</td>
<td>T.E.</td>
<td>1</td>
</tr>
</tbody>
</table>

T.E. Trumpet Shaped Exit Profile  
N.E. No Exit Profile

### TABLE 4.2 PROPERTIES OF YARNS PRODUCED BY THE MODEL NOZZLES

<table>
<thead>
<tr>
<th>NOZZLE NOZZLE NUMBER FEATURE</th>
<th>TENACITY (cN/dtex)</th>
<th>BREAKAGE ELONGAT. (%)</th>
<th>INSTAB. (%)</th>
<th>INCREASE IN LIN. DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 x=5.5mm</td>
<td>3.13</td>
<td>33.8</td>
<td>3.70</td>
<td>13.6</td>
</tr>
<tr>
<td>3 x=7.0mm</td>
<td>2.69</td>
<td>16.9</td>
<td>1.86</td>
<td>14.1</td>
</tr>
<tr>
<td>4 x=8.5mm</td>
<td>2.17</td>
<td>11.9</td>
<td>1.67</td>
<td>17.8</td>
</tr>
<tr>
<td>5 x=10.0mm</td>
<td>2.52</td>
<td>14.2</td>
<td>2.09</td>
<td>16.3</td>
</tr>
<tr>
<td>6 x=11.5mm</td>
<td>1.78</td>
<td>13.5</td>
<td>2.43</td>
<td>16.9</td>
</tr>
<tr>
<td>7 x=13.0mm</td>
<td>1.60</td>
<td>12.8</td>
<td>2.13</td>
<td>17.8</td>
</tr>
<tr>
<td>8 x=14.5mm</td>
<td>1.75</td>
<td>13.9</td>
<td>2.13</td>
<td>18.8</td>
</tr>
<tr>
<td>9 x=16.0mm</td>
<td>1.83</td>
<td>13.3</td>
<td>2.10</td>
<td>18.5</td>
</tr>
<tr>
<td>10 a=30°</td>
<td>1.83</td>
<td>14.0</td>
<td>2.98</td>
<td>16.8</td>
</tr>
<tr>
<td>11 a=60°</td>
<td>1.91</td>
<td>16.8</td>
<td>2.82</td>
<td>14.3</td>
</tr>
<tr>
<td>12 NO-EXIT</td>
<td>1.84</td>
<td>12.9</td>
<td>2.94</td>
<td>15.3</td>
</tr>
<tr>
<td>13 2-INLETS</td>
<td>1.89</td>
<td>12.1</td>
<td>1.79</td>
<td>14.0</td>
</tr>
<tr>
<td>14 b=1°</td>
<td>1.97</td>
<td>14.5</td>
<td>1.86</td>
<td>18.1</td>
</tr>
<tr>
<td>T100</td>
<td>2.06</td>
<td>12.8</td>
<td>1.59</td>
<td>15.6</td>
</tr>
</tbody>
</table>
## TABLE 4.3 STABILISING ZONE TENSION OF THE MODEL NOZZLES

<table>
<thead>
<tr>
<th>NOZZLE NUMBER</th>
<th>NOZZLE FEATURE</th>
<th>STABILISING ZONE TENSION (gram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>x=5.5mm</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>x=7.0mm</td>
<td>22.2</td>
</tr>
<tr>
<td>4</td>
<td>x=8.5mm</td>
<td>22.2</td>
</tr>
<tr>
<td>5</td>
<td>x=10.0mm</td>
<td>23.3</td>
</tr>
<tr>
<td>6</td>
<td>x=11.5mm</td>
<td>22.2</td>
</tr>
<tr>
<td>7</td>
<td>x=13.0mm</td>
<td>23.3</td>
</tr>
<tr>
<td>8</td>
<td>x=14.5mm</td>
<td>23.3</td>
</tr>
<tr>
<td>9</td>
<td>x=16.0mm</td>
<td>25.5</td>
</tr>
<tr>
<td>10</td>
<td>a=30°</td>
<td>24.4</td>
</tr>
<tr>
<td>11</td>
<td>a=60°</td>
<td>22.2</td>
</tr>
<tr>
<td>12</td>
<td>NO-EXIT</td>
<td>3.5</td>
</tr>
<tr>
<td>13</td>
<td>2-INLETS</td>
<td>0.0</td>
</tr>
<tr>
<td>14</td>
<td>b=1°</td>
<td>23.3</td>
</tr>
</tbody>
</table>
FIGURE 4.1 THE BASIC DESIGN
FIGURE 4.2a

MODEL NOZZLE 1-9

LOUGHBOROUGH UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
DRAWN: SULE BILGIN NOT TO SCALE A.R. = 0.67
TITLE: AJT MODEL NOZZLE (Various X)
FIGURE 4.2b
MODEL NOZZLE 10-11

LOUGHBOROUGH UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
DRAWN: SULE BILGIN | NOT TO SCALE | A.R.=0.67
TITLE: AJT MODEL NOZZLE (Various angle)
FIGURE 4.2c
MODEL NOZZLE 12

LOUGHBOROUGH UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
DRAWN: SULE BILGIN NOT TO SCALE
TITLE: AJT MODEL NOZZLE (NO TRUMPET EXI)
FIGURE 4.2e MODEL NOZZLE 14

LOUGHBOROUGH UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
DRAWN: SULE BILGIN NOT TO SCALE A.R. = 0.67
TITLE: AJT MODEL NOZZLE (DIVRG. MAIN CHA)
FIGURE 4.3a NOZZLE 2 (x=5.5 mm)

FIGURE 4.3b NOZZLE 5 (x=10.0 mm)

FIGURE 4.3c NOZZLE 9 (x=16.0 mm)

FIGURE 4.3d NOZZLE 10 (a=30 degree)
FIGURE 4.3e NOZZLE 11 (\(\alpha=60\) degree)

FIGURE 4.3f NOZZLE 12 (NO EXIT PROFILE)

FIGURE 4.3g NOZZLE 13 (2 INLETS)

FIGURE 4.3h NOZZLE 14 (DIV. MAIN CHA.)
FIGURE 4.4 STABILISING ZONE TENSION DATA OF THE MODEL NOZZLES
FIGURE 4.9a
Supply Yarn

Load (gram)

800

Elong. (%)
FIGURE 4.9b

Load (gram) vs. Elongation (%)

Model Nozzle 2
(x=5.5 mm)

400

36.5

FIGURE 4.9c

Load (gram) vs. Elongation (%)

Model Nozzle 3
(x=7.0 mm)

400

17.1
FIGURE 4.9d

Load (gram) vs. Elong. (%)

Model Nozzle 4
(x=8.5 mm)

Elong. (%)

13.8

FIGURE 4.9e

Load (gram) vs. Elong. (%)

Model Nozzle 5
(x=10.0 mm)

16.5
FIGURE 4.9f

Load (gram)  FIGURE 4.9f
400

Elong. (%)
Model Nozzle 6
(x=11.5 mm)
14.8

FIGURE 4.9g

Load (gram)  FIGURE 4.9g
400

Elong. (%)
Model Nozzle 7
(x=13.0 mm)
13.0
**FIGURE 4.9h**

Load (gram)

400

Elong. (%)

Model Nozzle 8
(x=14.5 mm)

12.1

**FIGURE 4.9i**

Load (gram)

400

Elong. (%)

Model Nozzle 9
(x=16 mm)

11.7
FIGURE 4.9j
Model Nozzle 10
(a=30°)

FIGURE 4.9k
Model Nozzle 11
(a=60°)
FIGURE 4.9l
Model Nozzle 12
(No Exit Profile)

FIGURE 4.9m
Model Nozzle 13
(2 Inlet Holes)
FIGURE 4.9n

Model Nozzle 14
(Divergent Channel)
The pulling force exerted during tensile tests.

**FIGURE 4.10** Breakage behaviour of yarns with parallel and entangled filaments during tensile tests.
FIGURE 4.11 SHADOWGRAPH OF THE PRIMARY JET CREATED BY THE MODEL NOZZLES
CHAPTER 5
EFFECT OF WETTING SUPPLY YARN ON AIR-JET TEXTURING

5.1 INTRODUCTION

In AJT, passing the supply yarn through a water bath or spray head is a common practise in industry since experience has proven that wet texturing is essential for improved texturing. In the case of dry texturing, the yarn has fewer, larger and looser loops, which can be removed more easily under tension. Improvements achieved in the AJT process due to wetting and differences between structures of dry and wet textured yarns have been investigated relatively thoroughly by other researchers [2, 3, 19]. However, it cannot be said that the mechanism of wetting is fully understood. Therefore it requires further investigations for a better understanding, which may in turn lead to improved textured yarn formation.

This chapter describes an investigation of the effect of wetting of the supply yarn on the texturing process. Firstly, possible factors through which wetting can affect the process are analysed in Section 5.2. Subsequently, several experiments are devised to quantitatively investigate the role of wetting in Section 5.3. Finally, the results with a final analysis are presented in Section 5.4.

5.2 METHOD OF APPROACH

Wetting can affect the process with respect to the following aspects:

i) effect of water on the air flows
ii) effect of water on the filaments
   a) filament-to-filament friction
   b) yarn-to-solid friction
   c) yarn-to-air friction
An investigation of these can assist the understanding how wetting actually improves the process.

5.2.1. EFFECT OF WATER ON AIR FLOWS

There are several ways for the water to influence an air flow; such as, flow velocity and shock wave pattern.

No experimental work has been reported in the literature as to the effect of water on air flow velocities in texturing nozzles. Some theoretical calculations by Acar [2], which used two-phase flow theory, predicted approximately 2-5% reduction in the air velocity. This reduction in velocity is too small to cause major changes in the process. Nevertheless, any effect on the air flow would be to reduce the air flow which may adversely affect the texturing.

As far as the effect of water on shock waves is concerned, shadowgraphs of both dry and wet jets as reported by Demir [19] did not exhibit any difference in their shock wave patterns, ruling out a possible explanation of the effect of wetting on the process through altering shock waves. Such an effect is highly unlikely since the shock waves have shown to play no role in texturing ([2] and also see Chapter 3 and 4 of this thesis).

Consequently, it can be concluded that filament wetting has no significant effect on the properties of the air flow in AJT nozzles.

5.2.2. EFFECT OF WATER ON THE FILAMENTS

As listed in Section 5.2, water can effect frictional behaviour of filaments in three ways:

a) filament-to-filament friction
b) yarn-to-solid friction
c) yarn-to-air friction
In order to be able to investigate these three types of friction, it is necessary to know the amount of water on the filament surface and/or amount and form of water in the surrounding air flows. It should be borne in mind that an AJT nozzle delivers flows along the yarn path in opposite directions, with differing flow properties. This nature of the flows in AJT determines the amount of water on the filaments and the water mixing into the flow during wet texturing, hence, the frictional behaviour of the filaments. In the secondary flow, for example, the air flows against the motion of the yarn and this prevents most of the water from entering the nozzle [2].

Consequently, first of all, the path that the yarn follows is divided into consecutive zones according to water content on the filaments and in the air flow. The yarn path considered is between the wetting unit and the delivery rollers and shown in Figure 5.1. After the partition of the yarn path, effect of wetting on filaments is comparatively investigated in each zones under the dry and wet texturing conditions.

Partition of Yarn Path in AJT for Analysis of Effect of Water on Filaments

As a first approximation, the yarn path can be divided into four zones according to water content on the yarn (Figure 5.1).

Zone 1: Yarn path between the wetting unit and the meeting point of the yarn with the secondary jet
Zone 2: Yarn path between Zone 1 and the position of the incoming air flow in the main channel.
Zone 3: Yarn path in the primary flow.
Zone 4: Yarn path after leaving the primary jet

Analysis of the Effect of Water in the Zones

In this section, the effect of water on filament-to-filament and yarn-to-metal friction, has been taken into account since
attempts to obtain data concerning yarn-to-air friction have failed.

**Wet Texturing:**

In Zone 1, between the wetting unit and the point where the yarn meets the secondary jet, the yarn is soaked in water and, hence, there is an excess amount of water in the yarn at all times enveloping it. A water flow rate of 11/h, which is well in the range of industrial practice, completely saturates the yarn. This water flow rate is more than sufficient to impart the effect of wetting since the minimum flow rates of water for effective texturing were reported to be 0.06, 0.2 and 0.1 l/h respectively by Demir [19], Artunc [4] and Bock et al [7].

In Zone 2, both the yarn and the flow are still moist. In Zone 3, water on the filaments is considerably less than that in Zone 2 since the secondary flow sprays out most of the water [2]. However some water trapped between the filaments enter the primary flow. This is evident in the water sprayed out by the primary jet. It is not practically possible, however, to quantify exact amounts of water remaining on the yarn and mixed into the flow. Since the air flow in Zone 2 and 3 contains moisture, the filament in Zone 1, 2 and 3 can be considered wet.

In Zone 4, the textured yarn feels dry since almost all the remaining water in Zone 3 is now blown from it by the primary flow.

It was shown by Acar [2] that in the case of wet texturing, some of the spin finish on the supply yarn is removed. The reduction in the spin finish level was reported to be in the range of 60-85% [3], depending on the types of the yarn and the spin finish material applied to the yarn.

It can, therefore, be assumed that the yarn which has just been textured in Zone 4
(a) is virtually dry and
(b) contains less spin finish than the supply yarn.
Dry Texturing:
Acar [3] showed that dry texturing makes no significant changes to spin finish on the surface of the yarn. So it can be assumed that in dry texturing, in the absence of water, frictional characteristics of the yarn remains much the same as its original form throughout all the subsections of the yarn paths considered.

5.3. EXPERIMENTATION

The experiments (yarn-to-yarn and yarn-to-metal friction) were comprised of two tasks:

i) preparation of the yarns for the friction tests
ii) performing yarn-to-solid and filament-to-filament friction experiments

5.3.1. PREPARATION OF YARNS FOR FRICTION MEASUREMENTS

A summary of the above analysis of properties of the yarns in each zone is presented as follows:

<table>
<thead>
<tr>
<th></th>
<th>DRY TEXTURING</th>
<th>WET TEXTURING</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIN</td>
<td>Zone 1 : as original</td>
<td>Zone 1 : as original</td>
</tr>
<tr>
<td>FINISH</td>
<td>Zone 4 : as original</td>
<td>Zone 4 : reduced</td>
</tr>
<tr>
<td></td>
<td>Zone 1 : dry</td>
<td>Zone 1 : immersed in water</td>
</tr>
<tr>
<td>WATER</td>
<td>Zone 4 : dry</td>
<td>Zone 4 : almost dry</td>
</tr>
</tbody>
</table>

The frictional behaviour of the yarn in Zones 2 and 3 during wet texturing would be more similar to that in Zone 1 than Zone 4, since the yarn is wet, although in different degrees in the different zones.

The above table shows that comparing frictional behaviour of filaments in Zone 1 in dry and wet texturing requires two types of yarns:
Yarn in Zone 1-WET AJT original level of spin finish and soaked in water
Yarn in Zone 1-DRY AJT original level of spin finish and dry

The table also shows that comparing frictional behaviour of filaments in Zone 4 in dry and wet texturing requires further two types of yarns:

Yarn in Zone 4-WET AJT reduced spin finish and dry
Yarn in Zone 4-DRY AJT original level of spin finish and dry

As can be seen, Yarn in Zone 4-DRY AJT and Yarn in Zone 1-DRY AJT are the same.

It should be noted that all yarns tested are of parallel structure, but vary in their spin finish and/or whether they are wet or dry during the tests. Wet situation was simulated by passing the yarn through tap water. Soxhlet Extraction Method, whose details are given in [52], was used for both determining the amount of spin finish and reducing it to the required level.

Prior to preparing the yarns for the tests, the amounts of spin finish on the yarn before and after wet-texturing were measured by the Soxhlet Extraction Method.

Two yarns with different levels of spin finish, but otherwise identical, were prepared. The first yarn (Yarn in Zone 4-DRY AJT) is the supply yarn. The yarn is the supply yarn which has been used in all texturing trials throughout this research. Its spin finish was measured by the Soxhlet Extract Method, and found to be 0.7% of its total weight. The second yarn (Yarn in Zone 4-WET AJT) is the same yarn as the supply yarn but with a reduced amount of spin-finish, representing the wet textured yarn in Zone 4. The spin finish on the yarn after being wet textured was found to be 0.2% of its total weight and the spin finish of the yarn to be tested (Yarn in Zone 4-
WET AJT) was reduced to this level by the same method. It should be noted here that the yarns are both untextured and differ only in the amount of their spin finish material.

5.3.2. YARN FRICTION EXPERIMENTS

Yarn-to-yarn friction experiments
Although this investigation seeks to analyse filament-to-filament friction, it has not been possible to identify a completely satisfactory experimental technique or procedure for such experiments. It was decided that it would be almost impossible to devise an experiment to determine the filament-to-filament friction without damaging the very fine filaments, of approximately 17 µm diameter. Therefore, instead, yarn-to-yarn friction experiments were carried out and it was assumed that these could closely simulate filament-to-filament friction experiments.

Yarn-to-yarn friction experiments under dry and wet conditions were conducted by using a simple technique which is based on the method suggested by Lindberg [43] and Prevorsek et al [48]. The technique, illustrated in Figure 5.2, basically involves determination of static friction coefficient of two yarns, which were twisted n times on each other. A constant tension, $T_1$, is applied to the first yarn. One end of the second yarn is left free and an increasing amount of tension $T_2$ is applied to the other end until slippage occurs. It is clear that high values of $T_2$ indicate high yarn-to-yarn friction.

In all texturing trials n was taken to be 50 and $T_1$ was chosen as 50 gram. The values of n and $T_1$ were found experimentally.

Yarn-to-solid friction experiments
In AJT the yarn has contact with the inner walls of nozzle as well as the yarn guide prior to the nozzle. Consequently, yarn-to-metal friction experiments were carried out not only to investigate the frictional behaviour of filaments on metal
surfaces but also to compare such behaviour with filament-to-filament friction.

The experimental rig devised (Figure 5.3) essentially consists of a highly polished steel rod to simulate the surface finish of the industrial nozzles, over which the yarn is hung. At one end of the yarn, a constant weight of 50 gram, $T_1$, was hung and at the other end weights increasing at increments of 5 gram, $T_M$, are applied. $T_M$ is the value at which the yarn slips over the rod. Clearly, high values of $T_M$ indicate high yarn-to-metal friction.

5.4. RESULTS AND DISCUSSIONS

Ten samples were tested for each set of experiments and $T_Y$ and $T_M$ values for each yarn are presented in Table 5.1. The results can be stated as follows:

**Yarn-to-yarn friction**

I) **ZONE 1**: $T_Y$ values of Yarn in Zone 1-WET AJT and Yarn in Zone1-DRY AJT 30.0 and 35.0 gram respectively; with standard deviations of 2.4 and 2.8 gram respectively. This result implies that in wet texturing the filaments experience lower yarn-to-yarn friction in Zone 1 than dry texturing. This confirms the results reported by Kothari et al [39], which state that water decreases interfilament friction in the case of PET yarns.

II) **ZONE 4**: Yarn in Zone 4-WET AJT and Yarn in Zone 4-DRY AJT have $T_Y$ values of 39.5 gram and 35.0 gram respectively with the standard deviations of 2.4 and 2.8 gram. The results lead to the conclusion that in wet texturing the filaments experience higher yarn-to-yarn friction in Zone 4 due to the removal of some of the spin finish material on the yarn.

**Yarn-to-metal friction**

III) **ZONE 1**: Yarn 1-WET AJT and Yarn 1-DRY AJT have $T_M$ values of 74.1 gram and 104.0 gram with standard deviations of 3.0
3.2 gram respectively. This means that wetting substantially reduces yarn-to-metal friction in Zone 1.

IV) ZONE 4: Yarn 4-WET AJT and Yarn 4-DRY AJT have almost equal values of $T_{M_2}$, 104.0 and 103.0 gram respectively. The slight difference in these mean values is not statistically meaningful because of the high standard deviations, 3.2 and 3.5 gram respectively. This means that wetting does not alter yarn-to-metal friction properties of the filaments in Zone 4.

5.5. CONCLUSIONS

The experiments clearly show that wetting, which reduces the amount of spin finish on the yarn, causes low interfilament friction prior to the nozzle (Zone 1), but high interfilament friction when formed into the textured yarn (Zone 4). The low interfilament friction in Zone 1, as reported earlier by Acar [2], may assist the longitudinal movement of filament relative to each other, which assists loop formation.

Wetting also causes yarn-to-metal friction to decrease considerably prior to the nozzle, which means that the filaments can move forward with less resistance.
TABLE 5.1. YARN-TO-YARN and YARN-TO-METAL FRICTION DATA

<table>
<thead>
<tr>
<th></th>
<th>YARN-YARN FRIC.</th>
<th>YARN-METAL FRIC.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_Y$</td>
<td>$\sigma_Y$</td>
</tr>
<tr>
<td><strong>YARN 1-WET AJT</strong></td>
<td>(original spin finish and soaked in water)</td>
<td>30</td>
</tr>
<tr>
<td><strong>YARN 1-DRY/YARN 4-DRY AJT</strong></td>
<td>(original spin finish and dry)</td>
<td>35</td>
</tr>
<tr>
<td><strong>YARN 4-WET AJT</strong></td>
<td>(reduced spin finish and dry)</td>
<td>39.5</td>
</tr>
</tbody>
</table>
ZONE 4
Rollers

dry, spin
finish free yarn

ZONE 3
Yarn Guide

ZONE 2
wet yarn
with spin finish

ZONE 1
wet yarn
with spin finish

FIGURE 5.1 DIVISION OF YARN PATH IN AJT ACCORDING TO AMOUNT OF WATER AND SPIN FINISH CARRIED BY THE YARN

feed rollers

wetting unit

air inlet hole
FIGURE 5.2 YARN-TO-YARN FRICTION MEASUREMENT SYSTEM
FIGURE 5.3 YARN-TO-METAL FRICTION MEASUREMENT SYSTEM
CHAPTER 6
HIGH SPEED FILMING OF YARN MOTION INSIDE AN AIR-JET TEXTURING NOZZLE

6.1. INTRODUCTION

In the AJT process, modification of compact, parallel filament yarn(s) into a more voluminous, entangled and convoluted one occurs as a result of the interaction between the air flow and the filaments. Investigation of this interaction can shed light on the loop formation mechanism, which, in turn, may assist the design process of improved AJT nozzles. In this chapter, the AJT process is investigated by drawing together the following experimental information in order to relate yarn motion to yarn structure:

i) Investigations of the AJT process under different process conditions by means of high-speed cine photography

ii) Examination of the structure of the yarn produced at these conditions

The air-flow/filament interaction takes place both inside and outside the nozzle. In the work of Acar [2] and Demir [19] high-speed cine films were taken outside AJT nozzles showing the filaments leaving the nozzle and being drawn at 90° degrees to the delivery rollers. Since both researchers used industrial nozzles in their work with circular cross-sections, it was not possible to visualise the flow and the filament behaviour inside such nozzles. Bock et al [8], used a two-dimensional rectangular cross-sectioned version of a converging-diverging type AJT nozzle with two parallel walls made out of glass for instantaneous Schlieren photography, which showed both shock waves and filaments inside the nozzle. Since these photographs were instantaneous single frame pictures, they did not provide
complete information about the motion of the AJT process. There has been no other visual information in the literature relating to filament behaviour inside the nozzle.

In this work a nozzle with rectangular cross-section has been used for high-speed cine-photography. Nozzles with rectangular main channels have been shown, in Chapter 4, to give satisfactory textured yarns. Such nozzles are easy to manufacture and eliminate image distortion associated with circular cross-section nozzles in visual investigation of the filament behaviour inside the nozzle.

The fast and complex yarn motion due to turbulent nature of the flow involved in AJT requires a large number of consecutive images of yarn motion at the highest possible rate of filming in order to capture the real texturing process. Therefore high speed photography with a maximum frame rate of 10,000 frames per second (fps) has been deployed for the investigation.

The high speed films have been taken at different process conditions (dry, wet, high overfeed and low pressure texturing) and evaluated by introducing a quantitative technique, which basically consists of counting a set of defined parameters over a number of frames for each set of process conditions.

This work makes it possible to observe and quantify the whole filament motion inside and outside the main channel where the filament yarn interacts with both primary and secondary flow as well as being impinged upon by the incoming jet from the air inlet channel.
6.2. EXPERIMENTATION

6.2.1. THE MODEL NOZZLE

The model nozzle used in the high-speed filming is Nozzle 5 reported in Chapter 4. Its glass sidewall enabled filming of the filaments inside the nozzle. Geometrical features of the nozzle are presented in Figure 6.1.

6.2.2. HIGH-SPEED PHOTOGRAPHY SYSTEM

The high speed photography system is schematically illustrated in Figure 6.2 and comprises the following units:

i) High speed camera

ii) Copper vapour pulse laser, comprising the laser head, control unit, Neon tank

iii) Optical fibre

A PHOTEC Rotating Prism 16 mm High Speed Motion Picture Camera by Photonic Systems Inc. [37] was used to take high speed-cine films of the AJT process. The camera takes interchangeable lenses from Mamiya 645 series of medium format still cameras. It can run at the maximum rate of 10,000 frames per second with a full frame-height prism. The frame rate can be doubled by fitting a half-frame prism (split prism). These frame rate values are only the maximum values; the frame rate in the actual film is governed by the length of the film which in turn determines the maximum speed of film transportation during filming, which obviously varies along the length of the film and accelerates with time. The actual film rate is indicated by the locally marked timing dots on the film.

Pulsed illumination with an average power of 10 Watts, provided by an Oxford Lasers Cu10, Copper Vapour Pulse
Laser, is deployed as the light source. Pulse repetition rate is set at 10 KHz and synchronised with the frame rate of the high-speed camera (for more information see Ref.37). The repetition rate of 10 KHz and the average output of 10 Watts give a pulse energy of 1mJ for a duration of approximately 25 ns. The single pulse is short enough freeze the motion of the filaments and powerful enough to obtain sufficient exposure.

The light is transported from the laser head through an optical fibre to the area to be filmed. The image is recorded on a 16mm Ilford motion picture film and the film is developed by using a 16/35B JHPI (John Hadland) Negative Film Processor.

Setting up the system requires the followings:

i) Selection of correct lens which covers the area to be viewed and with the required aperture and depth of focus.
ii) Correct location of the optic fibre with respect to the object to be filmed to ensure the right lighting conditions; i.e. uniform lighting with no shadows cast on the filaments.

6.2.3. PROCESS CONDITIONS

The AJT process has been filmed under the following test conditions to be able to compare extreme texturing conditions, such as wet and dry texturing, high overfeed texturing and low pressure texturing:
### Table

<table>
<thead>
<tr>
<th>Process Conditions</th>
<th>Air Pressure (gauge)</th>
<th>Overfeed (%)</th>
<th>Yarn Wetting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Process Conditions (SPC)</td>
<td>8bar</td>
<td>20%</td>
<td>11/h</td>
</tr>
<tr>
<td>Dry texturing</td>
<td>8bar</td>
<td>20%</td>
<td>dry</td>
</tr>
<tr>
<td>High Overfeed Texturing</td>
<td>8bar</td>
<td>50%</td>
<td>11/h</td>
</tr>
<tr>
<td>Low Pressure Texturing</td>
<td>3bar</td>
<td>20%</td>
<td>11/h</td>
</tr>
</tbody>
</table>

### 6.3. RESULTS AND DISCUSSIONS

#### 6.3.1. EVALUATION OF HIGH SPEED-CINE FILMS OF THE AJT PROCESS

Although 2000 consecutive frames have been viewed and visually analysed for each set of processing conditions, only reprints of a randomly selected set of 10 consecutive images from each series of 2000 frames are given in Figure 6.3a-d. When all the films are examined it has been noted that the filament yarn exhibits three main regimes of motion:

**Filament Motion 1**: The filament yarn moves as one bundle whereby individual filament stay compact

**Filament Motion 2**: Filaments open-up and separate.

**Filament Motion 3**: Separated filaments are mixed, form loops and become entangled.

Each of these types of yarn motion, which are schematically illustrated in Figure 6.4a, predominantly takes place in a different region of the nozzle. Hence the nozzles can also be divided into three corresponding zones as shown in Figure 6.4b. Although boundaries of these flow zones cannot be precisely defined due to the time dependent characteristics of the yarn motion, it is still possible to
divide the flow into certain flow regions for the purpose of the analysis:

**Flow Zone 1**: Secondary flow
**Flow Zone 2**: Mixing zone and primary flow
**Flow Zone 3**: Free jet

In Zone 1, the first type of yarn motion is dominant; i.e. the filament yarn appears to be a single yarn, the multifilament structure of the yarn is not evident since the yarn stays as a compact bundle. Subsequently the filaments separate but there is no fixed location for the filament separation point, which moves around the area of the introduction of air into the main channel, staying mostly on the secondary flow side of this point. After the separation point the filaments exhibit random wavelike movements in Zone 2, sometimes following almost a straight line (Figure 6.5a) but generally undulating (Figure 6.5b). In any case, filaments do not mix very much, but the same type of motion is experienced by the majority of filaments. In other words, if the filaments take up a wavy shape inside the nozzle, for example, the shape of the curve is similar for the majority of strands and, therefore, this waviness does not result in individual filaments having significant relative displacement in the direction of the nozzle axis. Consequently it can be argued that no loop on individual strand is formed in Zone 2. This suggests that the yarn in Zone 2 is still far from becoming "textured yarn", but mostly in its original parallel structure, although separated and opened up.

The parallel but mostly separated state of the filaments in Zone 2 changes into a more convoluted form in Zone 3. In this region, unlike Zone 2, individual filaments may have considerably different motion patterns from neighbouring filaments. Individual filaments mix and entangle and form into loops and their shape can be very different.
Therefore it can be stated that the interaction with the air flow preconditions the filaments in Zone 2 and actual texturing takes place in Zone 3.

Another interesting point to note is that in Zone 2 and partly in Zone 3, filaments are drawn together from time to time although in previous and subsequent views they were separated to a high degree and scattered in the main channel. This could suggest intermittent, very fast translational movement by filaments but it is much more likely that the filaments are rotating in the channel. The occurrence of local twist, let alone the magnitude and direction, cannot be ascertained by the present films, which only show what is happening to the filaments at one plane from a single view.

Having described the AJT process generally without reference to specific process conditions, the filament motion is investigated in more detail by quantitative analysis of a number of parameters which are counted over 100 consecutive frames for each set of processing conditions. Parameters of the quantitative analysis with the reference points are given in Figure 6.6.

Since the texturing speed is 200 m/min and the frame rate achieved is approximately 10 000 frames/s (the local frame rate calculated from the timing marks on the particular part of film), the 100 frames correspond to 33 mm of yarn approximately.

The parameters of the Quantitative Technique

a) \((A)\): Relative distance of the point where the constituent filaments of the yarn begin to separate, with respect to the intersection point of axis of the main channel and that of the inlet hole. This separation point defines the boundary between Zones 1 and 2.
b) **(B)**: Distance from the nozzle exit plane to the starting point of individual loop formation. This defines the boundary between Zone 2 and 3.

c) **(C)**: The distance between nozzle exit and the furthest point of any filament reached outside the nozzle.

The above parameters were counted over 100 frames of each processing conditions (Table 6.1) and the following results have been found:

**I. Yarn motion in Zone 1**
The filament separation point usually lies on the primary flow side but occasionally moves up to 3mm from the reference point. Very rarely, it lies on the exit side of this point. Variations in process conditions do not appear to result in a large change in the location of the separation point (see Table 6.1). On average, A has been found to be 1.51 mm, 1.33 mm, 2.11 mm and 1.59 mm for the standard processing conditions (SPC), dry texturing, 50% overfeed and low pressure texturing respectively. Standard deviations of A are 0.69, 0.96, 0.64 and 0.78 mm respectively. The relatively high standard deviation of dry texturing indicates that fluctuation of the separation point is the highest.

Although it was expected that the filaments would constantly be pushed against the opposite wall due to impinging effect of the incoming jet, this was not observed to be the case. The films clearly show that filaments in the region of the incoming flow into the main channel are sometimes even not touching the opposite wall of the main channel. It has also been observed that they are sometimes undulating. This suggests that the impingement effect of the incoming flow does not seem to be that intense.
II) Yarn motion in Zone 2

In Zone 2, the filaments stay separated and do not seem to be experiencing high tension, which is evident from their oscillating motion.

Filament motion in Zone 2 looks very similar for all the filmed processing conditions. Even in the case of 50% overfeed the filaments do not exhibit any accumulation inside the nozzle but intermingle and form loops around the exit. In other words regardless of the overfeed ratio, the filaments are still separated in the primary flow. Briefly, filament behaviour from one set of processing conditions to another is hardly distinguishable until the boundary between Zone 2 and 3.

The similarity for different processing conditions in the pattern of filament motion inside the nozzle is not unexpected because the filaments inside the nozzle are mainly under the effect of air dragging them along the flow. As far as the supply pressure is concerned, which governs flow velocity, the way that the filaments are carried along is similar no matter whether the flow is fast or slow, except at extremely low pressures.

With respect to the high overfeed, the flow is quite capable of carrying the excess amount of filaments with similar yarn tension as those of SPC. It is not possible to measure yarn tensions inside the nozzle, but their slackness, which exhibits no significant difference from one process to another, confirms that the yarn in the nozzle experiences similar drag. Similarly, in the case of dry texturing the flow carries the filament inside the nozzle in no different way from the other conditions.

This situation leads to the conclusion that the function of the air flow inside the nozzle is simply to carry the filaments forward and, in the mean time, open them up.
The distance $B$ has been found to be 0.72 mm and 0.26 mm for SPC and dry texturing. This means that in the case of dry texturing loop formation takes place further outside the nozzle. Standard deviations of dry and wet texturing are very close, 0.61 and 0.67 in Table 6.1.

The point where loop formation starts cannot be identified clearly in the cases of 50% overfeed and 3bar. In the case of 50% overfeed there are too many filaments obscuring the exact point of loop formation. With respect to 3bar operation, the fact that the loops are in the form of open arcs, rather than closed loops, makes it difficult to pinpoint the point of beginning of loop formation. Consequently Parameter $B$ for these two cases are denoted with N/A.

**III) Yarn motion in Zone 3**

e) In Zone 3 in the case of SPC the filaments follow the contour of the exit shape more closely whereas in other conditions they are jetted further away from the nozzle in the direction of the primary jet. Table 6.1 presents the furthest point that the filaments reach at each processing conditions, Parameter $C$. It has been found that the filaments are carried out of the nozzle in the direction of the primary flow at an average distance of 1.41mm from the nozzle exit for SPC and 2.10, 1.85 and 2.04 mm in the case of dry texturing, 50% overfeed and low pressure texturing respectively. Similar investigations performed by Acar [2], in which he used single shot high-speed photography technique and a cylindrical type HemaJet nozzle, found $C$ to be 1.4 and 2.2 mm for wet and dry texturing respectively. These results are very close to the present results. It should be noted that all the process conditions were the same as those of the present investigations, except process speed in Acar’s investigations was 450 m/min, whereas in the present experiments it was 200m/min.
Standard deviations of C in the cases of SPC, dry texturing, 50% overfeed and 3 bar are 0.56, 0.60, 0.57 and 0.78 respectively. With the exception of 3 bar pressure the results are very close.

The sum of B and C approximately gives the range in which loop formation occurs and it has found to be 2.13 and 2.35 mm for SPC and dry texturing. This means that loops are created almost within a similar range of distance.

The loops and arcs created in Zone 3 are quite similar in shape for all sets of process conditions; except in 3bar operation, in which the formations are relatively larger and more open.

6.3.2. VISUAL INSPECTION OF YARN STRUCTURE

In order to relate the information of yarn motion obtained from the high speed films to the structure of the resultant yarns created by these process conditions, yarns have been visually inspected and photographs of yarns produced at the four different set of processing conditions are presented in Figure 6.7a-d, which show yarns made at SPC, dry texturing, 50% overfeed and 3bar operations respectively.

The photograph of the yarns produced at the SPC, Figure 6.7a, shows a uniformly textured yarn with loops regularly distributed along the yarn. The dry textured yarn, shown in Figure 6.7b, has occasional untextured sections and it has larger and fewer loops than the yarn produced under SPC. In the case of 50% overfeed operation there is a more identifiable core and relatively larger number of loops than the other three cases investigated. The uniform structure of the yarn in Figure 6.7c suggests that the model nozzle is capable of converting the extra overfed yarn into textured yarn successfully. Figure 6.7d shows the yarn produced at 3bar operation and exhibits an
inadequately textured yarn. The yarn is distinctively different from the remaining yarns with its long untextured sections and large loops.

6.3.3. EVALUATION OF THE FILMS AND YARN STRUCTURE TOGETHER

In this section the information obtained from the films and examination of yarn structure are evaluated together in an attempt to identify the elements necessary for successful texturing.

As far as the SPC and dry texturing operations are concerned it can be seen in the high speed-cine films that the loops as they form have similar shapes in both cases. That there are differences in the structure of the resultant yarn leads to the conclusion that the loops formed at the exit are probably not fixed into the core of the yarn in the same way in both dry and wet texturing conditions, resulting in yarns with different stabilities.

The distinctly different structure of the yarn obtained at the low pressure operation is also evident in the high-speed films, with the large loops being formed in the area of texturing.

From the above discussions it can be argued that there are two major elements in texturing:

a) The formation of loops
b) Fixing the formed loops in the yarn permanently

6.3.4. THE MECHANISM OF AJT PROCESS

In the above section, two elements were identified for successful texturing, namely loop formation and fixing the loops in the yarn. In this section, these two elements are investigated in detail:
Loop formation during texturing: Considering in general, without specific reference to AJT, if a loop is to be formed in a piece of yarn it must be bent by turning, at least, one end of it at a large angle (Figure 6.8a). The 90° delivery in AJT, therefore, has a crucial importance in loop formation. However the deflection in the yarn path is not enough on its own to create the loops desired in AJT; the trailing end should be moved forward and, hence, making the loop formed smaller (Figure 6.8b). If the trailing end of the yarn is not moved forward, a mere turning of the leading end creates a loop which simply consists of an open arc with a high radius of curvature. In AJT process in Zone 3, the leading end of the filaments does not experience the effect of air jet due to the 90° delivery whereas the trailing end is still inside the jet, hence, moved forward by the pressure and friction drag forces created by the jet. In other words, as long as the right angle delivery is present and the trailing end is forwarded then loop formation can take place. The inadequacy in low pressure texturing can therefore be explained by the fact that the second requirement of loop formation is not fulfilled; i.e. the drag force driving the upstream end forward is considerably small due to low pressure, resulting in large loops.

In the case of dry texturing, the operation is not successful. Presence of this unsuccessful texturing case, in which despite the fact that loops are formed in the same way as the wet texturing, can be explained by the inadequacy of the second element mentioned in Section 6.3.3, i.e. securing the loops in the yarn. The reason for the inadequate loop fixing in dry texturing could be due to low interfilament friction. In Chapter 5 it has already been found that wet texturing reduces the spin finish on the yarn resulting in a yarn with higher interfilament friction in the zone of texturing. Consequently it can be stated that in the case of wet texturing, the process is
successful because the loops created are fixed in the yarn more firmly due to higher interfilament friction.

Since fixing the loops is as important as creating them, this leads to the conclusion that the effectiveness of texturing can be improved by ensuring that the interfilament friction in the textured yarn is high during the final loop fixing stage of the process. Such an increase in the interfilament friction should be attained locally in the area of loop formation only. Wetting the filaments performs this task satisfactorily since it reduces the friction prior to the filament yarn entering the nozzle and inside the nozzle but gives a rise to the interfilament friction in the newly textured yarn by removing the spin finish. If the increase in the interfilament friction is not ensured in locally in the area of fixing the loops to the yarn but occurs in other zones as well, the process is adversely affected, because high interfilament friction between the filaments throughout the whole process prevents them having relative movement, which is essential for loop formation. This may also explain why Kothari et al [39] could not obtain adequate texturing with a supply yarn with high interfilament friction at all stages of the process.

In summary, in AJT low interfilament friction is desirable for loop formation but high interfilament friction is desirable for securing the loops created.

6.4. CONCLUSIONS

1. No loop formation takes place inside the main channel.

2. Evaluation of the high speed films clearly shows that successful loop formation is not sufficient on its own for successful texturing. In this case for successful texturing, it has been deduced, the loops created must be
firmly fixed to the resultant yarn as well.

It has been concluded that the AJT process occurs as a result of forming loops in individual filaments and then, equally importantly, somehow anchoring these loops in the yarn. The first element; loop formation, is achieved by,

* high speed flow which propels the filaments
* 90° turning in yarn path, facilitating formation of loops and increasing pressure drag force on the filaments
* wetting the filaments, reducing the friction between the filaments, which facilitates easy relative motion of the filaments

The second element necessary for adequate texturing, i.e. locking the created loops in the yarn, can be achieved by increasing interfilament friction locally in the area of texturing only. Wetting the filaments has been shown in Chapter 5 to be achieving the local high friction in the area of texturing.

3. In the case of low pressure operation the loops created are larger than in the case of high pressure operations, leading to the conclusion that the resultant yarn is deficient because the loop formation is not successful; the first element for successful texturing is not complied.

4. It appears from the films that during texturing the filaments are moving laterally inside the nozzle, suggesting a twisting action.

5. In the case of dry texturing loop formation starts further downstream than wet texturing, but the distance within which loop formation takes place is approximately the same for both dry and wet conditions. Also the shape of the loops is similar in both cases.
### TABLE 6.1 QUANTIFIED YARN MOTION

<table>
<thead>
<tr>
<th>S.P.C.</th>
<th>DRY TEXTURING</th>
<th>OVERFEED=50% PRESS.=3bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>s.d.</td>
<td>mean s.d.</td>
</tr>
<tr>
<td>A (mm)</td>
<td>1.51</td>
<td>1.33 0.96</td>
</tr>
<tr>
<td>B (mm)</td>
<td>0.72</td>
<td>0.25 0.61</td>
</tr>
<tr>
<td>C (mm)</td>
<td>1.41</td>
<td>2.10 0.60</td>
</tr>
</tbody>
</table>

S.P.C.: Standard Processing Conditions; i.e. pressure=8bar, overfeed=20%, wet texturing (l/h).

N/A: Not Applicable

s.d.: Standard Deviation
FIGURE 6.1 THE MODEL NOZZLE USED FOR HIGH SPEED-CINE PHOTOGRAPHY

Loughborough University of Technology
Department of Mechanical Engineering
Drawn: Sule Bilgin Not to Scale
Title: Flat AJT Model Nozzle (A.R.=0.667)
FIGURE 6.2 ILLUSTRATION OF THE HIGH SPEED PHOTOGRAPHY SYSTEM
FIGURE 6.3  HIGH SPEED FILMS OF AJT PROCESS
FIGURE 6.4a DIVISION OF FILAMENT MOTION INTO THREE REGIMES

ZONE 1: SECONDARY FLOW
ZONE 2: MIXING ZONE
ZONE 3: PRIMARY FLOW

FIGURE 6.4b DIVISION OF AIR FLOWS INTO THREE ZONES
WITH RESPECT TO YARN MOTION AFTER FIGURE 6.4a
FIGURE 6.5a EXAMPLE I FOR YARN MOTION IN ZONE 2

b EXAMPLE II FOR YARN MOTION IN ZONE 2
FIGURES 6.6 REFERENCES FOR QUANTITATIVE ANALYSIS OF THE HIGH SPEED FILMS
FIGURE 6.7a-d YARNS MADE AT (a) SPC, (b) DRY,
(c) 50% Overfeed and (d) 3 bar OPERATIONS
Processs Direction

STRAIGHT YARN

leading end

trailing end

Figure 6.8a
LOOP FORMATION
BY BENDING A PIECE
OF YARN

Figure 6.8b
SMALLER LOOP
BY MOVING THE TRAILING
END FORWARD

FIGURE 6.8 SCHEMATIC ILLUSTRATION OF LOOP FORMATION
CHAPTER 7
EFFECT OF NOZZLE GEOMETRY ON INTERMINGLING

7.1. INTRODUCTION

In this chapter the effect of nozzle geometry on the INT process is investigated. For this purpose, a number of INT nozzles have systematically been generated from the same basic geometric design by varying its dimensions as shown in Figure 7.1. The reason for using this particular design is its simple structure, which makes the nozzles easy to manufacture and operate.

The nozzles have been tested at supply pressures between 2 and 4 bar in increments of 0.5 bar and their mingling performance have been evaluated in two ways: (1) a preliminary qualitative assessment, (2) nip frequency measurements.

7.2. DESCRIPTION OF THE NOZZLES USED IN THE INVESTIGATIONS

There is a very wide range of INT nozzles used in industry, as illustrated in Figure 2.13. These show significant variations in their detailed designs. The main channel of such nozzles can be of circular, semi-circular, rectangular, triangular or any other convenient shape. This shows that the shape of the main channel cross-section is not too critical to the performance of the nozzle.

The incoming jet is usually supplied by a circular inlet hole. Although the number of holes may be more than one, most industrial nozzles have only one air inlet hole.

With these observations in mind, two basic nozzle geometries for the main channel were chosen for the investigations in this chapter: (i) rectangular cross-section and (ii) semi-circular cross-sections. The air
inlet hole is unconventional in that it extends over the whole width of the main channel, in the form of an extended hole.

The nozzles consist of two pieces, as shown in Figure 7.1: (1) the base has the extended hole to introduce the compressed air into the main channel (2) the cover accommodates the main channel through which the yarn runs. The extended air inlet hole is considerably wider than the width of the main channel. Hence, when the two pieces are brought together the incoming air flow can cover the whole width of the main channel without requiring any precise adjustments and setting of the nozzle. This is known to be a major problem in certain industrial nozzles, but in this design slight variations in relative positions of the base and cover due to tolerances and setting do not affect the performance of the nozzle. Consequently, this design enables the incoming flow to always impinge on the filaments travelling through the channel, guaranteeing all constituent filaments of the yarn to be subjected to the incoming air flow. This feature of the nozzle design is unique and has not been seen in any industrial nozzle.

The cross-section of the main channel can be either semi-circular or rectangular. Furthermore, a variation of these nozzles has a pair of air vents on both sides of the air inlet slot, in the base piece. The air vents allow the air flow in the main channel to be exhausted into atmosphere, before it reaches the ends of the nozzle. In doing so, it was aimed to achieve an early expansion of the flow in the main channels, which was believed to affect the nip creation. This is a feature seen in some industrial nozzles and it was intended to investigate the effect of such air vents.

The base/cover combinations are labelled according to the following convention: The first four of the eight digits
denote 10 times of channel width and depth of the cover in mm respectively. The subsequent two digits denote nozzle length and finally the last two expresses 10 times of the slot width of the base in mm. The presence of air vents is denoted by adding letter v at the end of the label. The nozzle, for example, 2520-20-15v has main channel width of 2.5mm, main channel depth 2.0mm, nozzle length of 20mm and an air inlet hole with 1.5mm. It also has air vents in the base.

Area ratio of the nozzles is defined as follows:

Area Ratio = \( \frac{\text{Area}_{\text{air inlet}}}{\text{Area}_{\text{main channel}}} \)

where,
Area_{\text{air inlet}} = x*s for the semi-circular nozzles
Area_{\text{air inlet}} = w*s for the rectangular nozzles
(for w, x, and s, see Figure 7.1)

Area ratio smaller than unity means that the air choked in the inlet hole expands into the main channel as soon as it reaches the channel.

Another geometrical parameter, termed the aspect ratio, has been defined for rectangular nozzles as follows:

Aspect Ratio = \( \frac{w}{d} \) (where w and d are width and depth of the main channel)

Geometry of the rectangular nozzles is presented in Table 7.1. That of semi-circular nozzles is omitted since none of them can create nips, as detailed in Section 7.4.

7.3. EXPERIMENTATION

7.3.1. YARN PRODUCTION SYSTEM

The nozzles are installed on-line on the laboratory false-
twist texturing machine built by Rieter-Scragg Ltd for Loughborough University of Technology for a research project which took place from 1988-1991. As schematically illustrated in Figure 7.2, the machine consists of a heater, a triple stack disk twister; i.e. the Positorq false twist unit, three sets of yarn transport rollers which are driven and controlled independently and a high-speed yarn winder. The independently driven yarn transport rollers enable the yarn to be drawn or overfed at any rate in the texturing and/or intermingling zones by changing the relative velocity of the intermediate rollers and the winder.

125/f34 PET Dacron has been used as the supply yarn and the following set of machine parameters has been kept constant throughout all the tests:

* Yarn Production Speed = 600 m/min
* Heater Temperature = 217 °C
* Overfeed (in the intermingling zone) = 4%

Yarn production speed and heater temperature are dictated by the false twist texturing of this particular type and count of yarn.

Several tests were carried out in order to determine an overfeed (or draw ratio) at which the nozzles can produce nips and after several trials an optimum overfeed ratio of 4% was established. The trials for determining effect of the overfeed ratio on the process has been discussed in Section 7.3.2.

All the tests were carried out with the nozzle axis turned at 45° with respect to the normal yarn path. In industry, nozzles are not turned but yarn guides are used. Since yarn guides give rise to jet noise, in the present INT trials the nozzle is turned with respect to the yarn path. The
nozzle turning practice has been found to produce nips much more consistently than the case in which the nozzle axis is aligned with the yarn path. The improvements recorded in the INT process will be discussed in detail in Chapter 8.

7.3.2. EXPERIMENTAL PROCEDURE

Firstly, two groups of nozzles, with semi-circular and rectangular cross-sections, were designed and manufactured. In order to eliminate the effect of the main channel length the nozzles were manufactured to the same length, of 20 mm, only the cross-sections were varied.

Secondly, after having tested the performance of the aforementioned nozzles, the effect of length was studied on one of the nozzle cross-section combinations which performed adequately over a wide range of operating pressures.

Briefly, the experiments comprised the following two phases:

i) Phase 1: Investigation of the effects of the cross-section of main channel and air inlet hole of the nozzles on the process

ii) Phase 2: Investigation of the effect of the nozzle length on the process

A suitable overfeed, or draw, ratio, which indicates the rate of yarn input by the intermediate rollers divided by the rate of removal from the intermingling zone by the take-up unit, was determined after several tests so that all the nozzles can work at one single overfeed ratio and an overfeed of 4% was found to be suitable for all nozzles to work without any problem. Overfeed ratio determines overall yarn tension, which has a paramount effect on nip creation as well as process stability. When the tension is
too low no nip creation occurs or yarn becomes too slack and gets caught by the intermediate rollers, consequently it becomes impossible to have a stable and continuous yarn running. When, on the other hand, the tension is too high, again, no nip formation takes place or the yarn breaks.

**Phase 1 : Effect of main channel cross-section and air inlet hole on the INT process**

In this section, 78 combinations of nozzles with varying cross-sectional shapes and dimensions have been tested. Six base pieces with air-inlet slots of 1.5, 1.0 and 0.7 mm wide and versions of these with air vents have been used. A total number of 13 cover pieces, eight of which were of semi-circular, and the remaining five were of rectangular cross-section, have been used. As a result, with six base pieces and eight semi-circular cover pieces 48 semi-circular nozzle combinations have been created; similarly, with the same six base pieces and five rectangular cover pieces a further 30 rectangular nozzle combinations have been obtained. The dimensions of both base and cover pieces are shown in Figure 7.1.

**Phase 2 : Effect of nozzle length on INT process**

After testing all the 20 mm long nozzles, one combination which can perform adequately at a large range of pressure; namely 2020-20-15, was selected to investigate the effect of the channel length on INT process. Five more versions of this nozzle with lengths of 15, 25, 30, 35 and 40 mm were manufactured and tested. Nozzle performance was similarly assessed.

7.3.3. **YARN ASSESSMENT**

Yarns produced by each of the nozzles were divided into three categories:

* Group 1 : Yarns which were not intermingled at all
* Group 2 : Inadequately intermingled yarns with sections in with more than 3 consecutive missing nips (Figure 7.3a)  
* Group 3 : Adequately intermingled yarns (Figure 7.3b)

After a preliminary visual assessment, yarns were classified into one of the three groups and Group 1 and 2 yarns were discarded for further analysis. Group 3 yarns, which were adequately intermingled, have been quantitatively assessed, which required determination of nip frequency. The most reliable method of determining the nip frequency was found to be the manual count, which involved counting the number of nips in 1 meter long yarn under a fixed tension of 8 gram. The count was repeated for ten samples from each yarn. The 8 gram tension has been experimentally determined in such a way that the tension must not be too high to remove nips but, on the other hand, must be high enough to overcome elastic forces caused by helical structure of the FTT yarn. Normally filaments of an FTT yarn act like extended springs, which tend to contract in the absence of tension. In other words if during nip frequency measurement the yarn tension is smaller than these elastic forces then the yarn can shorten. Since this shortening process is dynamic the length over which nips are to be counted varies in time. The nip frequency measurement tension of 8 gram enables a constant length of yarn to be maintained throughout the tests without removing any nip, in turn providing consistent nip frequency measurements.

7.4. RESULTS AND DISCUSSIONS

Average values of nip frequency data of the Phase 1 experiments are presented in Table 7.2. The table contains data of rectangular nozzles only, because semi-circular nozzles did not produce any intermingling. In the table, some places are left blank and this denotes that the nozzle
at the given pressure produces no nips (Group 1). Asterisks in the table denote Group 2 yarns. Since Group 2 yarns have nips irregularly distributed along the yarn it is not possible to give a constant average nip frequency for the nozzles. The nip frequency data presented in Table 2 are of Group 3 yarns. Their maximum standard deviations are also shown.

7.4.1. EFFECT OF PROCESSING CONDITIONS

Effect of supply pressure
Nip frequency data of Group 3 yarns are presented in Figure 7.4a,b. The figure shows that only few nozzles perform at 2.5 bar pressure, whereas most of the nozzles intermingle satisfactorily at 4 bar pressure. It also depicts that nip frequency generally increases with supply pressure. However there are few exceptions, in which high pressure does not seem to enhance nip frequency, and in the case of nozzle 2020-20-10v the reverse correlation has been recorded. Taking into account the standard deviation values it can be argued that in some cases, for example Nozzle 2020-20-15V, the difference in nip frequency between two consecutive pressures is not statistically meaningful. These close values, therefore, do not give definite results but still suggest a slight general tendency that nip frequency increases with increasing supply pressure.

This conclusion was also reached by Chono et al [17] and Iemoto et al [33]. However Basu [5] found the opposite conclusion. He found two regions as far as effect of air pressure on nip frequency is concerned. In the first region; i.e. low pressure region, nip frequency increases with increasing pressure. After a certain value of pressure (4bar), the trend reverses (the second region). Basu recorded that in the first region the flow is subcritical whereas in the second region it is supercritical. However, the flows created by the present nozzles are all

7-8
supercritical for the supply pressure range used, but generally nip frequency still increases with air pressure, unlike the findings of Basu.

**Effect of compressed air consumption**

Air consumption of all the rectangular nozzles is measured at all working pressures by a rotameter and given in Table 7.3 together with the effective throat area of the inlet slot. The data is plotted against nip frequency at 4 bar in Figure 7.5, which shows at the given pressure that higher nip frequencies are obtained with nozzles that use less compressed air. Nozzle 29 is a typical example of high performance at low pressure. This nozzle produces 120 nips/m at 4 bar at a 3.3 litre/h air consumption, lowest recorded.

7.4.2. EFFECT OF CROSS-SECTIONAL SHAPE OF THE NOZZLE

The nozzles with semi-circular cross-section did not create nips adequately. Only a small number of them show intermingling action but extremely irregularly distributed.

In terms of nip frequency, nozzle 1515-20-7 (Nozzle 29) is the most superior combination in terms of nip frequency, with average nip frequency of 120 operating at 4 bar pressure. Other combinations of cover 1515-20 with bases 7V, 10, 10V and 15 also produced yarns with high nip frequencies at 4 bar; 116, 109, 110 and 92 nips/m respectively, compared with other nozzle combinations.

7.4.3. EFFECT OF NOZZLE DIMENSIONS

**Effect of area ratio**

Area ratio versus nip frequency at 4 bar is presented in Figure 7.6, excluding the nozzles which did not produce adequately intermingled yarns (Group 1 and 2 yarns). Area ratio values of the nozzles vary between 0.35 and 1.5. It
has been found that nozzles with area ratio greater than unity did not create nips. It can be concluded from the figure that nozzles with area ratios lower than unity are more likely to produce nips. In such nozzles, due to the abrupt enlargement in the area, the incoming air flow expands suddenly, which may be playing a significant role in nip formation.

In Table 7.2 the nip frequency of all the nozzles, with their area ratio values, is presented. It can be seen that no combination of cover 1510 produces successfully intermingled yarn. This could be attributed to area ratio, because four out of six combinations have area ratios of either 1.5 or 1. However, the fact that the other two combinations, which have area ratio smaller than unity, do not create nips suggests that the above-mentioned rule that the area ratio must be smaller than unity is not a sufficient but a necessary condition for nip formation.

**Effect of aspect ratio**

In Table 7.2 the nip frequency of all the nozzle is presented with their aspect ratio values. It shows that no nozzle with aspect ratio of 1.5, which is the maximum, can perform adequate entanglement. Aspect ratio versus nip frequency data is also presented in Figure 7.7, excluding the nozzles which did not produce adequate intermingling. This figure indicates that the majority of the nozzles have an aspect ratio of unity and the frequency of the intermingling is generally higher at this aspect ratio. This means that generally square cross-sections may be preferable to rectangular cross-sections for high nip frequency.

**Effect of main channel depth**

In Figure 7.8 channel depth versus nip frequency at 4 bar is plotted, excluding the nozzles that do not perform adequately. The figure crudely suggests that nozzles with
small depth perform better in terms of nip frequency. Average nip frequencies obtained at 2.5, 2.0 and 1.5 mm depths are 79.0, 89.4 and 107.0 nips/m and, hence, suggest a the relation between nip frequency and main channel depth. However this relation is not statistically meaningful since the corresponding standard deviations are high, 2.9, 5.8 and 11.2 nip/m respectively. The relation, statistically not meaningful, still suggest a crude tendency, which may be useful in nozzle design. It should be noted that no nozzle with depth of 1.0 mm was found to be making nips. This result suggests that there is a lower limit of depth for successful intermingling.

Effect of main channel width
In Figure 7.9 channel depth versus nip frequency at 4 bar is plotted, excluding the nozzles that do not perform adequately. It can be stated that narrow nozzles can create more nips for a given yarn length. Average nip frequencies obtained at 2.0 and 1.5 mm depths are 86.4 and 99.2 nips/m and, hence, suggest a the relation between nip frequency and main channel width. However this relation is not statistically meaningful since the corresponding standard deviations are high, 6.9 and 13.9 nip/m respectively. The relation, statistically not meaningful, still suggest a crude tendency, which may be useful in nozzle design.

Effect of nozzle length
Experiments of Phase 2 were carried out with nozzles 15, 20, 25, and 30 mm long. Nozzles with greater length cannot be turned at 45° with respect to yarn path because the yarn breaks and without turning these nozzles cannot create regular nips. The reason for yarn breakage in the case of the longer nozzles is that for a given angle the deflection of the yarn from its original path due to the nozzle orientation increases with increasing nozzle length, which results in high tension, and, in turn, causes the yarn to break.
create nips on the yarn. Rectangular nozzles performed variably but mainly successfully, depending on the nozzle dimensions and the supply pressure.

IV) Nozzles with area ratios greater than or equal to unity do not create nips. Smaller area ratios have been shown to be beneficial and an area ratio of approximately 0.5 is recommended.

V) Nozzle length does not play a significant role in the nip formation process. Longer nozzles make the nozzle orientation at 45° difficult, hence it should be avoided. Since nozzle length is not critical it should be kept at minimum.

VI) Nip frequency increases with decreasing channel width and depth, suggesting that nozzles with small main channel can produce yarns with high nip frequency. However there is a lower limit of depth for successful intermingling, 1.5 mm for the nozzles tested.

Nozzles with small main channel are also beneficial in terms of air consumption since nozzle width, together with the width of the incoming air slot, directly determines the throat area.

VII) An aspect ratio unity appears to be beneficial for INT process in terms of nip frequency.

VIII) Air vents are not necessary because they do not improve the nozzle performance.

IX) Smaller air inlet holes, where possible, are preferable since they reduce the air consumption and increase the nip frequency.
<table>
<thead>
<tr>
<th>NOZZLE</th>
<th>COVER w (mm)</th>
<th>d (mm)</th>
<th>BASE s (mm)</th>
<th>AREA RATIO</th>
<th>ASPECT RATIO</th>
<th>l. (mm)</th>
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</thead>
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<tr>
<td>1</td>
<td>2.5</td>
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<td>0.75</td>
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<td>1.5V</td>
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s : slot width of the air inlet
V denotes nozzles with air vents vents
AREA RATIO = (s\*w)/(w\*d) = s/d
ASPECT RATIO = w/d
### TABLE 7.2 NIP FREQUENCY DATA

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(i) V denotes nozzles with air vents
(ii) m: mean
(iii) sd: standard deviation
### TABLE 7.3 AIR CONSUMPTION DATA OF THE INT NOZZLES

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### TABLE 7.4 NIP FREQUENCY DATA OF INT NOZZLES WITH VARIOUS LENGTH

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<th>Nozzle Length (mm)</th>
<th>Nip Frequency (nip/m)</th>
<th>mean</th>
<th>s.d.</th>
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s.d. : standard deviation
FIGURE 7.1 GEOMETRY OF THE INT NOZZLES
FIGURE 7.2 THE FTT SYSTEM THAT THE INTNOZZLES ARE INTEGRATED WITH
FIGURE 7.3a INADEQUATELY INTERMINGLED YARN

FIGURE 7.3b ADEQUATELY INTERMINGLED YARN
FIGURE 7.4a
NIP FREQUENCY vs SUP. PRESS. (Group I)

FIGURE 7.4b
NIP FREQUENCY vs SUP. PRESS. (Group II)
FIGURE 7.5 AIR CONSUMPTION vs NIP FREQ.
FIGURE 7.6 AREA RATIO vs NIP FREQUENCY
FIGURE 7.7 ASPECT RAT. vs NIP FREQUENCY
FIGURE 7.8 CHANNEL DEPTH vs NIP FREQ.

FIGURE 7.9 CHANNEL WIDTH vs NIP FREQ.
FIGURE 7.11a AIR INLET WIDTH vs NIP FREQUENCY

AIRTHERM (mm)

FIGURE 7.11b AIR INLET WIDTH vs NIP FREQUENCY

AIRTHERM (mm)
CHAPTER 8
INVESTIGATION OF INTERMINGLING PROCESS BY MEANS OF HIGH SPEED VIDEO, HIGH SPEED CINE PHOTOGRAPHY AND TENSION MEASUREMENTS

8.1. INTRODUCTION

In this chapter the INT process is investigated in an attempt to gain a better understanding of the process mechanism. Hence it was decided to investigate the process by correlating information obtained from process investigations to yarn structure.

The techniques used in the investigations are as follows:

* High speed video recording
* High speed-cine photography
* SEM images of yarns
* Yarn Tension Measurements

8.2. EXPERIMENTATION

8.2.1. DESCRIPTION OF THE NOZZLE USED IN THE INVESTIGATIONS

Nozzle 7, whose geometry was detailed in Chapter 7, is used in this chapter. A sketch of it is given in Figure 8.1. As seen in the figure the nozzle consists of two pieces. The main channel is machined in the cover piece and the compressed air is introduced through the base piece. The reason for using this particular nozzle is that from the investigations in Chapter 7 it has been found to be one of the nozzles which can produce regular nips over a wide range of supply pressures.

8.2.2. EXPERIMENTAL SET-UP

The yarn intermingling system is as described in detail in Section 7.3.1.
The same supply yarn (125/f34 PET Dacron) has been used as the supply yarn for consistency and also the machine parameters given in Section 7.3.1 have been kept constant throughout all the tests.

8.2.3. HIGH SPEED VIDEO

Yarn vibration before and after the nozzle was investigated by means of a high speed video technique. A NAC HSV 400 High Speed Video System was deployed in the investigations of INT process. Recording was at the rate of 400 frames per second, which is the maximum attainable rate for the system. The light source, a sync strobe light, delivers 1/50000s flash duration. A standard VHS tape was used for recording the images.

8.2.4 HIGH SPEED CINE PHOTOGRAPHY

The cover piece of the nozzle was replaced with a perspex one to enable to observe the filaments inside the nozzle by the high speed cine photography technique. The high-speed photography set-up is the same as the one used in Chapter 6. INT process was investigated by means of the high speed cine photography system at two different supply pressures, 2 and 4 bar (gauge) to be able to see differences at relatively high and low pressures.

8.2.5. YARN TENSION MEASUREMENTS

The WIRA tensiometer was used for measuring average yarn tension during INT. The measurements were taken at both before the nozzle (T₁) and after the nozzle (T₂).
8.3. RESULTS AND DISCUSSIONS

8.3.1. PROCESS OBSERVATIONS

When the INT process is observed closely with naked eye it was found that the yarn sometimes follows a stable yarn path, running almost in the middle of the main channel along the nozzle axis, and then runs towards one of the sidewalls of the nozzle for a fraction of a second. At the instant that the yarn runs against a sidewall, a detectable change in the audible jet noise takes place. The yarn produced under such conditions is successfully intermingled in places, but there are also sections of yarn with consecutive missing nips. The interval and the length of the successful intermingling along the yarn do not exhibit a regular pattern. During the process, the yarn does not escape to the sidewalls very often and the resultant yarn has only small sections of missing nips comparing with the remaining successfully intermingled sections. From this it was surmised that the running of yarn near the sidewalls corresponds to the sections of missing nips and can be the reason for the missing nips. The assumption that the missing nips are associated with unstable yarn paths was tested by turning the nozzle with respect to the usual path of the yarn, which forces the yarn to travel diagonally across the nozzle channel and hence reduces the intermittent running of the yarn to the sidewalls. This arrangement, referred to as off-thread arrangement hereafter, was found to be eliminating missing nips considerably, confirming the initial assumption.

8.3.2. EFFECT OF THE NOZZLE ORIENTATION ON NIP FORMATION

The effect of nozzle orientation, in other words the angle of the nozzle axis with respect to the yarn path, on nip formation was investigated by increasing the angle from 0° to 45° with the increments of 15°. Number of missing nips in a meter of yarn at each orientation angle is given in Table 8.1
after 10 counts from each sample. The results clearly show that the higher nozzle turning angles give fewer missing nips.

At orientation angles greater than $45^\circ$ it was not possible to produce any yarn due to appearance of a new type of process instability. While the yarn is forced to follow a certain path imposed by the off-thread alignment, the jet forces it to follow the nozzle axis; therefore under the effect of the two opposing forces it tries to adjust itself, flapping between nozzle axis and the normal path (Figure 8.2). Consequently vehement vibration takes place and yarn breaks.

Consequently it can be argued here that optimum nozzle turning angle to reduce the missing nips and, hence, to maximise the nip frequency is in the region of $45^\circ$.

For more detailed investigations on the effect of nozzle orientation angle on the INT process, high speed video recording technique was deployed.

8.3.4. HIGH SPEED VIDEO IMAGES

Yarn motion during the INT process was investigated by the high speed video recording system at the rate of 400 frames per second.

* when various paths were imposed on the yarn (the nozzle is straight or orientated at $45^\circ$)
* at supply pressure $p=4$ bar (gauge)
* 4% overfeed

Figure 8.3a-c show photographic prints of the high speed video images taken with the nozzle axis aligned with the yarn path. These photographs illustrate that the yarn vibrates at both inlet and exit side of the nozzle. Figure 8.3a depicts four consecutive images illustrating such vibration and the first two images are shown at greater magnification in Figure 8.3b
and 8.3c respectively.

Figure 8.4 shows photographic prints of similar video images at the same processing conditions but with the nozzle axis orientated at 45°. These photographs clearly show that the vibration, which was present in the case of aligned yarn path and nozzle axis was mostly eliminated.

The off-thread arrangement can lead to wear problem in long run in industry. As an alternative, an industrial yarn guide by Rieter-Scragg was fitted on the nozzle but did not eliminate missing nips as successfully as the off-thread arrangement. The vibration pattern in this case is given in Figure 8.5 and reveals that the guide reduces downstream vibration only because it holds the yarn higher than the level the main channel. The yarn is free to vibrate upstream because the eye of the yarn guide is lined up with the main channel, but not constraining the yarn. The fact that the Rieter-Scragg guide did not eliminate missing nips significantly has led to the conclusion that the yarn should be confined at both upstream and downstream, giving complete control of the yarn path.

The vibration pattern of a longer nozzle, the 30 mm nozzle investigated in Chapter 7 (Nozzle 2020-30-15), is given in Figure 8.6 when it is not turned. It shows similar vibration pattern to that of the 20 mm long nozzle, indicating that the longer channel cannot eliminate vibration and it is necessary to turn this nozzle as well with respect to the usual yarn path.

8.3.5. HIGH SPEED CINE PHOTOGRAPHY

The films were analysed in two ways:

Qualitative analysis of the high speed cine-films
Figure 8.7a and b give 12 consecutive images selected randomly
from 2 bar and 4 bar operations respectively. The time over which the 12 frames lapsed is 1.2 ms. This corresponds to 1.2 cm of yarn.

The figures show that the yarn moves across the nozzle in both cases. Since the nozzle was turned at neither pressures the yarn sometimes falls near the sidewalls and stay there.

ii) Quantitative analysis of the high speed-cine films
Investigations of periodic nature of INT process required more frames to be examined. For this purpose, 200 consecutive frames were quantitatively analysed by investigating occurrence of the filaments staying open or closed inside the nozzle in the area of the incoming air flow. The number of occurrences of the filaments being open in that area was defined as Parameter O. It was counted for 200 consecutive frames for 2bar and 4bar processes. The results are given in Table 8.2. It shows that the average values of Parameter O are 24.5% and 37.5% for 2 bar and 4 bar operations respectively, indicating that the reason for inadequate nip creation at 2bar operation might be due to the fact that the filaments are not able to be opened up by the incoming flow.

The sequence of Parameter O for the 200 consecutive frames is presented in Figure 8.8a-b for 4 and 2 bar operations respectively. The figures exhibit an almost periodically alternating pattern. It should be borne in mind that in some of the closed sections the filaments in fact might be open in the vertical plane. For this reason, it can be argued that in the cases of 1 or 2 closed sections which take place between long open sections the filaments are most likely open to be open in the orthogonal plane along the nozzle axis. With this consideration, the cycles in Figure 8.8a-b have been numbered and within the 200 frames 12 complete periods have been found.

Since an INT yarn consists of periodically situated nips, the periodicity in the figures must correspond to nip formation.
Whether the cycles in the figures correspond to actual nip formation can be tested as follows:

The average speed of the intermingling process is 10 m/s and frame rate is 10 000 frames/s approximately. This means that 20 cm of yarn passed over the 200 frames counted. In Figure 8.8.a there are 12 complete periods, leading to the conclusion that in the 20 cm of yarn there are 12 nips. This means that the frequency of nip formation of the process is 60 nips/m. In Chapter 7 the nip frequency of this particular nozzle was measured to be 87 nips/m at 4bar, with average number of missing nips of 8.7 nips/m. The discrepancy between the frequency of nip formation (60 nips/m), which has been calculated from the analysis of the films, and the off-line nip frequency measurement (87 nips/m) can be due to the following reason: During the time elapsed over these 200 frames there might have been a high number of missing nips. In Figure 8.8a there are long consecutive closed sections, where nip creation most likely failed. If the long consecutive closed sections between Periods 1 and 2 and Periods 5 and 6 indicate missing nips then frequency of nip formation becomes 70 nips/min.

Figure 8.8a-b also show that periods of the cycles are not constant, indicating yarns with different nip periods.

8.3.6. YARN TENSION RESULTS

The tension measurements, which were presented in Table 8.3., were taken

* when various paths were imposed on the yarn (the nozzle is aligned with or orientated at 45°)
* at various supply pressures (p=0/2/4/8 bar (gauge))
* at various overfeed ratios (0/2/4%)  

It should be pointed out that the nozzle investigated can
produce regular nips at 4 bar supply pressure with 2% and 4% overfeed. The quality of yarn with these two overfeeds are similar; the yarns made at 4% and 2% overfeeds have 87 and 84 nip frequency respectively. In the case of 0% overfeed no INT is possible at any pressure. At 2 bar supply pressure, regardless of overfeed, no INT is possible.

* Yarn Tension Data Taken at OVERFEED = 4%
As expected, there is no tension in the yarn when there is no air and the nozzle is aligned, since the yarn is overfed. When air is introduced at 2 bar the situation hardly changes. At 4 bar and 8 bar, both the upstream and downstream yarn tension slightly increase, occasionally up to 1 gram, but mostly stay close to zero. This, virtual zero situation, is expressed in the table as 0+. It is interesting to see that during nip creation at 4% overfeed, the yarn experiences almost zero tension. As the supply pressure is increased to 8 bar the yarn tension stays the same, contrary to expectations that the higher the pressure the more stimulated the yarn, hence, the higher the tension.

As far as the no-air and 2 bar situation is concerned, when the nozzle is orientated at 45° the yarn still experiences zero tension. In the case of 4 bar pressure, however, turning the nozzle causes upstream tension, $T_1$, to drop from 0+ to 0 and downstream tension, $T_2$, remains the same. Still the nozzle is turned and when the air pressure is increased to 8 bar yarn breaks, therefore, no tension data related to this case is available.

* Yarn Tension Data Taken at OVERFEED = 2%
When the yarn is running straight and no air is present the yarn experiences no tension. As soon as air is introduced at 2bar $T_1$ and $T_2$ both become 4 gram; whereas in the case of 4% overfeed $T_2$ stayed at 0 at every pressure tested. As the supply pressure is increased to 4 bar, still keeping the nozzle straight, both upstream and downstream tensions become
7 gram. A further increase in the pressure to 8 bar increases both T₁ and T₂ to 9 gram.

When the nozzle was orientated at 45° T₁ was zero at all air pressures, whereas T₂ values were 5 and 8 gram at 2 bar and 4 bar pressures respectively. Further increase in the pressure causes the yarn to break.

* Yarn Tension Data Taken at OVERFEED = 0% *

When the yarn is running straight T₁ and T₂ were the same, 15 gram, at every pressure tested. Pressure had no effect on yarn tension. Evidently the yarn was initially so much tensioned that the effect of air flow was relatively insignificant.

When the nozzle is turned at 45° T₁ drops from 15 gram to 0 but T₂ increases from 15 to 17 gram. This result shows the same trend as 2%; i.e. turning of the nozzle results in zero upstream tension and increased downstream tension.

8.3.7. EVALUATION OF THE YARN TENSION DATA TOGETHER WITH THE HIGH SPEED VIDEO IMAGES AND HIGH SPEED CINE FILMS

When overall yarn tension is too high; i.e. zero overfeed, no nip can be created at all, neither with the nozzle turned nor straight. This suggests that there must be slackness in the filaments for freedom of movement. On the other hand, low overall yarn tension does not necessarily guarantee regular nip creation, as in the cases of 2% and 4% overfeed but with a straight yarn path. That is to say that yarn tension is a crucial factor but not the only factor which determines regular nip creation. The yarn tension measurements clearly show that a certain amount of slackness is necessary for nip creation but at certain places the yarn should be confined, in a way that it is brought opposite to the incoming flow.
The above discussion suggests that overall yarn tension determines whether nips can be created at all. Turning the nozzle, however, makes already possible nip creation regular. In short, INT yarns with regular nips can be produced if the yarn tension is correct and, at the same time, the yarn is under constant effect of the incoming air flow.

8.3.8. YARN STRUCTURE

Nip creation is a result of an interaction between the filaments and air flows created by an INT nozzle. One of the ways of comprehending the interaction is to investigate the structure of the outcome; i.e. the INT yarn.

Figure 8.9a–c show SEM images of an INT yarn. Figures 8.9 a and c show a closed section (nip) and an open section respectively. Magnifications of Figure 8.9a and 8.9b–c are 90 and 160 times respectively. It is evident in the photographs that in both open and closed sections the filaments have moved in and out of the paper plane, making an entangled structure; but there is no regular pattern in terms of certain direction and amount of movement. And also the filament movement seems to be individual or of small number of filaments only, rather than in large and definitely identifiable groups. This rules out a regular twisting or plaiting action of the filaments, suggested by Weinsdorfer et al [63]. A comparison of entanglement pattern of filaments between the closed (Figure 8.9b) and open section (Figure 8.9c) suggests that the filaments exhibit a similarly entangled structure; irregularly and individually. The difference is that in the closed section the filaments are relatively tightened, straight and compact whereas in the open section they are slack, even forming bows and arcs. In other words, in the open section the filaments are so relaxed that they can retain their voluminous structure obtained from the earlier FTT process whereas in closed sections they are relatively tight. This consideration leads to the conclusion that what constitutes a section may be
closed due to local tension in the filaments, rather than their degree of mixing. How the local tension is inserted to the filaments, making a closed section, and why this occurs periodically is discussed in Section 8.3.9.

Overall inspections of the INT yarns reveals that nip period can vary along a given yarn (Figure 8.10). The figure, which is of an extreme variation, shows that one nip can be twice as long as the proceeding one. This finding discloses a rather irregular nature of the phenomenon. The irregularity in the periodicity of the yarn is also evident from Figure 8.8a-b.

8.3.9 FINAL DISCUSSIONS

Having stated the results of the investigations of the process and yarn structure, a better understanding of the mechanism of INT process can be summarised as follows:

The process results from the incoming flow and the two opposite flows created in the main channel acting on the filaments. For simplicity, the flows have been assumed to be steady and unaffected by the presence of the filaments, whose location in fact is randomly varying and, as a result, may affect the flow pattern.

The flows in the main channel are not unidirectional because the incoming jet is divided into two opposite flows, creating subflows in different directions with different velocities across the nozzle. This creates a situation where the direction and amount of filament displacement is determined by the location of the filament across the nozzle. The high speed-cine films show that during INT process the yarn moves from side to side in the nozzle. The significance of this motion is that filaments constituting a certain group at a given cross-sectional plane can be parts of different groups of filaments at a subsequent plane. This results in the filaments to be mixed and intertwined with different filaments.
In addition to the mixing and intertwining effects of the flows in the main channel, the filaments are also subjected to the incoming jet. A possible effect of the incoming jet can be to open up the filaments by pushing them towards the sidewalls, which in return increases local tension in both upstream and downstream parts of the whole yarn. It has already been established that the filaments are being intertwined by the flows inside the main channel prior to the air inlet hole. It is believed that the incoming jet manages to open up the filaments for a while and as a result of this opening, the local tension builds up in the intertwined section up to a certain degree, which results in entangling the intertwined section into a form of knot. This knot created prior to the air inlet hole is impossible to be opened up by the incoming jet when it comes underneath the jet as the whole yarn moves along the nozzle. As the process continues, a part of the intertwined section which is far from the opened section and, consequently, where the filaments are not firmly entangled, comes to the opposite of the incoming jet. This time the jet is capable of opening the filaments because they are not tightly knotted. As the process continues, the local tension in the intertwined section again reaches the threshold above which no more tension can be exerted to the yarn by the action of opening up. The whole process repeats itself in this way. This is evident from high speed-cine photographs, where filaments stay all closed for a number of consecutive frames and then open up and stay open for another number of frames.

Weinsdorfer [63] also reported that a nip is created prior to the air inlet and it can be opened after it has passed the air inlet.

Briefly INT process can be modelled as a superposition of the following two opposing actions, which gives an alternating outcome:

i) a continuous intertwining action, caused by the non-
unidirectional flows inside the main channel.

ii) a continuous opening up action, by the incoming jet

Having summarised INT process in general, it is now possible to explain the reasons why under certain process conditions the process is not successful.

As far as the low pressure operation is concerned, the reason for the inadequate INT process at 2bar can be the ineffectiveness of the second action; i.e. opening action. From the analysis of the high speed films it has been found earlier that the filaments can stay open almost 1.5 times longer at 4bar operation than 2bar operation.

Also in the case of the straight operation (aligned nozzle-yarn path operation), the reason for the unsuccessful process is the ineffectiveness of the second action, because the filaments occasionally escape from the incoming jet, which does the opening.

With respect to high overall tension operation, the process is not successful because the first element is not complied with; i.e. the excessively high overall tension does not allow the filaments to be mixed and intertwined.

The above discussions have led to the identification the following factors for nips creation:

* high supply pressure (greater than 2 bar), in which the intensity of the incoming jet is able to open filaments, which in return forms the intertwined filaments into a knot.
* yarn confinement, to subject the yarn to the opening effect of the incoming jet constantly.
* correct overall tension, to enable the filaments to have freedom of movement for mixing and tangling.
8.4. CONCLUSIONS

I) An improved understanding of INT process can be outlined as follows: The filaments are first subjected to the effect of the flows inside the nozzle, which moves filaments in different amounts and directions depending on their location in the nozzle. Since the filaments move across the nozzle as the process continues, different filaments are displaced together in various directions, which intertwines the filaments. As the intertwined filaments come underneath the incoming jet, it opens up the filaments by pushing the filaments towards the sidewalls. This action exerts tension on the filaments in the vicinity of the air inlet hole. Consequently tension builds up in the intertwined section, resulting in a tightly entangled knot. As the process continues, the incoming jet also continuously tries to open the filaments but when the tightly knotted section created upstream comes underneath the incoming jet no opening of the filaments is possible. As the knot moves along it becomes easier to be opened because it has not experienced the opening effect of the incoming jet, which makes the intertwined section into a tight knot. The whole sequence of opening and non-opening follow one another periodically. Briefly the process can be considered as an outcome of two actions:

i) intertwining of the filaments by the flows inside the main channel
ii) opening up action by the incoming jet, which results in tightly knotted section in the yarn.

The repetitive nature of the phenomenon is assumed to be due to a oscillating change in the local tension in the intertwined section, which firstly increases until a threshold value above which the knot created in the intertwined section cannot be tightened any more and then, as a result, no more opening is possible which causes the tension to decrease.
II) In order to produce INT yarns with no missing nips it is necessary to
* have correct overall tension.
* confine yarn movement within the main channel which prevents the yarn from escaping from coming against the incoming jet. This can be achieved simply by turning the nozzle at about 45°.
* introduce high supply pressure, greater than 2bar for the nozzle investigated

III) Nip period of INT yarns can vary along a given yarn.
### TABLE 8.1 EFFECT OF NOZZLE TURNING ANGLE ON MISSING NIPS

<table>
<thead>
<tr>
<th>NOZZLE TURNING ANGLE (degree)</th>
<th>NO OF MISSING NIPS (nip/m)</th>
<th>mean</th>
<th>st. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.7</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>7.4</td>
<td>1.78</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>5.2</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>2.3</td>
<td>0.67</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 8.2 QUANTITATIVE ANALYSIS OF THE HIGH SPEED FILMS OF INT PROCESS

<table>
<thead>
<tr>
<th>SUPPLY PRESSURE (bar)</th>
<th>PARAMETER O (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>24.5</td>
</tr>
<tr>
<td>4</td>
<td>37.5</td>
</tr>
</tbody>
</table>
### TABLE 8.3 YARN TENSION IN INT

**OVERFEED=0%**

<table>
<thead>
<tr>
<th></th>
<th>nozzle straight</th>
<th>nozzle turned</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sub&gt;1&lt;/sub&gt; (gram)</td>
<td>T&lt;sub&gt;2&lt;/sub&gt; (gram)</td>
<td>T&lt;sub&gt;1&lt;/sub&gt; (gram)</td>
</tr>
<tr>
<td>p=0 bar</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>p=2 bar</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>p=4 bar</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>p=8 bar</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

**OVERFEED=2%**

<table>
<thead>
<tr>
<th></th>
<th>nozzle straight</th>
<th>nozzle turned</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sub&gt;1&lt;/sub&gt; (gram)</td>
<td>T&lt;sub&gt;2&lt;/sub&gt; (gram)</td>
<td>T&lt;sub&gt;1&lt;/sub&gt; (gram)</td>
</tr>
<tr>
<td>p=0 bar</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>p=2 bar</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>p=4 bar</td>
<td>7</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>p=8 bar</td>
<td>9</td>
<td>9</td>
<td>Y.B.</td>
</tr>
</tbody>
</table>

**OVERFEED=4%**

<table>
<thead>
<tr>
<th></th>
<th>nozzle straight</th>
<th>nozzle turned</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sub&gt;1&lt;/sub&gt; (gram)</td>
<td>T&lt;sub&gt;2&lt;/sub&gt; (gram)</td>
<td>T&lt;sub&gt;1&lt;/sub&gt; (gram)</td>
</tr>
<tr>
<td>p=0 bar</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>p=2 bar</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>p=4 bar</td>
<td>0+</td>
<td>0+</td>
<td>0</td>
</tr>
<tr>
<td>p=8 bar</td>
<td>0+</td>
<td>0+</td>
<td>Y.B.</td>
</tr>
</tbody>
</table>

T<sub>1</sub> : upstream yarn tension  
T<sub>2</sub> : downstream yarn tension  
Y.B. : yarn breaks  
0+ : tension slightly greater than or equal to 0
FIGURE 8.1 GEOMETRY OF THE INT NOZZLE
FIGURE 8.2 UNSTABLE INT PROCESS DUE TO EXCESSIVELY HIGH TURNING ANGLE
FIGURE 8.3a VIBRATION PATTERN OF THE NOZZLE ALIGNED WITH THE YARN PATH (4 consecutive images)
FIGURE 8.3b-c VIBRATION PATTERN OF THE NOZZLE ALIGNED WITH THE YARN PATH
(larger magnification)
FIGURE 8.4 ELIMINATED VIBRATION AFTER THE NOZZLE TURNED AT 45 degree WITH RESPECT TO YARN PATH (4 consecutive images)
FIGURE 8.5 VIBRATION PATTERN OF RIETER-SCRAGG YARN GUIDE
(4 consecutive images)
FIGURE 8.6 VIBRATION PATTERN OF THE LONGER NOZZLE (Straight)
(4 consecutive images)
FIGURE 8.7a-b A SELECTION OF HIGH SPEED CINE FILMS OF INT PROCESS at 2 bar and 4 bar
FIGURE 8.8 SEQUENCE OF OPEN AND CLOSED SECTIONS at 2 and 4 bar
FIGURE 8.9a CLOSED SECTION OF AN INT YARN
(90 magnification)

FIGURE 8.9b CLOSED SECTION OF AN INT YARN
(160 magnification)
FIGURE 8.9c OPEN SECTION OF AN INT YARN
(160 magnification)
FIGURE 8.10 APPEARANCE OF AN INT YARN WITH REFERENCE TO VARIATION IN NIP PERIOD
CHAPTER 9
GENERAL CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

9.1. INTRODUCTION

Hitherto each chapter has been reported one aspect of AJT or INT process only, rather independently from each other. In this chapter firstly, the findings are combined in a coherent way and general conclusions extracted from the whole research are summarised. Furthermore, suggestions for future work are presented.

9.2. GENERAL CONCLUSIONS

9.2.1. AJT PROCESS

The research has contributed to the knowledge in the following areas of AJT process:

a) An improved understanding of the AJT process and its mechanism, including the effect of wetting on AJT
b) Effect of nozzle geometry on the AJT process
c) Load-Elongation tests can be used to assess as a yarn/nozzle assessment.

Improved understanding of the AJT process
At the current level of knowledge of AJT process it is still not possible to comprehend the phenomenon fully. In other words, what element affects the process in what way is still not clearly understood. However the current research has found that texturing can be performed in the absence of a few elements which were concluded by earlier researches to be necessary for producing textured yarns (e.g. the jets created by an AJT nozzle does not have to be asymmetric). Additionally it has brought some new elements to attention, which are necessary for texturing (e.g. fixing the loops into the resultant yarn). By doing so; i.e. trying to identify what makes AJT possible and what is not necessary for it, it has
been possible to reach to a better understanding the process, which is summarised as follows:

Movement of the filaments along the yarn from where they start changing their original structure until they become the textured yarn has been investigated by means of high-speed cine filming. It has been found that the first change that the filaments experience is opening up. This takes place about 1.5mm upstream of the meeting point of the axes of the incoming jet and the main channel. Along with mere opening, they are also surmised to experience twisting. However it is not possible to conclude definitely whether the apparent twisting is due to turbulence in the flow, since there is no evidence linking properties of the turbulence, such as turbulence intensity, to the amount and direction of twist and their variation. Since the filaments are mostly parallel in that region it can be stated that the function of the internal air flow is mainly to open up the filaments.

During the opening, the filaments experience little tension, which is evident from their slight slackness. Afterwards the filaments become considerable more slack and loops, arcs and similar forms are created in the filaments in the vicinity of the nozzle exit. The loop creation is a result of the 90° turning of the yarn from the nozzle by the take-away rollers. The zone within which loop formation takes place covers the vicinity of the nozzle, but lays mostly outside the nozzle. As the yarn comes out of the free jet the loops are entangled and trapped in the yarn and, consequently, textured yarn structure is formed.

Whilst the interfilament friction in the section prior to the nozzle is reduced due to the soaking effect of filament wetting, the investigations on the effect of wetting on AJT have shown that reduction in spin finish causes higher interfilament friction in texturing area. This assists locking the loops formed firmly in the yarn. This has been concluded to
be one of the ways through which wetting improves AJT process.

**Effect of nozzle geometry**

Several geometrical parameters of the model rectangular cross-section AJT nozzles have been investigated and the following results are recommended for the purpose of designing nozzles with respect to producing textured yarns with improved quality.

It has been found that a divergent main duct is beneficial for texturing and also that the air inlet hole is necessary to be located at least 7mm from the exit plane. Another important geometrical parameter affecting nozzle performance is tilt angle of the air inlet hole, which has found to be 30-45°. As far as number of inlet is concerned, a nozzle with single inlet hole performs better than that with two inlet holes.

In addition to the progress in the classical design of cylindrical AJT nozzles, summarised above, the following points can assist design of new nozzles.

The investigations on AJT process have led to the conclusion that texturing does not consist of forming loops only, but fixing the loops is equally important (Chapter 6). This deduction can lead to new types of nozzles which can use the compressed air, the most expensive element of the process, more efficiently (See section 9.1.).

9.2.2. INTERMINGLING PROCESS

The research has recorded progress in the following areas of INT process:

a) An improved understanding of INT process
b) Effect of nozzle geometry on INT process
c) Improving nip regularity by means of changing yarn path with respect to orientation of the nozzle in INT
Improved understanding of INT process
INT process can be considered as an alternating outcome of two opposing actions imposed by the air flows in the main channel on the filaments. The two opposing actions take place continuously but one overcomes the other alternately. The first action is to intertwine and mix the filaments together, by the flows in the main channel. The second action is to open up the already interwined filaments, by the incoming jet. The second action can be successfully performed until its very effect creates a knot in upstream section of the yarn by creating high tension in that section.

Effect of nozzle geometry on INT
Investigations on INT nozzles with rectangular main channel have made it possible to specify several geometrical parameters of the nozzle so as to improve nozzle performance in terms of nip frequency.

As far as shape of cross-section of the main channel is concerned, rectangular main channels have been found to be superior over semi-circular nozzles. The performance of the nozzles depends on their dimensions. The first important geometric parameter is area ratio and has been found to be necessary to be smaller than unity. Secondly it has been found that smaller channels are much more beneficial with respect to high nip frequency. Aspect ratio approximately 0.5 is also beneficial for high nip frequency. Width of the air slot has also found to be necessary to be small. Nozzle length has found to have no effect on nip frequency, therefore, for the interest of economy, it can be as short as 15mm.

An improvement in nip regularity in INT
Creating nips regularly distributed along the yarn has been a major problem in INT. Findings on the process have demonstrated that this can be improved by confining the yarn simply by means of turning the nozzle. In industrial practice this effect can be created by equipping nozzles with specially
designed yarn guides to ensure a confined yarn path.

9.3. SUGGESTIONS FOR FUTURE WORK

9.3.1. AJT NOZZLE DESIGN

The model nozzles used in Chapter 4 and 5 have been proven to texture successfully. Since they are manufactured by milling, instead of by boring, it is possible to manufacture nozzles with awkward geometry both for research as well as industrial purposes.

Investigations on AJT process have led to the hypothesis that texturing does not consist of forming loops only, but fixing the loops is as much important (Chapter 6). This deduction can lead to new types of nozzles which can use the compressed air more effectively, which is the most expensive element of the process. Before going into details of design of new nozzle it is necessary here to summarise the widely accepted comprehension of the process and the approach that it has brought to nozzle design. AJT has been considered to be forming loops with filaments. Since loop formation is very much affected by the end of the yarn still inside this has led to the conclusion that if the yarn is pushed from the nozzle faster loop formation will be more effective. This conclusion has led to designing nozzles which can deliver higher speed. However this requirement can be little improved by designing nozzles which can convert the pressure energy of the compressed air to kinetic energy effectively, since many improvements in this respect has already been recorded (see Chapter 2). In this case, obtaining a jet with high velocity mostly relies on supply air of high pressure which results in higher air consumption, hence, more costly. If the emphasis is shifted from loop formation, therefore, designing nozzles with high speed, to fixing the loops in the yarn then new types of nozzle with less air consumption can be designed. Since securing the loops in the textured yarn is also
important adequate texturing nozzles which can increase interfilament friction in the texturing zone can attain improved texturing. A way of increasing interfilament friction can be imposing new paths on the yarn.

9.3.2. FURTHER INVESTIGATIONS OF YARN MOVEMENT IN AJT

Investigations of yarn movement inside a rectangular model nozzle, which are detailed in Chapter 6, have already yielded valuable information although it is the first of its kind. More information can be obtained if a yarn with one coloured filament; i.e. tracing fibre technique. As concluded in Chapter 6, filament groups are twisted inside the model nozzle. This aspect of yarn movement can be investigated by deployment of pre-twisted yarn, especially to find out how much twist is inserted to the yarn by the air flow. Having two orthogonal images by the high speed photography technique can also yield valuable information about filament movement.

9.3.3. STUDY ON DYNAMICS OF YARN IN AJT

Basically AJT is a process of filaments moving relative to each other. An introductory study of the dynamic of the filament movement was carried out by the author and detailed in Appendix C, but it requires considerable amount of experimental work for quantifying drag coefficient of the filaments at several flow regimes which are involved in AJT. Combination of this work with the information gathered from the above work can lead to a better understanding of the process.

9.3.4. NOISE STUDIES IN INT WITH REFERENCE TO PROCESS MECHANISM

It is very interesting about INT that the air jet is, in most cases, continuously introduced to the yarn, which also runs continuously, but the outcome of the process; i.e. INT yarn,
exhibits a discontinuous pattern with its consecutive open and closed sections. This curious phenomenon can be investigated by studying noise created by the process, which is discontinuous by nature. If typical process speed is taken to be as 10 m/s and nip frequency to be 100 nips/m this means that the process of nip creation takes places with a frequency of 1 KHz. Consequently any study of noise in INT requires measurements of higher frequency than this value.
APPENDIX A
INTERFERENCE OF A PITOT TUBE INSERTED INTO A SUPERSONIC FLOW

A fine pitot tube is usually deployed for measuring total pressure in supersonic air flows. Velocities can be calculated from the total pressure data with enough accuracy if only the shock waves formed due to presence of the pitot tube is a normal shock front (Figure A.1), through Eq.A1 and A2. If the shock wave is oblique then it become impossible to calculate the velocity in the direction of the pitot tube since the flow changes its direction due to the shock wave.

\[
\frac{P_0}{P_1} = \left[ \frac{(\gamma+1)(\gamma+1)}{2\gamma + M_1^2} \right]^{\frac{1}{\gamma-1}} (A.1)
\]

\[
c_p T_0 = c_p \frac{u_1^2}{\gamma R M_1^2} + \frac{u_1^2}{2} (A.2)
\]

where 1 and 0 denote the upstream conditions and stagnation conditions respectively.

As far as interaction of a pitot tube and the air jets created by commercial AJT nozzles is concerned the above condition cannot always be complied with because sometimes an oblique shock front is formed ahead of the pitot tube, depending on its position in the flow. An investigation has been carried out by the author and Joyce [A.1] on the effect of presence of the pitot tube with respect to the flow. The pitot tube traced an air jet created by a pipe with at right angle to the jet axis and it has been found that, especially near the jet boundaries, an oblique shock front is created ahead of the pitot tube (Figure A.2a-c).

As a result, a pitot tube cannot be used for velocity measurements in jets created by the nozzles that were used in

A-1
Chapter 3. It can, however, be used for measuring total pressure.

REFERENCE

FIGURE A.1 UPSTREAM and DOWNSTREAM VELOCITIES IN NORMAL and OBLIQUE SHOCK WAVES
FIGURE A.2 a-c EFFECT OF PRESENCE OF A PITOT TUBE IN A SUPERSONIC JET
APPENDIX B
DEFINITIONS OF DRAG COEFFICIENTS

When the total drag experienced by a body is of interest then drag coefficient, \( c_D \), is defined as follows:

\[
c_d = \frac{D*2}{\rho *(U-V)^2 *A}
\]  

(B.1)

where \( U \) is velocity of the undisturbed flow, \( V \) is mean body velocity, \( \rho \) is fluid density and \( A \) is the area projected to the flow. Assuming the body to be a circular cylinder, if it is aligned with the flow \( A \) is equal to \( \pi*d*L \), if drag is acting vertical to the cylinder axis then \( A \) is \( d*L \); where \( d \) and \( L \) are cylinder diameter and length respectively.

As total drag consists of pressure drag and skin friction, drag coefficients related to the two components can be formally defined as follows:

\[
c_d = \frac{p*2}{\rho *(U-V)^2}
\]  

(B.2)

\[
c_f = \frac{T*2}{\rho *(U-V)^2}
\]  

(B.3)

In practise when total drag is almost equal to one of the components only \( c_D \) is mentioned without specifying its being pressure drag or skin friction.

Another concept in drag coefficient classification is being local or total. The hitherto drag coefficients are local ones. Total skin friction, for example, is expressed as follows and the same applies to pressure drag.
Drag coefficients are function of Reynolds number, Re, and when compressibility becomes significant they are that of both Re and Mach Number, M, (depending on the flow characteristics compressibility should be taken into account around M=0.4 and onwards)
C.1. INTRODUCTION

A typical AJT process involves air speed of 350 m/s in its free jet, whereas average yarn transportation speed (average of velocity of input and output rollers) is in the order of 10 m/s. This large relative velocity creates large amount of air drag on the filaments. The effect of drag is particularly important in the area of delivery. In that area, one end of the yarn is travelling in nozzle direction and the other is taken up by the delivery rollers at right angle. If there was no air drag acting on the yarn, the filaments would simply slacken. The air drag, however, jets one end of the yarn in the flow direction while the other end is deflected from the direction of its movement by the delivery rollers. Under the circumstances the yarn tries to adjust itself, creating an arc at its furthest part in the jet. By the time the arc leaves the flow and becomes a part of the textured yarn, new arcs and loops are created in different filaments in a similar way, disarranging the whole yarn into a more voluminous and loose structure. Therefore it can be said that air drag is one of important aspect of AJT process.

C.2. AIR DRAG OF A YARN

In this section, a monofilament in an air stream is investigated firstly and it is modelled as a rigid cylinder with infinite length as a first approximation. Afterwards a review of some textile processes in which yarn-air interaction takes place, such as melt spinning, spunbonding, air-jet weaving, is presented.
C.2.1. A RIGID CONTINUOUS CYLINDER IN AIR

C.2.1.1. AN OBJECT IN A FLUID

In general when a rigid body is immersed in a fluid it is subjected to two stresses: Shear stress, \( \tau \), due to viscous effects and normal stress, \( p \), due to pressure. The resultant force acting on the body can be divided into two components: Drag force, \( D \), which is in the direction of the surface vector of the body, and lift, \( L \), which is in the normal direction to the former.

\[
D = \int p \cos \theta \, dA + \int \tau \sin \theta \, dA \quad (C.1)
\]

\[
L = -\int p \sin \theta \, dA + \int \tau \cos \theta \, dA \quad (C.2)
\]

where \( \theta \) is the angle between flow direction and \( dA \) surface element.

As seen in Eq.C.1, total drag consists of two components. They are termed as pressure drag, or form drag, and friction drag, or skin friction, respectively.

When fluid flows past a fairly slender object which is positioned along the flow, rather than a blunt and complex shape one, pressure gradient along the body surface is negligibly small since the presence of the object does not very much disturb the flow field. Therefore the first terms in each equation are practically zero (In the case of compressible flow, however, if shock waves are present then the situation is more complex: Even if presence of the object does not alter flow field, pressure gradient is already created in the flow due to shock waves, resulting in non-zero pressure drag.). The remaining second term in lift equation is also zero, because the object has been
assumed to be positioned along the flow. Having assumed the flow to be incompressible, the object to be slender and oriented with the flow, therefore, the resultant force acting on the body is reduced to friction drag only. (Discussion on validity and applicability of these assumptions to AJT is given in Section C.4.)

C.2.1.1.1. FRICTION DRAG ON A CONTINUOUS CYLINDER

As discussed in Section C.2.1.1 the resultant force exerted on a body approximately equals to friction drag, only in the following conditions:

I. The flow is incompressible.
II. The object is slender.
III. The object is aligned with the flow.

In the literature there are three theoretical works dealing with the above situation [C.2, C.13, C14] of Sakiadis, [C.10] of Matsui and [A17] of Tsou. In Sakiadis’s work the friction drag of a circular cylinder is investigated for both turbulent and laminar flow by momentum boundary layer equations. The equations were solved by assuming velocity and shear stress profiles describing each case. It is reported that in the case of turbulent flow the assumptions do not lead to accurate representation of the flow, so only skin friction coefficient for laminar and incompressible flow is presented here:

\[ C_D = 1.8 \times Re_D^{-0.5} \]  \hspace{1cm} (C.3)

(The above form is given by Shimizu et al [C.16] in their comparative work on drag coefficients of filaments.) Apart from Sakiadis’s work given above, drag of a
continuous cylindrical body is investigated semi-empirically by Matsui [C.10]. A laminar boundary layer is assumed to be formed in a turbulent core flow. Momentum along the filament direction is assumed to be constant in boundary layer and the momentum balance equation is numerically solved with the aid of Prandtl’s mixing length concept and then a theoretical relation between drag coefficient and Re_d is expressed as follows:

\[ C_D = 1.22 \times K^{0.78} \times Re_D^{-0.61} \]  

(C.4)

where K is determined by experiments.

Turbulent flow in the boundary layer on a continuous moving surface is analytically and experimentally investigated by Tsou et al [C.17]. The boundary layer is divided into two regions; a region near to the wall and the far region between the adjacent region and the core flow. The former is treated by Deissler’s model [C.5] and a logarithmic velocity profile is assumed to establish in the latter. These assumptions are subsequently proved to be realistic by a series of experiments by the authors (in the experiments a cylindrical steel pipe 12.6 in. in diameter is used). With the velocity profiles in the boundary layer available, \( \tau \) can be calculated from a momentum balance.

C.2.2. A REVIEW OF EXPERIMENTS ON DRAG OF A YARN

There are several textile processes in which air acts on filaments. In these processes air drag is created due to relative velocity between air flow and the filaments (Appendix B). In this section drag coefficient data related to the processes has been presented firstly and then experimental drag coefficient measurements, with no reference to any particular textile process, have been
discussed later on.

Most of the work is based on the approximation that when a filament is subjected to an air flow in its direction, yarn tension in the filament is almost equal to the drag experienced by it and, hence, drag coefficient can be calculated by using Eq.C.5.

\[
C_D = \frac{\frac{\Delta T}{\Delta L}}{0.5 \rho_a U^2 \pi d}
\]  

(C.5)

where \( U \) is average filament velocity and \( d \) is filament diameter.

Matsui [C.10] measured filament tension in spinline in melt spinning, \( \Delta T \) and then calculated \( c_f \) by using the above equation, where \( \Delta L \) is yarn length. Since he has found earlier in his theoretical analysis that drag coefficient is proportional to \( Re \) (Eq.C.4), \( K \) can be calculated, hence, drag coefficient-\( Re \) relation for spinning speed=300-6000 m/min is found as follows:

\[
c_D = 0.37 Re_D^{-0.61}
\]

(C.6)

Following the same approximation, several experiments are carried out by Lim et al [C.9] on spunbonding, in which filaments pumped down through the spinneret are drawn by high velocity air jet and integrated to a nonwoven fabrics on a conveyor belt. They used a nozzle, which is similar to a cylindrical HemaJet AJT nozzle, in order to create the air flow. The experiments could be summarised as follows:
I. The above method; i.e. measure tension in the filament, substitute it in Eq. C.5 and then calculate $c_r$.  

II. Calculation of $c_r$ through the following formula:

$$C_r = \frac{2 \tau \omega}{\rho U^2}$$  \hspace{1cm} (C.7)

where $\tau$ is the shear stress, which is determined as follows:

$$\tau = \frac{d}{dx} \int_0^x \rho U^2 dy$$  \hspace{1cm} (C.8)

The velocity distribution in the above equation was obtained by measuring the mean velocity distribution of a turbulent plane wall jet flow with the same nozzle shape used in the air-tensioning experiment in Method I.

However when the drag coefficient data obtained by the two methods were plotted together (Fig.C.3) the profile did not match completely, but showed the same linear decaying behaviour. The discrepancy between the two sets of drag coefficient data is due to the fact that they are not the same by definition. The drag coefficient calculated from air tensioning experiment corresponds to the total drag whereas the latter only takes the contribution of friction drag.

Lim et al also investigated effect of nozzle angle on drag force and found that maximum drag is attained when the air is exerted on the filaments with zero incidence.

Similar experiments on PES and PP melt spinning where maximum take-up speed is about 6000 m/min are performed by Shimizu et al (C.16) and $c_r$ obtained by method I is expressed as follows:
\[ C_f = 0.49 Re_D^{-0.61} \]  
(C.9) 

(yarn vibrates, 1 or 4 filament)

\[ C_f = 0.39 Re_D^{-0.61} \]  
(C.10) 

(no vibration, 1 filament)

\[ C_f = 0.23 Re_D^{-0.61} \]  
(C.11) 

(yarn vibrates, 16 filaments)

\[ C_f = 0.77 Re_D^{-0.61} \]  
(C.12) 

(yarn vibrates)

Sano et al [C.11] also calculated air drag coefficient in melt spinning of PP with velocities between 200 and 1200 m/min by Method I.

\[ C_f = 0.68 Re_D^{-0.8} \]  
(C.13) 

(yarn vibrates, 40<Re<400)

Adanur [C.2] also did air tensioning experiments in air-jet weaving by deploying a straight tube in order to obtain uniform velocity and his results are expressed in the following form:

\[ C_f = 0.4193 U^{-0.4863} \]  
(C.14) 

(50/2 Ne cotton, 20 m/s<U<200 m/s)

(125 denier textured PES)
$C_f = -0.4274 U^{-0.4887}$ \hspace{0.5cm} (C.15)

Uno [18] found $c_f$ for air velocities smaller than 20 m/s by using similar technique to that of Adanur's, but arranging the tube vertically.

$$C_f = 0.02 + \frac{1}{U+2} \hspace{0.5cm} (C.16)$$

Gould et al [C.8] gave a review of previous work (Andrew et al, Selwood's) as well as measured air drag in a wind tunnel (air velocity is smaller 100 m/s) and found the following relation:

$$C_D = 0.41 Re_D^{-0.61} \hspace{0.5cm} (C.17)$$

(40<Re<400, U<100 m/s)

Gould reported that Andrews et al [C.4] found the following relation in their similar work to Gould et al:

$$C_f = 1.3 Re_D^{-0.61} \hspace{0.5cm} (C.18)$$

(40<Re<300)

Gould attributed the difference between Andrew's and his work to the fact that in the case of Andrew's experiments the filaments were allowed to vibrate, resulting in high air drag.

Another air-tensioning measurement experiment was carried out by Selwood [C.15] on monofilaments of 6, 15 and 60 denier, at filament speeds of 5-20 m/s and the following relation was obtained (A9 in A8).
Glicksman [C.7] investigated glass fibre production and expressed his findings for turbulent boundary layer in the following form:

\[ C_f = 0.56 Re^{-0.61} \quad (C.19) \]

(Re < 108)

Glicksman [C.7] investigated glass fibre production and expressed his findings for turbulent boundary layer in the following form:

\[ C_f = 0.65 Re^{-0.7} \quad (C.20) \]

(Re < 200)

C.2.3. FACTORS EFFECTING AIR DRAG ON YARNS

Effect of vibration: Gould et al and Shimizu et al (compare Eq.C.9 and C.10) found that vibration causes air drag to increase. Gould et al reported that the increase is due to the introduction of pressure drag and is in the order of 80% in the case of 167 dtex PES yarn.

Effect of neighbouring filaments: Gould et al reported that drag forces on normal diameter textile filaments are not affected by the presence of other filaments by the distance of 1 mm, closer filament arrangements result in reduced drag force.

Effect of filament diameter: Most of the drag coefficient data reviewed here are expressed as a function of Re, suggesting that the higher the diameter the higher the drag is. Anderson et al [C.3] also experimentally found increase in air drag force as diameter is increased.

Effect of filament length: As stated before most of the drag coefficient data is based on air-tensioning measurements. In these experiments probe of the tensiometer is inserted in various distances with respect to a reference. These measurements show, as expected, that
the longer the yarn the higher the drag force (C.3, C.8, C.9, C.16). However there are different findings about effect of length on drag coefficient. While Matsui states that drag coefficient is not influenced by filament length, Lim et al finds drag coefficient to be a linear function of $Re_x$, Reynolds Number based on lengths. Tsou et al also found a relation between $c_r$ and $Re_x$, but not linear one. Sakiadis also expressed his $c_r$ data as function of length.

\[ c_r = g(x, d/l) \]  

(C.21)

where \( l \) is filament length exposed to air.

Effect of air incidence with respect to filaments: Air drag increases with decreasing angle between flow direction and filament axis.

C.3. YARN DYNAMICS IN AJT

As discussed in Section C.1 there is considerable amount of air drag involved in AJT due to high relative velocity of air to filaments. Filament velocity can be quantified if drag coefficient is known along with drag force acting on the filaments, air density, air velocity and projected filament area (See Eq.B.1 in Appendix B). Since, however, there is no average drag coefficient which is valid for a complete AJT flow, local drag coefficients should be obtained (See Section C.4), therefore, filament velocity in each section can be worked out.

C.3.1. DISCUSSIONS ON AIR DRAG DATA IN THE LITERATURE

Drag coefficient data available in the literature, reviewed in Section C.2, need to be scrutinised in terms of flow conditions and the assumptions in order to apply AJT.
I. Since drag coefficient data reviewed are mostly experimental, that is, results heavily depend upon yarn surface characteristics and diameter, drag coefficients related to AJT need to be determined (See Section C.4).

II. As given in Section C.2.1.1.1, investigation of yarn motion in an air stream has been based on several assumptions, which enable the resultant force to be reduced to friction drag (skin friction). These assumptions need to be examined in order to be able to apply the data based on them to AJT. Assumption I; i.e. the flow is incompressible, does not give accurate results due to the fact that possibility of shock wave presence inevitably introduces non-zero pressure drag. Since there is no drag coefficient data available taking effect of pressure gradient into account compressibility effect is to be neglected. Filaments in AJT comply with Assumption II; i.e. the object is slender. Assumption III is valid when the filaments are aligned in a settled flow; i.e. away from the incoming jets.

C.4. FUTURE WORK

I. Discussion of applicability of drag coefficient data has revealed the necessity of determination of them which are valid for AJT. The following experiments are proposed for this purpose:

a) Air-tensioning experiments: Wind tunnel experiment

A simplified version of this technique utilised by Uno and Adanur, which requires use of a plastic tube as the flow generator can be appropriate to adopt. The tube has constant circular cross-section along L in order to create velocity profile as close as possible to uniform one, which is required in calculation of drag coefficient. It is slightly bent and the yarn is introduced to the tube at the
bending point The length L is variable in order to obtain various flow velocities. The yarn is clamped at both ends, giving a certain pre-tension $T_0$ and after introduction of air $T_1$ is measured. Since $T_0 - T_1$ gives the drag force $D$ can be calculated through Eq.C.5.

The above technique can be deployed to yield drag coefficients of various flow conditions, which can be generated by changing supply pressure, pipe diameter and length. (High pressure, small diameter, short pipe deliver high velocity; high pressure and short pipe also promote turbulence.). Putting an obstacle in the way of the flow (a mesh, etc) can increase turbulence. This technique, however, is not suitable creating high speed flows.

b) Air-tensioning experiments: During AJT

In finding local drag coefficient the whole AJT flow is divided into sections and then drag force is measured, as described above. The total drag acting the filament in the whole flow should be equal to summation of drag in each section. In order to test this, global drag during texturing must be known, which can be approximated to yarn tension. Probe of a tensiometer is most conveniently inserted in the yarn path at the entrance side of the nozzle, because under normal texturing conditions there is a vehement vibration of overfed yarn at the exit side. Alternatively the yarn can be not deflected by the delivery rollers, but taken up in the direction of jet flow and then the probe is inserted in yarn path at far downstream.

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