An analysis of the air-jet yarn texturing process and the development of improved nozzles

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AN ANALYSIS OF THE AIR-JET YARN TEXTURING PROCESS
AND THE DEVELOPMENT OF IMPROVED NOZZLES

By

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BS (METU, Ankara), MSc (Manchester)

A DOCTORAL THESIS

Submitted in Partial Fulfilment of the Requirements

For the Award of

DOCTOR OF PHILOSOPHY
of the
LOUGHBOROUGH UNIVERSITY OF TECHNOLOGY

MAY 1984

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"Science is the real guide for success, for civilisation, for life, and for everything." (22 Sept. 1924)

M. K. Atatürk
The Founder of Modern Turkey

O'nun devrimlerine ve ilkelerine gerçekten inananlara

To those who believe in Atatürk's principles
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The author is indebted to his supervisor and director of research, Professor Gordon R Wray, Head of the Department of Mechanical Engineering, for so enthusiastically introducing his specialised interest in this topic to the author. He is also indebted to his other joint supervisors Dr. A.J. Alexander and Mr. R. K. Turton for their specific advice on fluid dynamic aspects of the investigations. He would like to express his sincere thanks to each of them for their encouragement and support during the course of the work. Special thanks are also due to Prof. G. R. Wray for his invaluable help in the editing of the thesis.

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ABSTRACT

The air-jet texturing process for synthetic continuous multifilament yarns is more versatile than any other texturing process and provides the most effective simulation of natural staple spun yarns. The process itself is inadequately understood, and the ultimate goal of the work is to achieve a better understanding of the mechanism of the texturing process and to make suggestions for more efficient nozzle designs in order to increase productivity and thereby reduce production costs.

Reviews of historical development of the texturing nozzles and of the previous investigations are reported. Various designs of texturing nozzles are available but, in general, they possess similar flow characteristics i.e., a supersonic, turbulent, asymmetric, and non-uniform flow. Therefore this research was confined mainly to one type of nozzle investigated on a purpose-designed single-head texturing machine.

A mathematical flow model of the nozzle was developed to compare with the results of the experimental work; this model was also used as a basis for the design of new texturing nozzles. Experiments were conducted using scaled-up models of the texturing nozzle in order to determine the flow characteristics.

Flow visualisation, high-speed cine and still photography were among the techniques used in the investigations. The work was extended to include tension and drag force measurements, filament speed measurements and yarn tests. The effects of filament cross-sections on the texturing were theoretically studied. The effects of wetting the filaments on the air flow were analysed theoretically whereas their effect on the friction were investigated experimentally.

In the light of these experiments and the associated theoretical analyses, a loop formation mechanism has been suggested in order to provide an improved understanding of the process. Effects of process parameters on the yarn properties have also been examined and the results observed to be an good agreement with those predictable by the mechanism postulated.

Finally new texturing nozzles were designed, manufactured, and tested, and these proved to be more economic as regards air consumption. Suggestions for future work and further improved nozzle designs have been made.
NOMENCLATURE

Principal Notation

\( a \)  speed of sound  \\
\( a_0 \)  stagnation speed of sound  \\
\( a^* \)  critical (i.e., sonic) speed of sound  \\
\( A \)  flow cross-sectional area  \\
\( C \)  drag coefficient  \\
\( c_p \)  specific heat at constant pressure  \\
\( c_v \)  specific heat at constant volume  \\
\( D \)  drag force  \\
\( E \)  modulus of elasticity  \\
\( G \)  modulus of elasticity in shear  \\
\( I \)  area moment of inertia  \\
\( J \)  polar moment of inertia  \\
\( L \)  characteristic length, or the dimension length  \\
\( m \)  mass  \\
\( m \)  mass flow rate  \\
\( M \)  Mach number,  \\
\( p \)  absolute static pressure  \\
\( p^* \)  critical static pressure  \\
\( P_0 \)  stagnation pressure  \\
\( T \)  absolute static temperature,  \\
\( T_0 \)  stagnation temperature  \\
\( V \)  velocity magnitude  \\
\( V_{max} \)  maximum isentropic speed  \\
\( R \)  gas constant
**Greek Letters**

\[ \gamma = \frac{c_p}{c_v}, \text{ specific heat ratio} \]
\[ \mu, \text{ absolute dynamic viscosity} \]
\[ \rho, \text{ static density} \]
\[ \rho_0, \text{ stagnation density} \]
\[ \tau, \text{ shear stress} \]
\[ \psi^*, \text{ critical flow factor, defined by equation 3.3} \]

**Superscripts**

\[ \cdot \] denotes that the state is reached by an isentropic process

\[ * \] critical condition

**Abreviations**

CTA constant temperature anemometer

fps frames per second

rpm revolutions per minute

abs. absolute

**Note on Units Used**

SI units are used generally throughout this thesis, except in discussing tension measurements, where current terminology includes the gramme as a 'force' unit.
1.1 Yarns Made From Man-made Fibres

Yarns spun from natural staple fibres have excellent visual and tactile qualities such as good covering powers, excellent comfort factors, and naturally textured features. Characteristics of an acceptable textile yarn would also usually involve good tensile strength and high flexibility together with good dimensional stability. Flat and parallel continuous filaments, as produced by a spinneret, do not possess any of these properties except strength and uniformity, and they are thus less acceptable as textile yarns.

Yarns made from man-made fibres are often intended as more economic substitutes for traditional yarns spun from natural staple fibres provided that they are caused to possess similar characteristics. One of the methods for achieving this is first to crimp the continuous filaments permanently to simulate the crimp and waviness of the natural fibres, and then cut or break them into staple fibres which are compressed into bale form. These fibres are spun by the whole range of conventional spinning methods originally designed for natural short fibres, such as cotton. Since the method involves additional processes to convert the continuous filaments into fibres it makes the process wasteful and time-consuming. It has always been realised that such processing is illogical, in that the early processing stages, such as opening, carding, and sometimes gilling and combing, would be obviated if the orderliness and parallelism already present in the producer's filament tow, prior to its being chopped and baled, could be preserved during a process of converting it directly into sliver form and therefore tow conversion processes were introduced about 40 years ago to eliminate some of these early processes.
Later it was realised that synthetic fibres in their continuous filament form could also be converted into yarns by various texturing methods. Texturing methods impart bulkiness and texture without converting continuous filaments into staple fibres. Therefore, texturing in general can be thought of as a technique by which closely packed parallel arrangements of continuous synthetic filaments are changed into a more open, voluminous structure. Hence improved crimp, bulk, texture, and sometimes extensibility are imparted to the continuous filament yarns.

1.2 Texturing Methods

The majority of texturing methods comprise a mechanical deformation of the constituent thermoplastic continuous filaments, while they are heated to a semi-plastic condition, thereby giving them a permanently crimped and very open structure. This imparts a common characteristic of high extensibility under quite low loads. False-twist, edge-crimp, and compression-crimp (stuffer-box) texturing methods are typical of the methods in this category.

The false-twist method is the most widely used 'deform and set' process. It comprises twisting, heat-setting, and untwisting in one continuous operation. The twisting/untwisting sequence is simultaneously provided by means of spindles rotating at about 1 million rpm or friction twisters where the yarn rotation can be as high as 3 million rpm. Such high-speed operations permit very high production rates.

The false-twist method imparts a permanently set bending crimp into the flat and parallel continuous filaments, as shown in Fig. 1.1, and such yarns often inadequately simulate the characteristics of staple spun yarns.
1.3 Air-jet Texturing

In contrast to other texturing methods, the air-jet texturing process is a purely mechanical method which uses a specially designed texturing nozzle to provide an air stream to entangle the continuous filaments into a voluminous (bulked) spun-like construction with loops on the surface locked in the core of the yarn (Fig. 1.2). This versatile process does not require heat treatment and therefore offers the possibility of texturing non-thermoplastic fibres such as glass, as well as the production of blends from thermoplastic and non-thermoplastic materials. Heaters can optionally be used for suitable fibres in order to achieve extra desired effects. Water is often used in this process to wet the filaments prior to their entrance into the nozzle in order to achieve improved yarn quality. Air-jet textured yarns can be produced from one supply yarn (single-end texturing) or from two or more similar or dissimilar components (multi-end texturing). The latter processing system can yield either "parallel", "core-and-effect" textured yarns. Consequently the air-jet texturing process is by far the most versatile yarn texturing method and offers the texturiser the greatest possible scope for a wide range of end-uses.

1.4 Air-jet Textured Yarns

Yarns produced by the air-jet technique are unique in that they more closely simulate the spun yarn structures both in their appearance and physical characteristics. Whereas the bulkiness of the yarns produced by other texturing methods decreases with the degree of tension imposed on them, the form of air-jet textured yarns can be made to remain virtually unaffected at loads corresponding to those normally imposed in fabric production and during wear. This is due to the stability of the entangled filament structure within the core of the yarn (Fig. 1.2). Air-jet textured yarns more closely resemble conventionally spun yarns in that the yarn surface is covered with fixed resilient loops (Fig. 1.1), and these serve the
same purpose as the protruding hairs in spun yarns by trapping still air and hence forming an insulating layer between neighbouring garments.

Current application fields of air-jet textured yarns are very broad\textsuperscript{7-12} and can be summarised as follows:

i) outerwear and lightwear apparel fabrics;
ii) upholstery and car seat furnishing;
iii) knitted and bonded fabrics;
iv) sewing threads and shoe laces; and
v) industrial fabrics.

1.5 State of the Air-jet Texturing Process

Developments in the air-jet texturing process in the period since its introduction in the early 1950's have led to:

i) increased texturing speeds from about 50 to about 500 m min\textsuperscript{-1};
ii) reduced air consumptions from about 22 to about 12 m\textsuperscript{3} hr\textsuperscript{-1}/jet;
iii) reduced energy consumption by about 50%;
iv) elimination of the necessity for a pretwisted supply yarn; and
v) improved yarn quality.

These improvements have reduced the conversion cost of the air-jet textured yarns to a level comparable with those of the cotton or wool spinning processes\textsuperscript{9,11,13-15} and consequently have led to a current upsurge in interest in the air jet-texturing process both in industry and in research institutions owing to its unique capability to produce textured yarns closely simulate spun yarns. On the other hand, its lower production speeds and high conversion costs with respect to other texturing methods have hindered its full exploitation in industry.
The compressed air used in the process accounts for about half of the conversion costs\textsuperscript{15} and therefore further reductions in air consumption could result in substantial savings in the production costs of the air jet-textured yarns. While the texturing speeds of other texturing methods are approaching $1000 \text{ m min}^{-1}$, current production speeds of air-jet texturing processes are limited to about $500 \text{ m min}^{-1}$. Developments in the process which could lead to reductions in the compressed air consumption, or alternatively to an increase in the texturing speed, would increase the productivity of the process and contribute to its successful exploitation.

There are also other problems associated with the air-jet texturing process such as those related to the water used during wet texturing and to contamination of the nozzle by the spin finish applied to the filaments by the synthetic yarn manufacturers. Satisfactory solutions to these problems demand a better understanding of the process. Unfortunately existing published information fails to provide an adequate explanation of the air-jet texturing process or the causes of such associated problems. Most of the postulated mechanisms to explain the texturing phenomenon are either invalid for today's modern texturing techniques or reveal a vague and imprecise understanding of it as will be explained in Chapter 2.

1.6 Future of the Air-jet Texturing Process

World textile fibre production is growing, mainly because of rising demands due to increasing population. Production trends show the market share of the natural fibres is decreasing while that of synthetic fibres is increasing\textsuperscript{16-18}, and it is predicted to continue on these lines\textsuperscript{19}, as summarised in Fig. 1.3 which is based in the figures provided in Table 1.1. With the ability to simulate more closely the properties of the natural fibre yarns, the air-jet texturing process might be expected to encroach further upon the natural fibre market, and also, depending upon its economic
competitiveness, to capture some portions of the market currently enjoyed by the false-twist and similar techniques. Therefore success of the air-jet texturing process in the textile industry will rely upon reductions in conversion costs which could make it more economical when compared not only with spun yarns, but also with the yarns textured by other methods.

Air-jet textured yarns have a great potential for industrial exploitation on account of their unique characteristics including improved comfort, warmth, and dimensional stability in addition to their better wear resistance and easy-to-care properties. Research leading to a better understanding of the air texturing phenomenon could be worthwhile if it results in further technical improvements and reductions in conversion costs.

1.7 Scope of the Work and the Methods Used

The goal of this thesis is to analyse the air-jet texturing process in detail by theoretical and experimental means, in order to achieve a better understanding of its mechanism, and consequently to suggest improvements to the process in order to increase its productivity and efficiency. In the light of the experimental findings, it is also aimed to design new nozzles which consume less air and yet improve the effectiveness of the process and hence reduce the conversion costs.

Mathematical models for the texturing nozzles are developed for the analysis of the flow in these nozzles. These models are compared with the experimental findings, and are used as an aid for further nozzle developments. Experimental techniques include scale modelling of the nozzle, flow measurements, flow visualisation, high-speed cine and still photography to investigate the air flow and behaviour of the filaments during texturing. Effects of filament cross-sections and wetting the filaments are investigated and the fluid forces acting on the filaments are analysed by theoretical and experimental
means. In the light of these a mechanism of loop formation is postulated and yarn tests are undertaken to verify the postulated mechanism. New nozzles are designed, made and tested.

1.8 Limitations

This research has been mainly concerned with the air flow through texturing nozzles, in particular flow in the standard HemaJet nozzle. The minute size of such nozzles made their use impracticable for experimental investigation, and scaled-up models were therefore used for this purpose. The high air flow rate requirements of the scaled-up nozzles were limited to a maximum pressure of $7 \times 10^5 \text{ N m}^{-2} \text{(abs)}$ by the compressed air supply available in the Mechanical Engineering laboratories. The upper limit of the compressed air supply to the research texturing machine was $10.5 \times 10^5 \text{ N m}^{-2} \text{(abs)}$.

Not having the facilities of a textile testing laboratory in an engineering department, yarn tests were avoided unless they were absolutely necessary. These yarn tests were usually confined to one type of supply yarn to avoid the effects which otherwise might be introduced by using different types of yarns.

Since the manufacture of the prototype texturing nozzles requires specialised machinery and skills, the nozzles designed and developed by the author were made by the Heberlein Company of Switzerland, one of the major texturing nozzle producers, but the cost of producing such nozzles limited the number of nozzles that were actually made and tested. Some other nozzles were designed but cost limitations have prevented their being made and tested.
### Table 1.1

World textile fibre productions and forecasts.

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural Fibres $10^3$ tonnes</th>
<th>Cellulosic Fibres $10^3$ tonnes</th>
<th>Synthetic Fibres $10^3$ tonnes</th>
<th>Total Man-made Fibres $10^3$ tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1940*</td>
<td>8 153</td>
<td>1 127</td>
<td>5</td>
<td>1 132</td>
</tr>
<tr>
<td>1950*</td>
<td>7 713</td>
<td>1 608</td>
<td>69</td>
<td>1 679</td>
</tr>
<tr>
<td>1960*</td>
<td>11 591</td>
<td>2 597</td>
<td>702</td>
<td>3 298</td>
</tr>
<tr>
<td>1970*</td>
<td>13 304</td>
<td>3 227</td>
<td>4 694</td>
<td>8 121</td>
</tr>
<tr>
<td>1980*</td>
<td>15 903</td>
<td>3 242</td>
<td>10 476</td>
<td>13 718</td>
</tr>
<tr>
<td>1982*</td>
<td>16 348</td>
<td>2 949</td>
<td>10 100</td>
<td>13 049</td>
</tr>
<tr>
<td>1990‡</td>
<td>17 700</td>
<td>3 200</td>
<td>19 000</td>
<td>22 200</td>
</tr>
<tr>
<td>(forecast)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995§</td>
<td>21 000</td>
<td>4 000</td>
<td>23 000</td>
<td>27 000</td>
</tr>
</tbody>
</table>

* Source: references 16-18;
+ Source: reference 19;
@ Source: reference 20.
FIGURE 1.1: Visual comparison of (a) cotton yarn, (b) air-jet textured yarn, and (c) false-twist textured yarn.

FIGURE 1.2: Close-up photograph of the air-jet textured yarn, showing the loops and the entangled filament structure within the core of the yarn.
FIGURE 1.3: Percentage shares of natural and man-made fibre productions since 1940 up to 1982, and future forecasts
2.1 Description of the Process

The heart of the air-jet texturing process is the texturing nozzle. This may vary in design and details, as shown in Section 2.2, but remains similar in its underlying principles. Fig. 2.1 shows an example, the HemaJet, a typical industrial texturing nozzle.

Fig. 2.2 schematically illustrates the requirements for air-jet texturing. The process involves the 'overfeed' principle where the multifilament supply yarn, as supplied 'over-end' from a creel, is fed into the nozzle at a greater rate than it is taken away. To achieve this degree of overfeed the yarn passes through the feed rollers W1.1 and/or W1.2 faster than it does through the delivery rollers W2. When the overfed filaments enter the nozzle, they are carried along through the nozzle, blown out from the texturing end, and formed into textured yarn by the effect of the cold air stream provided by a compressed air supply.

The zone between the feed rollers and the nozzle is termed the feed zone, and the zone between the nozzle and the delivery rollers is termed the delivery zone. The supply yarn is normally wetted just before it is fed into the texturing nozzle by passing it through a water bath or through a wetting unit which can either be separate or integrated in the nozzle assembly. Wet texturing apparently improves the quality of the yarn produced. Texturing nozzles are usually enclosed in a chamber, not only to reduce the noise created by the air-jet, but also to collect the used water and some of the spin finish washed away from the filaments during the process.

Some texturing nozzles have an impact element at the nozzle exit, to be used optionally in certain cases recommended by the
manufacturer. This can have different shapes, cylindrical, flat, or spherical as shown in the HemaJet design in Fig. 2.1. These elements are believed to improve the process stability and yarn quality in the texturing of certain yarns.

As well as a single supply yarn, two or more yarns of the same or different types can be textured at the same speed (parallel end texturing), or can be textured at different speeds (core and effect texturing) by the use of separate feed rollers W1.1 and W1.2. Another set of take-up rollers W3, running at slightly higher speeds than the delivery rollers W2, are used to apply tension to the textured yarn in order to stabilise the loops formed during the process, the zone between these two sets of rollers being termed stabilising zone. The textured yarn is then wound-up by means of a high speed take-up unit, WW. Heaters can be optionally used in the stabilising and take-up zones to impart further desired properties to thermoplastic and thermosetting filament types.

A single-head research machine, as designed and developed by the author according to these principles, is described in Appendix A.

2.2 Industrial Nozzle Developments

The air jet-texturing process spans three decades but in that time it has seen many variations in nozzle design. Piller\(^3\) claims that one of the earliest air-jet texturing nozzles, as shown in Fig. 2.3, was used on a standard ring twisting machine in Czechoslovakia; the air emerging from the annulus entrains the yarn and blows it against a "bridge" (an impact element) where the yarn is separated and formed into loops. However, it is doubtful whether the Czechoslovak jets were earlier than the rather similar nozzle (Fig. 2.4) that was patented by du Pont\(^20\) in 1952. The best-known du Pont Taslan Type 9 nozzle\(^21\) was introduced in 1954 and was used until the early 1970's. The Taslan process consisted of overfeeding the multifilaments into the nozzle by means of a stepped hollow needle
inclined at 45° to the nozzle axis, the air entering axially as shown in Fig. 2.5a. Normally this nozzle was positioned with the nozzle axis in the vertical plane, but it is here shown in the horizontal plane so that its different yarn feed and air supply arrangement can be compared with those of the other nozzles illustrated.

The du Pont Type 10 nozzle\textsuperscript{22}, introduced in 1960, had the overfed yarn entering a needle with the air flow passing through a uniform gap around the needle circumference as shown in Fig. 2.5b. The Type 11 nozzle\textsuperscript{23}, introduced in 1961, had several design changes including that of feeding the air through an inlet hole displaced to one side, see Fig. 2.5c. The Type 14 nozzle\textsuperscript{24}, introduced in 1973, was very similar except that a plate was situated at the exit to impact with the air flow and the emerging yarn as shown in Fig. 2.5d.

Fig. 2.6 shows a nozzle, different in construction but similar in principle, that was introduced in the 1950's in Czechoslovakia to make Mirlan yarns\textsuperscript{25}. The texturing nozzle was designed such that three air inlets were inclined so as to cause the air flow to carry the yarn on its path through the nozzle. In later versions of the Mirlan nozzle, an impact element was attached to the nozzle exit which did not appear in the early models.

A nozzle similar in construction was introduced by Heberlein Company of Switzerland in the late 1970's under the trade name of HemaJet\textsuperscript{26}. The air was fed into the main duct of the nozzle by means of three small inlet bores where it impinged upon the overfed supply yarn from three sides as shown in Fig. 2.7. Radially equispaced air inlet bores were axially staggered and make an angle of approximately 48° with the axis of the main duct.

Several other nozzles have not been reviewed in this section but the underlying principles of all texturing nozzles have remained unchanged with only slight differences in their detailed construction.
2.3 Review of Previous Investigations into the Texturing Mechanism

There is a scarcity of published knowledge about the texturing mechanism, particularly the relation between the air flow and the mechanism of loop formation. Publications in the 1960's by Wray\textsuperscript{27,28}, Wray and Entwistle\textsuperscript{29,30}, were followed by Wray and Sen\textsuperscript{31-33}, Sen\textsuperscript{34}, and Sivakumar\textsuperscript{37} in the early 1970's. The mechanisms claimed by these researchers were all based on the use of pre-twisted yarns and therefore are not valid for today's no-twist yarn texturing process. Further research by Bock and Lünenschloss\textsuperscript{38-40} in the early 1980's claimed that loop formation mainly resulted from the retardation of the filaments by shock waves, but this was not entirely new as Sen\textsuperscript{34} had observed such shock waves in 1970 and Sivakumar\textsuperscript{37} in 1975 suggested a similar mechanism based on his theoretical work and Sen's experimental findings.

Wray\textsuperscript{27} analysed the structure of the air-jet textured yarns by tracer filament and other optical techniques, and observed that a longitudinal displacement of the filaments relative to each other occurred during the process. Wray\textsuperscript{28} also studied the effects of process parameters, namely overfeed ratio, air pressure, texturing speed, filament linear density, and supply yarn pretwist, on the properties of the yarn produced. In the 1960's the first researchers to analyse the mechanism of the air-jet texturing process with a Taslan Type 9 nozzle were Wray and Entwistle\textsuperscript{29,30}. They observed the false-untwisting of the filaments during the process by the aid of high speed photography. They studied the air flow and related the vortex shedding in the flow to the untwisting of the yarn. They also analysed the effect of needle setting with a Taslan Type 9 nozzle and a modified Type 9 nozzle. Their postulation of the texturing mechanism were based on the untwisting and retwisting of the overfed filaments, as follows:

"The most significant observation has been the rotational nature of the turbulent air-stream. This gives rise to a false-twisting action such as would untwist the yarn temporarily during its passage through the jet and thereby causing an opening of the multifilament structure for the overfeed to take effect. The filaments are first convoluted
into U-shaped waves, which in turn, snarl into looped coils owing to the twist-liveliness of the slackened filaments."
(Ref. 29, page 36)

This hypothesis presupposed that a vortex-shedding action was occurring in the venturi to cause the observed rotations of the textured yarn.

In 1970, Sen\textsuperscript{34}, working under Wray's supervision, analysed the texturing mechanism by using a scaled-up model of the Taslan Type 9 nozzle and showed that the yarn structure inside the nozzle was open and the texturing was seen to occur at the nozzle exit. He also claimed that the periodic shedding of the vorticities in the wake of the yarn feed needle, as postulated by Wray and Entwistle\textsuperscript{29}, could not exist at the highly turbulent flow with high Reynolds numbers which he verified by measurements. He concluded that the previously suggested false-untwisting vortex mechanism is invalid, although the overall principle of texturing by a temporary removal and reassertion of the twist was still applicable. An alternative hypothesis of loop formation based on false untwisting was suggested as follows:

"The highly turbulent air flow blows the overfed parent yarn out of the jet, and this causes the portion of the 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 the 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."
(Ref. 34, page 146)

Like Wray, Sen used high-speed photography. However he was also able to show, for the first time, that shock waves occurred in the
flow just outside the nozzle; this was observed by Schlieren photography\textsuperscript{34} and the photographs have only recently been published more widely\textsuperscript{35-36}.

Their various analyses of the air-jet texturing process led Sen and Wray\textsuperscript{31} to develop an apparatus for manufacturing yarns of the air-jet bulked type without the use of air. They claimed that the properties of these yarns were generally comparable with those of air-jet yarns and that these were related to common features in their physical structures\textsuperscript{33} but, like the known air-textured yarns at that time, pre-twisted supply yarns were used.

In 1975, Sivakumar\textsuperscript{37} interpreted Sen's findings in a slightly different way and he extended the research into the use of a nozzle based on the principles of Taslan Type 10 nozzle. He verified the existence of shock waves in the flow by theoretical means and concluded that these played a very important role in loop formation by forming a "pressure barrier" and retarding the filaments at their place of occurrence. He based his hypothesis of texturing mechanism on the effect of shock waves on the filaments and stated that:

"When a highly pre-twisted yarn is overfed into the jet, it comes under the influence of the air flow in the jet and travels along with it. When it reaches the place where the shock waves occur, it comes under the influence of the "pressure barrier" which suddenly retards the yarn. This reduces the tension in the yarn suddenly and the filaments in the yarn tend to snarl and form loops over the snarled length. This along with the turbulence of air causes the yarn to texturise." (Ref. 37, page 32)

All of these hypotheses were based on the assumption that the supply yarns were pre-twisted. Therefore, without reference to any other aspect of the process, these hypotheses do not apply to current processing technology where no pre-twist is involved.

Some attempts have been made to improve the understanding of the events that occur during texturing of no-twist yarns by today's texturing nozzles. Bock and Lüenschlose\textsuperscript{38-40} analysed the mechanism
of texturing by using a Taslan Type 14 nozzle. Their research confirmed the findings of Sen\textsuperscript{34} and Sivakumar\textsuperscript{37} by verifying the occurrence of the shock waves in the free jet from this nozzle by using Schlieren photography. They also gave evidence of asymmetry in the flow, which they verified by pressure measurements, as expected from the asymmetric design of the nozzle. By using high-speed photography, they showed that the filaments were opened on emergence from the nozzle. Like Wray\textsuperscript{29} and Sen\textsuperscript{34} they showed that the velocity gradients, and the turbulence within the stream helped the texturing by altering the forces acting on individual filaments which in turn caused longitudinal displacement of the filaments relative to each other. However they argued that there is a force within the stream which causes the filaments to change their directions, and stated: "otherwise bending of the filaments would not have been possible". They concluded that this bending force was due to a "pressure barrier" caused by the shock waves. They summarise the loop formation mechanism as follows:

"The filament yarn is opened in the nozzle by turbulence and/or gradients of the flow velocity, and places itself in a stream of high kinetic energy below the nozzle axis. With a right-angled draw-off after the nozzle, an interlacing point forms above the axis, at the interface between two zones of different flow states. The filaments blown through below this interlacing point pass through a zone of high air turbulence, and are decelerated by the subsequent drop of the dynamic pressure. When the filaments interlace, loops projecting from the yarn are formed by the differently sized filament bends."
(Ref. 39, page 375)

The Bock and Lüenschloss hypothesis of loop formation was also based on the "retardation" or "deceleration" of the filaments by the variations in the pressure as a result of the shock waves, as Sivakumar\textsuperscript{37} claimed in 1975. The validity of texturing mechanisms attributed to the presence of shock waves is discussed in Chapter 4 as a consequence of high-speed photography and flow visualisation experiments.
2.4 Miscellaneous Other Works

Although they did not analyse the mechanism of the loop formation, other workers such as Kollu, Artunc, Piller, Hes and Piller, Bock and Lüenschloss, Rozmarinowska and Godek, and Datye and Bose, all investigated either various aspects of the textured yarn properties or the effect of various parameters on the properties of the textured yarns.

Wilson gives a useful review of the process together with a list of references and patents published up to 1977. There are also many minor publications relating to the end-uses, economic factors, and future potential of air-jet textured yarns, as well as other patents, but they are too numerous to mention here.
FIGURE 2.1: The HemaJet, an industrial texturing nozzle, showing the standard nozzle core (1), integrated wetting unit (2), and impact element (3).
FIGURE 2.2: Schematic illustration of the air-jet texturing process as used in the current research
FIGURE 2.3: An early texturing nozzle (Czechoslovakia)

FIGURE 2.4: An early du Pont texturing nozzle (USA)
FIGURE 2.5: The du Pont (USA) Taslan texturing nozzles
FIGURE 2.6: The Mirlan texturing nozzle (Czechoslovakia)
FIGURE 2.7: The HemaJet texturing nozzle (Switzerland)
Designs of the texturing nozzles vary in detail but remain similar in underlying principles because of the common need to create a supersonic, turbulent, asymmetric, and non-uniform air flow. The known texturing nozzles, according to their construction, can be categorised in two main groups as follows:

i) Converging-diverging (de Laval) type nozzles, i.e., a converging-diverging nozzle is attached to the yarn exit end of the nozzle assembly; e.g. du Pont's Taslan Type 14 nozzle (see Fig. 2.5d);

ii) Cylindrical nozzles, i.e., one or more air inlets opening with an angle to a cylindrical straight uniform main flow duct of the nozzle; e.g. Heberlein's HemaJet (see Fig. 2.7).

3.1 A Model for Converging-diverging Nozzles

Properties of the flow in this group of nozzles are determined by the converging-diverging shaped nozzle attachment at the yarn exit end, providing that the air passages and gaps are larger than the throat area. At typical texturing pressures, the air flow is 'choked' at the throat of the nozzle, since the critical condition of unity Mach number is reached. It then continues to accelerate in the diverging part making the flow supersonic. Properties of the flow are determined by the well established theory of compressible flow in a converging-diverging nozzle and these can be calculated for a frictionless nozzle by applying the principal equations for the steady one dimensional isentropic flow as described in standard texts such as Zucrow and Hoffman, and Shapiro.
3.2 A Model for Cylindrical Nozzles

The flow in this group of nozzles is more complex. The main flow duct is a straight, uniform, and cylindrical where several, usually convergent air inlet bores enter radially at an angle. Flows from these inlet bores are intermixed at their meeting point in the main flow duct and are divided into two axially opposing flows namely (see Fig. 2.7):

i) Primary flow, in the direction of the yarn exit; and
ii) Secondary flow, in the direction of the yarn inlet.

This division into primary and secondary flows is determined by the geometry of the nozzle. The total mass flow rate through the cylindrical texturing nozzles is usually determined by the throat areas of the air inlet bores, because the flow is choked when conventional texturing pressures are used.

No readily available mathematical model can be adopted to these types of nozzles and therefore the development of a new model will be attempted. In order to simplify the calculations the following assumptions are necessary:

i) flow is steady, one-dimensional, and isentropic throughout the nozzle (as is assumed in the case of the converging-diverging nozzle);
ii) there are no frictional losses;
iii) the summation of the air inlet bore throat areas is smaller than the cross-sectional area of the main duct;
iv) the flow from air inlet bores meet at one single point on the centre line of the main duct;
v) the static pressures at the exits of both the primary and secondary flows are atmospheric;
vi) the velocity profiles of the primary and secondary flows are uniform; and
vii) the air is assumed to be free of any water or other particles.

Since the structure of the cylindrical nozzles and hence the flow in these nozzles is highly complicated, the laws of fluid dynamics governing compressible flows cannot be directly applied to them. Therefore, for mathematical treatment, it is convenient to divide the nozzle into three smaller sections or control volumes as shown in Fig. 3.1, and accordingly apply the principles of gas dynamics and thermodynamics to each of these. The properties of the outgoing flow from one control volume are fed into the succeeding control volume as the properties of incoming flows, and hence the final properties of the primary and secondary flows at the exit planes can be calculated.

3.2.1 Control volume 1

Since the air inlet bores are usually in the form of converging nozzles (Fig. 3.3), the theory of steady one-dimensional isentropic flow of a perfect gas in converging nozzles, as described by Zucrow and Hoffman, can be applied to control volume 1. The operating pressures, required for texturing in practice, are usually well above the critical pressure to cause choking of the flow in these inlet bores. Therefore, the flow properties at the throat are the critical properties; the mass flow and the velocity are the maxima attainable. These are:

\[
(V'_t)_{\max} = a^* = a_0 \left[ \frac{2}{\gamma + 1} \right]^{1/2} \tag{3.1}
\]

and

\[
\dot{m}^* = \lambda_c \rho^* (V'_c)_{\max} = \left( \Psi^* p_0 \lambda_c \right) / a_0 \tag{3.2}
\]

where:

\[
\Psi^* = \left[ \frac{2}{\gamma - 1} \right]^{(\gamma + 1)/(\gamma - 1)} \tag{3.3}
\]
and

\[ a_0 = \left( \gamma R T_0 \right)^{1/2} \tag{3.4} \]

The critical pressure, temperature, and density are each determined by the following equations (after Shapiro\textsuperscript{51}):

\[ p'_c = p^* \left[ \frac{2}{\gamma+1} \right] \frac{\gamma}{\gamma-1} p_0 \tag{3.5} \]

\[ T'_c = T^* \left[ \frac{2}{\gamma+1} \right] T_0 \tag{3.6} \]

and

\[ \rho'_c = \rho^* \left[ \frac{2}{\gamma+1} \right]^{\gamma/(\gamma-1)} \rho_0 \tag{3.7} \]

These flow properties at the throat of the inlet nozzles (control volume 1) are then fed into the control volume 2 as the input properties of the entering jet stream.

3.2.2 Control volume 2

In control volume 2 (see Fig. 3.1), jet streams from several incoming nozzles (in the case of two or more inlet bores) collide and intermix and are diverted into the two opposing primary and secondary flows, along the line of the texturing nozzle axis; this diversion is determined by the physical boundaries of the texturing nozzle. Therefore the momentum in the y and z directions after collision and mixing is zero for the symmetrically arranged air inlets with respect to the nozzle axis. In the case of asymmetric arrangement of inlet bores the momentum in the y and z directions create a force to act on the nozzle, although the momentum in the x direction is determined by the same principles which are applicable to the symmetric nozzles. Therefore the number of air inlet bores and their asymmetry does not
affect the momentum in the x direction and the same principles apply regardless of the number of the inlet bores involved.

The flow properties in the core of a free jet from a nozzle do not change at distances up to about 6 diameters away from the nozzle exit\textsuperscript{52}. Therefore it is reasonable to assume that flow velocity, pressure, density, and temperature at the throat in control volume 1, are unchanged on entering control volume 2.

One of the conditions for development of the mathematical model, as stated earlier, is that the total throat area of the inlet bores is smaller than the cross-sectional area of the main duct, meaning that the the cross-sectional areas of the primary and secondary flows after collision and mixing in control volume 2 are also smaller than the main duct cross-sectional area and these will spontaneously expand to the wider boundary of the main duct of the texturing nozzle (see Fig. 3.1). Since the effect of this expansion is taken into account in control volume 3, it can be assumed that no expansion takes place within control volume 2 and that the properties of the outgoing flows are unaffected after collision and mixing of the jets from the inlet bores. This is the case for incompressible collision and mixing of jets, and the theory for this, as described by Gurevich\textsuperscript{53}, can be adopted to control volume 3. Therefore thickness (areas) of the primary and secondary flows and the mass flow rates can be calculated by adopting this theory of collision of two jets to any number of jets meeting at the same point on the axis of the texturing nozzle.

Continuity states that the total mass flow of the incoming jets is equal to the total mass flow of the primary and secondary air flows. Thus:

\[
\sum_{i=1}^{n} (\rho A V)_i = (\rho A V)_p + (\rho A V)_s
\]

(3.8)
Since the density and velocity of the incoming and outgoing flows are assumed to be same, the continuity equation simplifies to:

\[ \sum_{i=1}^{n} A_i = A_p + A_s \]  \hspace{1cm} (3.9)

Conservation of momentum in the x direction leads to:

\[ \sum_{i=1}^{n} (\rho A v^2 \cos \alpha)_i - (\rho A v^2)_p - (\rho A v^2)_s = 0 \]  \hspace{1cm} (3.10)

Equation 3.10 can similarly be simplified to

\[ \sum_{i=1}^{n} A_i \cos \alpha_i - A_p + A_s = 0 \]  \hspace{1cm} (3.11)

where:
- \( p \) and \( s \) denote primary and secondary flows respectively;
- \( n \) is the total number of jets;
- \( A_i \) is the throat area of the \( i \)th incoming jet;
- \( \alpha_i \) is the angle that this incoming jet makes with the x axis;

and

\( A_p \) and \( A_s \) are the areas of the primary and secondary jets on leaving control volume 2 respectively.

Rearranging these two equations for the case where all the incoming jets make the same angle with the x axis:

\[ A_p = \frac{1}{2} \sum_{i=1}^{n} A_i \left( 1 + \cos \alpha \right) \]  \hspace{1cm} (3.12)
and

\[ \lambda_s = \frac{1}{2} \sum_{i=1}^{n} \lambda_i (1 - \cos \alpha) \]  

(3.13)

Hence, the mass flow rates for the primary and secondary flows can be calculated by using continuity as follows:

\[ \dot{m}_p = (\rho AV)_p \]  

(3.14)

\[ \dot{m}_s = (\rho AV)_s \]  

(3.15)

where:

\[ \rho_p = \rho_s = \rho_t \quad \text{and} \quad v_p = v_s = (v_t)_{\max} \]

The collision and mixing theory of incompressible jets gives an approximate solution to the problem of division of incoming compressible jets to primary and secondary flows. Since the static pressure in the secondary flow drops to atmospheric, the velocity profile is uniform, and the flow is very steady, the flow velocity and the mass flow rate can be measured with considerable accuracy (see Section 4.3.3). This can be substituted into the mathematical model in control volume 2; hence a more precise division of the total mass flow into the primary and secondary flows is obtainable. Consequently improved predictions of the primary flow properties can be obtained by using this empirical correction.

3.2.3 Control volume 3

The expansion of the outgoing flows from control volume 2 to the nozzle boundary (see Fig. 3.1) can be treated as a sudden expansion of a flow across an abrupt enlargement as shown in Fig. 3.2, as discussed by Benedict et al. This is treated in control volume 3, where \( \Lambda_p \) and \( \Lambda_s \) are being enlarged to \( \Lambda_n \), where \( \Lambda_n \) is the cross-sectional area of the main duct. For such abrupt enlargements the static pressure ratio is given by:
where:

\[ \eta = \frac{\lambda_1}{\lambda_2} \]

It was assumed that the static pressure at the exit of both the primary and secondary flows are atmospheric and therefore \( M_2 \) can be calculated by using equation 3.16. Once \( M_2 \) is calculated the other properties of the flow can also be calculated by using the theory of a steady one-dimensional flow of a perfect gas. Thus

\[ v_2 = M_2 a_2 = M_2 \left( \gamma R T_2 \right)^{1/2} \]

(3.17)

\[ T_2 = \left[ \frac{2+\gamma-1}{2+\gamma-1} \frac{M_1^2}{M_2^2} \right] T_1 \]

(3.18)

and

\[ \rho_2 = \left( \frac{P_2}{P_1} \right) \left( \frac{T_1}{T_2} \right) \rho_1 \]

(3.19)

### 3.3 Mathematical Model Predictions and Experimental Velocities

The mathematical model developed in Section 3.2 was applied to experimental nozzles whose details are given in Fig. 3.3. These nozzles were designed such that they satisfy the conditions stated in Section 3.2. The triple air inlet nozzle resembles the HemaJet (Fig. 3.3) with slight simplifications as follows: all inlet jets meet at one point on the centre line (compared with the staggered positions in the HemaJet); the angle of the air inlet bores is 45° (compared with 48° in the HemaJet). Unlike the HemaJet, the yarn exit end of the nozzle is not trumpet-shaped in order to comply with the mathematical model which assumes a straight uniform main flow duct. Other particulars and dimensions of the nozzle are the same as the
geometrically 4-times scaled-up version of the standard HemaJet as detailed in Section 4.1. Both double and single air inlet bore nozzles were designed to give the same air flow rate as the triple air inlet bore nozzle, so that the properties of the primary flow at the exit plane as created by any of these nozzles are identical. Therefore the predictions of the mathematical model for any one of these cylindrical nozzles are also valid for the other two.

A computer program, based on the mathematical model, was written to compute the properties of the primary and secondary flows, as detailed in Appendix B. Experiments were undertaken to measure the axial velocities of the primary flow at the exit plane in order to verify the validity of the mathematical model.

For the velocity measurements, constant temperature heated element anemometers were first considered with miniature hot wire and hot film probes but these had to be abandoned due to the reasons explained in Section 4.3. A simpler system, namely a pitot tube was used to measure the stagnation pressure, and corresponding velocities were calculated by the technique described in Appendix C.

The results of the flow velocity measurements at the exit plane of the single, double, and triple air inlet experimental nozzles are shown in Tables 3.1a, 3.1b, and 3.1c respectively for 6 equispaced radial directions as denoted in Fig. 4.3. The velocity profiles are seen to be reasonably uniform, particularly for the triple inlet nozzle as illustrated in Fig. 3.4, thereby justifying the assumptions made in developing the mathematical model. Therefore the centre line flow velocities of the triple inlet nozzle could represent the axial velocities and these are compared in Fig. 3.5 with the velocities predicted by the mathematical model for varying pressures. Also compared are the results of introducing empirical corrections into the calculations as discussed in Section 3.2.2.

Empirical calculations show that the secondary mass flow rate varies between 22% and 26% of the total air flow rate for the
Pressure range of $4 \times 10^5$ to $7 \times 10^5$ N m$^{-2}$ (abs), as shown in Table 3.2, whereas the incompressible mixing theory gives a constant flow rate of 16.5% at any pressure. Introducing empirical values improves the mathematical model and this modified model gives a better agreement with the experimental results.

Centre line velocity with respect to distance from the exit plane, for the triple inlet cylindrical nozzle, is shown in Fig. 3.6. This figure shows that velocity decreases gradually with distance at lower pressures, while it shows a periodic rise and fall at high pressures, (e.g. $6 \times 10^5$ N m$^{-2}$), indicating the shock waves that are likely to occur at such pressures (see also Sections 4.5 and 4.9). These fluctuations gradually disappear as the flow expands to the ambient atmospheric pressure.

### 3.4 Discussion

Some assumptions have been made in developing the mathematical model as detailed in Sections 3.2. The most crucial of these was the incompressible flow approach adopted for a compressible flow in control volume 2, due to the lack of published information regarding the collision and mixing of compressible jet flows in the supercritical range. The effects of this assumption is more pronounced at higher pressures, due to the increasing compressibility of the air at such pressures. Improvements to this approach were made by introducing an empirical parameter.

Manufacturing faults are inevitable in making such precise scaled-up nozzles and these are likely to effect the experimental results slightly. In spite of these limitations, the developed mathematical model provides reasonably close predictions of the flow properties at the exit plane of the cylindrical texturing nozzles, and this model can be used as an aid for further nozzle developments.
Further experimentation with converging-diverging type nozzles was considered unnecessary on the account of the extensive published work\textsuperscript{38-40} and well established theory\textsuperscript{50,51}.
**TABLE 3.1**

Axial velocities at $6 \times 10^5$ N m$^{-2}$ (abs) at the exit planes of single, double, and triple inlet nozzles for 6 equispaced radial directions as denoted in Fig. 4.3.

<table>
<thead>
<tr>
<th>Radial distance (mm)</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(a) Single inlet nozzle:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (CL)</td>
<td>390</td>
<td>390</td>
<td>390</td>
<td>390</td>
<td>390</td>
<td>390</td>
</tr>
<tr>
<td>1</td>
<td>382</td>
<td>389</td>
<td>392</td>
<td>388</td>
<td>391</td>
<td>389</td>
</tr>
<tr>
<td>2</td>
<td>382</td>
<td>392</td>
<td>397</td>
<td>397</td>
<td>391</td>
<td>388</td>
</tr>
<tr>
<td>3</td>
<td>385</td>
<td>398</td>
<td>405</td>
<td>402</td>
<td>389</td>
<td>384</td>
</tr>
<tr>
<td>4</td>
<td>366</td>
<td>359</td>
<td>365</td>
<td>342</td>
<td>348</td>
<td>337</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>(b) Double inlet nozzle:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (CL)</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>(c) Triple inlet nozzle:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (CL)</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>
### TABLE 3.2

Secondary flow velocity and the mass flow rate.

<table>
<thead>
<tr>
<th>Pressure ($10^5$ N m$^{-2}$)</th>
<th>Secondary flow vel. (m s$^{-1}$)</th>
<th>Secondary mass flow rate ($\dot{m}_s$) (kg hr$^{-1}$)</th>
<th>Total mass flow rate ($\dot{m}_t$) (kg hr$^{-1}$)</th>
<th>Ratio of $\dot{m}_s/\dot{m}_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>215</td>
<td>46.5</td>
<td>182.6</td>
<td>0.26</td>
</tr>
<tr>
<td>6</td>
<td>187</td>
<td>40.5</td>
<td>156.5</td>
<td>0.26</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>32.5</td>
<td>130.5</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>104</td>
<td>22.4</td>
<td>104.4</td>
<td>0.22</td>
</tr>
</tbody>
</table>
FIGURE 3.1: Control volumes in cylindrical nozzles as used in mathematical modelling

- $d$ = nozzle diameter
- $d_t$ = throat diameter
- $d_{n1}$ = primary flow diameter after collision
- $P_0$ = stagnation pressure
- $P_a$ = ambient pressure
- $V_t$ = velocity at the throat of control volume 1
- $V_p$ = primary flow velocity at the nozzle exit
- $V_s$ = secondary flow velocity at the nozzle exit
\( d_n \) = nozzle diameter

\( d_p \) = primary flow diameter after collision

\( d_s \) = secondary flow diameter after collision

\[
\frac{P_1}{P_2} = 1 \left( \frac{M_1}{\varphi M_2} \right)^{-1} \left[ \frac{2 + (\gamma - 1) M_2^2}{2 + (\gamma - 1) M_1^2} \right]^{1/2}
\]

where: \( \varphi = \frac{A_1}{A_2} \)

FIGURE 3.2: Flow through an abrupt enlargement
(a) Cylindrical nozzles having single, double, and triple inlets

(b) Standard HemaJet with triple inlets

FIGURE 3.3: Single, double, and triple inlet cylindrical nozzles compared with the scaled-up model of the standard HemaJet: (a) cylindrical nozzles; and (b) scaled-up model of the HemaJet
FIGURE 3.4: Axial velocity distribution of the triple inlet nozzle at the exit plane
FIGURE 3.5: Comparison of the mathematical model predictions with the experimental centre-line velocities at the exit plane.
FIGURE 3.6: Centre line velocity variations of the flow from the triple inlet cylindrical nozzle with distance from the exit plane.
CHAPTER 4

EXPERIMENTAL INVESTIGATION OF THE AIR FLOW

The experimental nozzle referred to in Section 3.3 which was tested to comply with the predictions of the mathematical model for cylindrical nozzles, has some constitutional differences with respect to the standard HemaJet as typically used in industry. The HemaJet has longitudinally staggered air inlets introducing some asymmetry and swirl into the flow and has a trumpet-shaped diverging exit section; these differences are likely to exhibit slightly different flow properties when compared with those in the cylindrical nozzle model.

A dynamically similar scaled-up model of the standard HemaJet was used in these experiments because its minute size made the use of measuring probes for velocity measurements and drilling pressure tappings for static pressure measurements impracticable.

The flow properties, particularly the flow velocity at the exit region of the HemaJet nozzle, were analysed by experimental means in order to gain a better understanding of the flow in these nozzles. These experimental results were compared with the predictions of the mathematical model and with the experimental results from the cylindrical nozzles. The effects of a diverging trumpet-shaped exit were investigated; static pressure distributions inside the nozzle were measured and the measurement of turbulence was attempted.

Experiments were limited to a maximum pressure of $7 \times 10^5$ N m$^{-2}$ (abs), this being the highest pressure of the air supply available for the scaled-up model, but the results provided sufficient information to predict the flow properties at higher working pressures.
Shadowgraph and interferometer techniques were used to visualise the flow from the actual size nozzle at pressures used in practice to show the shock waves and the effects of the filaments on them.

Investigations of the air flow in the converging-diverging type Taslan nozzles were curtailed in order to avoid repeating the extensive research undertaken by Bock and Lühenschloss.48-40

4.1 Scaling-up the Nozzle

The main duct of the actual size standard HemaJet is about 25 mm long and its diameter is 2 mm. The throat diameters of all three inlet bores are 0.9 mm. These inlet bores are radially equispaced, slightly staggered longitudinally, situated nearer to the yarn exit end rather than to the feed end, and make an angle of approximately 48° to the axis of the main duct. The exit part of the nozzle is divergent with trumpet-shaped curved walls.

The information obtained from the experiments with a model should be representative of that provided by the original system (prototype). From the dynamical analysis standpoint, correct modelling is achieved if the conditions in the model are such that they are dynamically similar. Dynamic similarity exists when the model and the prototype each have the same length-scale ratio (geometric similarity), time-scale ratio (kinematic similarity), and force-scale or mass-scale ratio (dynamic similarity). Geometric similarity is the first requirement. Then dynamic similarity exists, simultaneously with kinematic similarity, if the model and prototype forces are in a constant ratio.

In the air-jet texturing process, the only predominant force acting on the filaments is the drag force. Drag force in general is a function of Reynolds number (Re), and Mach number (M). Therefore any dynamic similarity will result from the similarity of friction
force (resistance) and the force stemming from the compressibility of the fluid (elasticity), characterised by

\[ (\rho v L/\mu)_p = Re_p = Re_m = (\rho v L/\mu)_m \]  

(4.1)

and

\[ (v/a)_p = M_p = M_m = (v/a)_m \]  

(4.2)

where the suffices p and m denote prototype and model respectively. The Mach number becomes of paramount importance in high speed compressible flows, as in the texturing nozzles, where density variations from pressure become significant. In such cases the equalities of both Reynolds numbers and Mach numbers for the prototype and the model are not possible and only the equality of Mach numbers \((M_p = M_m)\) needs to be considered for dynamically similar modelling of this high speed compressible flow from texturing nozzles.

Since air at room temperature is the working fluid for both the prototype and the model, acoustic speeds \([a = (\gamma R T)^{1/2}]\) for both systems must be the same for the same operating pressures at room temperature, i.e., \(a_p = a_m\) and, hence \(V_p = V_m\). Therefore a geometrically similar model is also dynamically similar to the prototype when they operate at the same pressure. Hence the velocities at corresponding points in both the prototype and the model are caused to be equal, i.e., the time-scale ratio is unity. For a chosen length-scale ratio the force-scale (mass-scale) ratio is equal to the square of the length scale ratio.

A length-scaling factor of 4 was chosen as a compromise between the need to keep the compressed air consumption rate below the level that can be delivered by the installed compressor, and the desire for a reasonably large model in order to reduce the interference effects of the measuring probes.
This work has been mainly confined to the Heberlein standard core HemaJet, which is a typical example of an industrially used cylindrical type texturing nozzle with slight differences in construction as explained in Section 3.3. The scaled-up model of the HemaJet nozzle is shown in Fig. 4.1a while Fig. 4.1b shows the same nozzle installed in the experimental rig equipped for velocity and pressure measurements. Since the common characteristics of all types of texturing nozzles is to create a supersonic, turbulent, asymmetric, and non-uniform flow, the outcome of the investigations can, therefore, be generalised to any type of texturing nozzle.

4.2 Experimental Rig for the Flow Measurements

The experimental rig as shown schematically in Fig. 4.2 was designed and built to facilitate velocity, turbulence, static and total pressure measurements, and hot wire probe calibrations. The rig makes use of existing departmental compressed air supply(1) and an air receiver(2) incorporating an on-off valve(3). The rig itself consists of a prefilter(4), a fine filter(5) which is capable to filter out particles larger than 0.01 \( \mu \)m, a pressure regulator(6), an orifice meter(7) for the flow rate measurements, and a pressure gauge(8). The experimental scaled-up model(9) was mounted onto an old lathe bed, and a specially designed manipulator was used for precise positioning of the measuring probes (see Fig. 4.1b). A differential manometer was used with the orifice meter. A multi-tube mercury manometer for the static pressure measurements and an especially made six foot long U-tube mercury manometer were also used with the scaled-up model for the stagnation pressure measurements. Stagnation temperatures were measured by means of thermocouples and associated microprocessor temperature measuring apparatus.

4.3 Axial Velocity Measurements

The fluid forces (drag forces), acting on the filaments are a function of the local air velocity; therefore the distribution of the
flow velocity at the exit region plays an important role on the forces acting on the individual filaments.

For the velocity measurements constant temperature heated element anemometers (CTA) were first considered with miniature hot wire probes but this had to be abandoned due to the regular breakage of the wire element after several measurements at very high flow velocities. More robust and less sensitive hot film probes also suffered from the same problem.

A simpler system was used instead of the CTA system for the mean axial velocity measurements. Stagnation pressure was measured by a pitot tube and static pressure was assumed to be atmospheric at the exit plane, and hence corresponding axial velocities were calculated by the technique described in Appendix C.

4.3.1 Axial velocity distribution

Velocities at three different planes in the exit region, i.e., at planes 1, 2, and 3, were each measured at 6 equispaced radial directions at a working pressure of $6 \times 10^5$ N m$^{-2}$ (abs). For this exit region, the velocity distributions show a slight axial asymmetry in the flow, as shown in Table 4.1. However the degree of asymmetry, although it is shown to be higher towards the nozzle (Section 4.7), is sufficiently low outside the nozzle to assume that the velocity distributions in any radial direction for any plane would represent the characteristics of the velocity distribution at that plane. Therefore, measurements in only one radial direction were sufficient for further investigations of velocity distribution.

Fig. 4.4 illustrates the axial velocity distributions at various planes situated various distances away from the nozzle exit at $7 \times 10^5$ N m$^{-2}$ (abs). It is seen that substantial variations occur in the velocity distributions at planes near the nozzle exit; these have central depressions and the maximum velocity occurs approximately at
(3/4)r radial distance from the centre line, i.e., nearer to the nozzle walls.

Since the fluid force acting on the scattered filaments is a function of the square of the local velocity which depends on the position of the individual filaments within the nozzle, substantial variations occur on the drag force acting on these filaments, due to these non-uniform velocity profile. Therefore it would be expected that the scattered overfed individual filaments, each with an excess length free to be blown out by the air flow, will travel at instantaneously different speeds that are caused by the considerable variations of the air velocity, and will be displaced longitudinally relative to each other.

The effects of working air pressure on the variations of the velocity distribution at the exit plane are shown in Fig. 4.5. The nonuniformity of the distribution, i.e., the central depression, becomes greater at higher pressures, and therefore, variation of the forces acting on the dispersed filaments across any one plane will be greater than the corresponding force variations at lower pressures. These greater force variations result in greater longitudinal displacements of the filaments.

The boundaries of the free air-jet, as shown in Fig. 4.6, agrees with the linear relation between the linear distance, L, and corresponding diameter of the jet, D, as discussed by Schlichting.56

4.3.2 Effects of the trumpet-shaped diverging exit

In Section 4.3.1, it was shown that the velocity distribution of the flow from the HemaJet is of a non-uniform profile, whereas the velocity profile of the flow from the experimental cylindrical nozzle with a straight uniform main flow duct is uniform (see Fig. 3.4). The basic constructional differences between these two nozzles are that the HemaJet has a trumpet-shaped diverging exit and
longitudinally staggered air inlet bores. To analyse the causes of the nonuniform velocity distribution, the exit part of the triple inlet cylindrical experimental nozzle was modified to make it trumpet-shaped, similar to that of the HemaJet (Fig. 3.3). Experiments with this nozzle showed that exit velocity distribution is nonuniform, with a central depression (Fig. 4.7), similar to that of the HemaJet. Since the air inlet bores in the experimental nozzle are not staggered, it therefore can be concluded that this nonuniformity is caused by the trumpet-shaped diverging exit.

Consequently, it can be argued that nonuniformity in the axial air velocity distribution can be created or enhanced by modifying the exit of the cylindrical nozzles to a trumpet-shaped diverging exit. This may increase the differences in the magnitude of the forces acting on the filaments dispersed in the nozzle, which in turn enhances the longitudinal displacements of them relative to each other.

The staggered positions of the air inlet bores induce a swirl to the flow. This swirl can be observed by the twist inserted in a bundle of stationary filaments placed in the nozzle. Swirl induced by the staggered position of the air inlet bores in HemaJet could also contribute to the movement of the filaments to displace their positions, but it appears that this is not an essential requirement of the texturing process (Chapter 10).

4.3.3 Secondary flow velocities

As can be seen in Section 4.7, static pressure in the secondary flow drops to atmospheric very rapidly. Therefore the assumption of atmospheric pressure for the secondary flow at its exit plane is justified. By using the measured total pressures and atmospheric static pressure the secondary flow velocities can be calculated, with a high degree of accuracy, in the same way as the primary flow.
velocities (Appendix C). Therefore these empirical results can be used in the mathematical model to improve the predictions of the primary flow velocities.

The secondary flow velocities show no variation across the width of the jet at its exit plane, i.e., its velocity profile is uniform for both the HemaJet and the experimental nozzles. Fig. 4.8 shows the secondary flow velocities for varying working pressures, and compares these with those predicted by the mathematical model. Since the mathematical model assumes smaller mass flow rate for the secondary flow than it actually delivers (see Section 3.3), the agreement between measured and predicted velocities is not very successful.

4.4 The HemaJet Compared with the Mathematical Model

The mathematical model used to predict the flow properties of cylindrical nozzles assumes a uniform velocity profile. Since the axial velocity profile of the flow from the HemaJet was shown to be of a non-uniform distribution, a comparison of these with the predicted exit velocities is not possible. Therefore, the measured non-uniform velocity profile is transformed into a uniform profile (Fig. 4.9) by using the integral equation for the conservation of momentum. Since the total momentum per unit time should be same for all cross-sections normal to the jet, the total momentum at the exit plane is firstly calculated and this is then transformed into a uniformly distributed momentum flux corresponding to the cross-sectional area of the nozzle, as follows:

Total momentum flux, \( J \), at the exit plane for a free jet with a non-uniform velocity distribution is:

\[
J = \int u \, dm = \rho \int_0^{\infty} u^2 \, dA = \text{constant} \quad (4.3)
\]
where

\( U \) is the flow velocity at a given point;
\( \rho \) is the corresponding fluid density; and
\( dA \) is the corresponding differential flow area.

Total momentum flux, \( J_0 \), for a uniform velocity profile is:

\[
J_0 = \rho_0 U_0^2 A_0
\]  

(4.4)

Since

\[
J/J_0 = 1 \text{ for equal momentum flux, then:}
\]

\[
U_0 = \left[ \int_0^\infty u^2 \, dA / \rho_0 A_0 \right]^{1/2}
\]  

(4.5)

where:

\( U_0 \) is the transformed uniform flow velocity;
\( A_0 \) is the corresponding flow cross-sectional area.

The static pressure of a free jet is equal to the ambient pressure. Therefore the densities \( \rho_0 \) and \( \rho \) of the uniformly distributed flow and the flow from the HemaJet respectively, at the exit planes, correspond to atmospheric pressure. Hence, the transformed uniform velocity, \( U_0 \), for flows from the HemaJet can be calculated by numerically integrating the equation 4.5.

The transformed uniform velocities corresponding to the measured axial velocities are in reasonable agreement with those predicted by the mathematical model developed for cylindrical nozzles (Fig. 4.10). It was not possible to measure axial air velocities for supply pressures higher than \( 7 \times 10^5 \) N m\(^{-2}\) (abs); however these can be estimated by using the experimental results obtained at lower pressures. Consequently, it can be argued that this mathematical model also provides means of predicting the average properties of the flow from a modified cylindrical nozzle (e.g. HemaJet) and it can be
used as an aid to further nozzle design and development.

4.5 Centre-line Velocity Variations by Distance

The variations of the centre-line velocity by distance from the exit plane of the HemaJet are shown in Fig. 4.11 for various pressures. The periodic rises and falls in the flow velocity from a cylindrical nozzle at higher pressures (see Section 3.3), an indication of shock waves, are not evident in the flow from the HemaJet. What is observed is a gradual drop of the centre-line velocity after a slight initial rise, the maximum occurring at different distances to the nozzle exit for different pressures. This rise, which is more pronounced at higher pressures, may be due to very weak shock waves that are likely to occur in the flow.

The periodic rises and falls in the centre-line velocity are observable in flow from a Taslan Type 14 nozzle, as shown in Fig. 4.12, which were not evident with the HemaJet at similar pressures. This is because of the the stronger shock waves obtainable with converging-diverging nozzles (see Section 4.9). Consequently, it can be argued that relatively weaker shock waves occur in cylindrical type HemaJet when compared with the converging-diverging type Taslan nozzles.

4.6 Turbulence Measurements

Wray and Entwistle\textsuperscript{30}, in their explanation of the mechanism of texturing, referred to turbulence in the flow in Taslan Type 9 nozzle, which was later experimentally verified by Sen\textsuperscript{34}. Bock and Lüenschloss\textsuperscript{38-40}, although they did not give experimental evidence of the turbulence, referred to its role in the texturing process with a Taslan Type 14 nozzle.
In such high velocities provided by cylindrical nozzles, intense turbulence is expected. An attempt was made to measure it, but because of the difficulties encountered in employing hot wire anemometry (see Section 4.3), no satisfactory results were obtained. However these preliminary trials indicated a typical turbulence level in the region of 25-30%. Observations of the filament behaviour, as detailed in Chapter 5, also showed that intense turbulence occurs in such supersonic flows from a texturing nozzle. During texturing this turbulence will contribute to the movement of the filaments across the nozzle which will in turn cause further disturbances in the flow and hence increase the intensity of the turbulence. Therefore it is believed that the turbulence and movements of the filaments could mutually contribute to each other's activity.

4.7 Static Pressure Measurements

Because of the restricted accessibility, and the blocking effect of any velocity probe when used inside the nozzle, it was not practicable to measure the velocities inside the nozzle, but a series of pressure tappings, as shown in Fig. 4.13, enabled the static pressures to be measured. These pressures were measured at various distance planes along the nozzle axis and with up to 12 pressure tappings at each plane and these are shown in Figs. 4.14 and 4.15.

These results indicate that the static pressure distribution inside the nozzle is asymmetric in the region of the air inlet bores as expected from the staggered positions of these inlets. The distribution of the static pressures along the nozzle opposite to the air inlet bores shows that (Fig. 4.15) the distribution becomes more uniform and symmetric towards the nozzle exit region. Only a slight asymmetry remains in the flow outside the nozzle as was shown in Section 4.3.1.

Although the static pressure drops towards the exit it remains dependent on the upstream stagnation pressure and it is above
atmospheric for working pressures greater than $4 \times 10^5 \text{ N m}^{-2} \text{ (abs)}$ as shown in Fig. 4.15. By contrast, for the secondary flow it drops to atmospheric rapidly regardless of the upstream working pressure.

Supersonic flows from texturing nozzles, with static pressures above atmospheric nearer to the exit plane, obtainable at the practical working pressure range, suddenly expand to the ambient atmospheric pressure and cause expansion waves as discussed in Section 4.9.

### 4.8 Interactions between the Filaments and the Air Flow

Attempts to measure the air velocity while the filaments were in the nozzle failed because of their interference with the measuring probes. Attempts were also made to measure the static pressures when the filaments were in the nozzle, but these also failed. Steady static pressures of an undisturbed flow became very unsteady when the filaments were present in the flow. This could be due to the instantaneous blockages of the pressure tappings by the filaments, or to the disturbances caused by the filaments into the air flow.

It is shown in Section 7.2 that the homogeneously suspended particles mixed in an air flow reduce the air velocity. In an air-jet texturing nozzle, the filaments are continuously present in the nozzle in a dispersed form. They, analogous to the particles, act so as to reduce the air velocity, because the momentum required to blow out the filaments is transferred from the air flow alone.

As discussed by Wallis, in a gas flow containing homogeneously suspended particles, if strong shock waves occur in the flow, the gas is suddenly decelerated across the shock to a lower velocity, while the particles enter this zone at their upstream velocities (Fig. 4.16).
Continuous filaments dispersed in the air flow may behave in a manner similar to the particles in an air flow, and their velocities may not be affected by the shock waves. In addition, since the larger portions of the filaments are still inside the nozzle and are under the effects of the higher velocities of the upstream flow, they may continue to travel at a speed induced by this flow. Therefore even if strong shock waves occur in the flow during texturing, it is very unlikely that these will serve to decelerate the filaments.

4.9 Visualisations of the Free and Disturbed Flows

Static pressure measurements at plane 1, closest to the exit plane, as denoted in Fig. 4.13, indicated that the static pressures were above atmospheric at high working pressures. This means that the flow does not expand completely inside the nozzle and that this expansion occurs outside the nozzle in the form of successive expansion waves, where the pressure drops to ambient. Compression waves would be present when the exit pressure is lower than the ambient pressure, this rising above the ambient after the shock wave and then repeating itself outside the nozzle in the form of expansion waves through successive falls and rises of pressures until it completely expands into the ambient pressure.

4.9.1 Free air flow

Previous attempts by Sen\textsuperscript{34} using a scaled-up model of a Taslan Type 9 nozzle in Perspex failed to investigate the flow inside the nozzle because of the poor optical quality of the plastic material, particularly when used with such circular cross-sections. However he was able to obtain information regarding the pattern of the free flow outside the nozzle by Schlieren photography\textsuperscript{35,36}. Later, Sivakumar\textsuperscript{37} theoretically verified the existence of shock waves in a free flow from Taslan Type 9 and 10 nozzles at normal operating pressures.
Bock and Lüenschloss\textsuperscript{38-40} showed the shock waves in a free flow from a Taslan Type 14 nozzle also by using Schlieren photography.

A Michelson interferometer (Ealing Optics) as well as a laser shadowgraph system, as illustrated in Fig. 4.17, were used by the author to investigate the nature of the free flow in the actual HemaJet nozzle rather than a scaled-up model. Fig. 4.18 is the interferogram of the shock waves that occur in a high speed compressible flow from the HemaJet texturing nozzle. These shock waves diminish at low pressures. The pattern of the shock waves is affected by placing an impact element in the air stream as shown in Fig. 4.19 for the HemaJet and its associated spherical impact element. The possible effects of the impact elements on the properties of the yarns textured are examined in Chapter 9.

### 4.9.2 Disturbed air flow

The most recently postulated mechanisms of loop formation have been based on shock waves\textsuperscript{38-40}. The experiments on which these claims were based, were apparently all conducted with an undisturbed free flow, i.e., without filaments being present in the nozzle. To investigate whether these were valid, shadowgraphs showing the shock waves in the flow were obtained while the filaments were in the nozzle thus simulating actual texturing conditions.

Figs. 4.20a and 4.21a show shadowgraphs for a free (undisturbed) flow from the HemaJet and Taslan Type 14 nozzle respectively. Figs. 4.20b and c are shadowgraphs obtained from the HemaJet at the same working pressures, but with filaments present in the nozzle, as observed from two different viewing angles. The dark areas are the shadows of the emerging filaments. Figs. 4.21b and c show similar shadowgraphs for the Taslan Type 14 nozzle.

These shadowgraphs provide evidence to show that shock waves are destroyed in the flows disturbed by the filaments, whilst they can
exist in the undisturbed flows. Therefore any mechanism of loop formation based on such shock waves and retardation or deceleration of the filaments due to pressure barriers caused by these shock waves are very unlikely to be valid.

In addition, it is clear from Figs. 4.20a and 4.21a that the shock waves from a HemaJet are not as strong as those from a Taslan nozzle. If shock waves are effective in loop formation, this ought to reduce their effects on the filaments and on the entire process of texturing; nevertheless the HemaJet is at least as effective in texturing as Taslan nozzle and this throws doubt on the assumption that shock waves play a significant role in effective texturing.

4.10 Conclusions

Axial velocity measurements at the exit of the cylindrical type HemaJet nozzles showed that the flow is supersonic, turbulent, slightly asymmetric, and of a non-uniform distribution. Similar results were obtained recently by other researchers38-40, with converging-diverging type Taslan nozzles, thus confirming these characteristics to be fundamental to effective texturing.

Velocity and the degree of non-uniformity in the velocity distribution increase with the increasing pressure. Since the forces acting on the filaments are determined by the local flow velocity, the variation in the local velocity is an essential requirement of the texturing process, because this causes longitudinal displacements of the filaments relative to each other. High turbulence, as expected from the supersonic flow and from the complex design of the nozzle, also contributes to the movements of the filaments in the nozzle so as to interchange their dispositions within its cross-section.

Static pressures show that the flow in the nozzle near the air inlet bores is very complex, contributing to the asymmetry and non-uniformity of the primary flow. Although the secondary flow pressure
drops to atmospheric, the primary flow pressure, especially at higher working pressures (approx. above $5 \times 10^5 \text{ N m}^{-2}$ [abs]), stays above atmospheric at the exit of the nozzle, which causes expansion waves. Shock waves from a Taslan nozzle are much stronger than those from a HemaJet, even though the HemaJet is a very effective industrial texturing nozzle. These shock waves in free, undisturbed flows are destroyed by the filaments in the actual texturing process. This leads to the conclusion that the shock waves do not play any significant role in the texturing process.
### TABLE 4.1

Axial velocity distributions at $6 \times 10^5 \text{ N m}^{-2}$ at planes 1, 2, and 3 for equispaced radial directions (as denoted in Fig. 4.3) which show slight asymmetry.

<table>
<thead>
<tr>
<th>Radial distance (mm)</th>
<th>Axial velocity ($\text{m s}^{-1}$) at radial directions:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1</td>
</tr>
<tr>
<td>(a) at plane 1:</td>
<td></td>
</tr>
<tr>
<td>0 (CL)</td>
<td>308</td>
</tr>
<tr>
<td>1</td>
<td>320</td>
</tr>
<tr>
<td>2</td>
<td>349</td>
</tr>
<tr>
<td>3</td>
<td>363</td>
</tr>
<tr>
<td>4</td>
<td>331</td>
</tr>
<tr>
<td>5</td>
<td>176</td>
</tr>
<tr>
<td>(b) at plane 2 (exit plane):</td>
<td></td>
</tr>
<tr>
<td>0 (CL)</td>
<td>338</td>
</tr>
<tr>
<td>1</td>
<td>345</td>
</tr>
<tr>
<td>2</td>
<td>363</td>
</tr>
<tr>
<td>3</td>
<td>370</td>
</tr>
<tr>
<td>4</td>
<td>324</td>
</tr>
<tr>
<td>5</td>
<td>187</td>
</tr>
<tr>
<td>6</td>
<td>47</td>
</tr>
<tr>
<td>(c) at plane 3:</td>
<td></td>
</tr>
<tr>
<td>0 (CL)</td>
<td>351</td>
</tr>
<tr>
<td>1</td>
<td>353</td>
</tr>
<tr>
<td>2</td>
<td>358</td>
</tr>
<tr>
<td>3</td>
<td>343</td>
</tr>
<tr>
<td>4</td>
<td>288</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>109</td>
</tr>
<tr>
<td>7</td>
<td>47</td>
</tr>
</tbody>
</table>
FIGURE 4.1a: Scaled-up model of the standard core HemaJet
FIGURE 4.1b: Scaled-up model of the HemaJet nozzle as used in the experiments
FIGURE 4.2: Graphical representation of the experimental rig for the flow measurements
FIGURE 4.3: Vertical planes (1 to 6) to the nozzle axis and radial directions (R1 to R6) at which the axial velocities were measured.
FIGURE 4.4: Axial velocity distributions from the HemaJet at $7 \times 10^5 \text{ Nm}^{-2}$ (abs) at various planes
FIGURE 4.5: Axial velocity distribution from the HemaJet at the exit plane at various working pressures

at working pressures of
(a) $4 \times 10^5 \text{ N m}^{-2} \text{ (abs)}$
(b) $5 \times 10^5 \text{ N m}^{-2}$
(c) $6 \times 10^5 \text{ N m}^{-2}$
(d) $7 \times 10^5 \text{ N m}^{-2}$
FIGURE 4.6: Boundaries of the free air-jet from the HemaJet texturing nozzle
FIGURE 4.7: Velocity distribution at the exit plane of the modified triple inlet cylindrical type nozzle.
FIGURE 4.8: Secondary flow velocities compared with the theoretical predictions
FIGURE 4.9: Transformation of the non-uniform velocity profile to a uniform profile by using the principle of conservation of momentum.

FIGURE 4.10: Comparison of the transformed velocities with the theoretical predictions.
FIGURE 4.11: Centre-line velocity variations with distance from the HemaJet nozzle exit plane

FIGURE 4.12: Centre-line velocity variations with distance from the Taslan Type 14 nozzle exit plane
FIGURE 4.13: Scaled-up model of the HemaJet showing the positions of the pressure tappings
FIGURE 4.14: Static pressures at planes 2, 3 and 4 as denoted in Figure 4.13 (continued)
Plane 4

FIGURE 4.14
FIGURE 4.15: Static pressure distribution along the nozzle opposite to the air inlets
FIGURE 4.16: Effects of shock waves on the gas and particle velocities in a gas-particles mixture flow (after Wallis, Ref. 59)
FIGURE 4.17: Laser shadowgraph rig as used in the flow visualisations
FIGURE 4.18: Interferograms of the shock waves at 10, 8 and 6 x 10^5 N m^{-2} (abs)
FIGURE 4.19: Interferograms of the shock waves as affected by a spherical impact element
FIGURE 4.20: Shadowgraphs of free and disturbed flows from a standard core HemaJet, at $10 \times 10^5$ N m$^{-2}$ (abs)
FIGURE 4.21: Shadowgraphs of free and disturbed flows from a Taslan 14 nozzle, at $9 \times 10^5$ N m$^{-2}$ (abs)
In Chapter 4, the characteristics of the air flow in a currently used industrial texturing nozzle, namely the HemaJet, were investigated experimentally, largely by using a scaled-up model. In this chapter, the filament motion induced by the air flow is analysed in order to gain a better understanding of the texturing phenomenon itself. High-speed still and cine photography techniques and filament speed and tension measurements were involved in these analyses.

The experiments were performed with a standard HemaJet texturing nozzle as used on the single-head research texturing machine. A single end polyester filament yarn with the specifications shown in Table 5.1 was used in these investigations.

5.1 High-Speed Photography

The behaviour of the filaments in the HemaJet texturing nozzle, under various texturing conditions, was studied from high-speed still photography, taken with 400 ns exposure time, and cine photographs taken at 20 000 fps (frames per second).

5.1.1 Still photography

Fig. 5.1a shows a high-speed still photograph of a yarn being textured under wet conditions. This illustrates that the loops are being formed as the filaments emerge from the nozzle and that these occupy the lower half of the nozzle outlet (see also Fig. 5.4). This also indicates that the tension in the textured yarn, as a result of shortening the overall length of the yarn due to the effective loop
formation, is sufficiently high to pull the yarn close to the nozzle exit in a straightened form.

When the loop formation is not so effective, e.g. as in dry conditions, the overfed lengths of the filaments are not completely taken up by loops formed and the tension in the yarn becomes so low that the textured yarn slackens and is convoluted as shown in Fig. 5.1b. Occasionally the whole bundle of filaments is blown straight away from the nozzle as a consequence of very low tension in the yarn, this being caused by very poor loop formation as shown in Fig. 5.1c where the filament separation is seen to be poor. The filament bundle emerges at about the centre line of the nozzle in a parallel and compact form where the velocity profile of the air flow is reasonably uniform. Therefore the forces acting on the individual filaments are approximately equal and hence each filament emerges from the nozzle at about the same speed causing scarcely any longitudinal displacement relative to each other; this hardly leads to any loop formation.

5.1.2 Cine photography

All the above observations were amply confirmed by the high-speed cine photography but these results are naturally difficult to produce in a printed paper. They provided even better evidence that the dry texturing process becomes very unstable; straight compactly arranged filaments being frequently blown out from the nozzle, whereas wet texturing usually displayed stable process conditions. Fig. 5.2 shows prints from such high-speed cine films showing (a) stable process conditions where the yarn is tensioned and kept close to the nozzle exit by effective texturing; and (b) unstable process conditions where the yarn is blown out from the nozzle due to less effective texturing.
5.1.3 The emerging filaments

In order to give more insight to the loop formation mechanism, 100 still photographs of each dry and wet texturing process were taken and individually analysed. As shown in Fig. 5.3, the point most remote from the nozzle exit plane at which loops were instantaneously being formed, was measured by the horizontal coordinate, x, from this plane and by the vertical coordinate, y, from the nozzle axis. The vertical distance, d, from the nozzle axis to the uppermost filament in the emerging bundle, for a downward take-up, was also measured.

The results, summarised in Figs. 5.4a and 5.4b, show that the filaments occupy the lower half of the nozzle exit area in every case when wet textured and in most cases when dry textured. They also show that the filaments are pulled further down and closer to the nozzle exit in wet texturing conditions than in dry texturing. Shortening the overall length of the textured yarn is more effective in wet texturing, due to better loop formation achieved, consequently causing a rise in the yarn tension, and in turn pulling the emerging, loop-forming filaments down and against the nozzle, for a downward yarn delivery.

Similar research was carried out by Bock and Lünenschloss⁴⁰, but they defined "interlacing" or "integrating" points by usually referring to still photographs of the filaments being blown well away from the nozzle exit, similar to that shown in Fig. 5.1c. As stated above such conditions represent very poor loop formation and therefore it is misleading to explain an effective loop formation mechanism by referring to such photographs.

5.1.4 Free filament flow

Bock and Lünenschloss⁴⁰ have also claimed that: "There must be a force within the stream that make the filaments change their
direction" (Ref. 40, page 3). According to their hypothesis of loop formation, filaments are caused to make a right angle turn by these forces claimed to be existing in the air stream, which are due to the "pressure barriers" caused by the shock waves. They claim "otherwise bending of the filaments would have not been possible". However, as it was shown in Section 4.7, such shock waves were destroyed in a flow disturbed by the filaments.

Fig. 5.5 shows three of the many high-speed photographs showing the emerging filaments which were fed to the nozzle direct from a supply yarn package and left to travel in the direction induced by the air flow only. In none of these high-speed still photographs were any right angle turns observed as a result of a force existing in the air stream or of any other force. On the contrary, filaments were continuously blown out of the nozzle by the air flow, without any diversion from their natural path along the nozzle axis.

Therefore it can be concluded that, loop formation mechanisms based on the existence of shock waves or of forces in the flow caused by pressure variations which make the filaments to turn at right angles to the nozzle exit are unlikely to be valid.

5.1.5 Filament separation

Fig. 5.5a shows that the filaments are separated and scattered across the nozzle, whereas in Fig. 5.5b they are shown as closely packed as a result of poor filament separation. These cases correspond to effective and poor texturing respectively. Fig. 5.5c shows that the filaments are separated as they emerge from the nozzle whereas their preceding segments are closely packed. This illustrates that the opening and scattering of the filaments across the nozzle occur intermittently.

As seen in Fig. 5.4, fluctuations in the motion of the filaments might tend to form bows and arcs as they are blown out of the nozzle.
and these may appear to form loops. Since the upstream velocity of the air flow, (see Fig. 4.11) is higher than its downstream velocity, and this velocity gradually drops with distance, the part of a filament in the upstream flow travels faster than its counterpart in the downstream flow. This will force the filaments to form bows and arcs along its length in the flow. In addition, there also occur variations in the speed of the filaments due to the turbulence, and to the non-uniform velocity profile of the flow which causes it to induce instantaneously, different magnitudes of driving forces to act on the individual filaments that are changing their locations across the nozzle continuously.

Examination of the filaments after being blown away from the nozzle showed that no loops were formed and the intermittent filament separation was observed in the form of randomly scattered balloons along the filaments which disappears under a slight tension. Therefore these provide further evidence for the intermittent occurrence of the filament separation which causes intermittent loop formation.

It can be concluded that loop formation occurs intermittently when the filaments are separated and a better separation of the filaments is essential for effective texturing.

5.2 Average Filament Speed

Since the filaments are overfed into the nozzle, some excess lengths of filaments are free to travel at a speed induced by the supersonic, turbulent and non-uniform air flow (see Chapter 4). Therefore the speeds of the filaments during texturing are similar to those of free filaments in an air stream; these would approach the air velocities when the frictional losses are small. Non-uniform velocity distribution of the air flow, turbulence, swirl imparted to the filaments, friction between the filaments themselves and friction between the filaments and the contacting surfaces, will cause
variations and fluctuations in the individual filament speeds across the nozzle and these in turn will cause longitudinal displacements of the filaments relative to each other as evidenced by Wray\textsuperscript{27}.

It was not practical to measure the speeds of the individual filaments, but the average speed of the filament bundle was estimated by allowing it to travel freely in the air stream by feeding it into the nozzle direct from a supply yarn package without making contacts with any yarn guides, thereby reducing friction to a minimum. The emergent filaments are collected for a timed period, weighed and the average filament speed calculated.

Unfortunately the friction, due to the ballooning and fast unwinding speeds from the supply package, was difficult to overcome and the speeds measured by this method will be much lower than the normal filament speeds under actual texturing conditions where no such unwinding frictional problems are encountered. Fig. 5.6 shows how the average filament speed varies with the air pressure. It will be noted that, in spite of the frictional losses during unwinding, these values are very much higher than typical yarn texturing speeds of 500 m min$^{-1}$. Had there been no frictional losses it is estimated that the actual filament speeds would be approximately an order of magnitude of 10 times the typical yarn texturing speeds or higher, where the ratio of air velocity to the typical yarn speed is about 40.

5.3 Tension in the Yarn During Texturing

An examination of the structure of the textured yarns shows that they consist of randomly distributed sections with loops interspersed with sections of virtually straight parallel filaments with very few loops if at all. The sections with loops occur more frequently in a yarn textured under wet conditions (effective texturing) than those textured under dry conditions (poor texturing). This suggests that loop formation is an instantaneous process which occurs
intermittently, as discussed in previous sections, and thence causes the yarn tension to increase as the loops are formed. Therefore such fluctuations in the yarn tension in the texturing zone could provide evidence regarding the frequency of loop formation.

The average value of the tension in the yarn is another useful property which could provide information regarding the effectiveness of the texturing and the stability of the loops produced. Since the tension in the yarn between the nozzle and the delivery rollers is a result of loop formation itself, it gives a measure of the effectiveness of the texturing. Also, because less stable loops are removed under applied loads, while more stable loops offer a resistance which gives rise to increased tension in the yarn, an indication of the stability of the loops formed during the process can be obtained by measuring the tension in the stabilising zone.

The magnitude of the tension varies according to the stabilising ratio applied to the yarn and therefore comparative results can be obtained for different process conditions by keeping the stabilising ratio constant at a pre-set value. This tension could be related to the eventual yarn instability.

5.3.1 Tension fluctuations

The frequency response of the only available yarn tensiometer (Rothschild R-1092) was limited to 300 Hz which was insufficient to respond to the high frequency of tension fluctuations during texturing. Therefore such fluctuations had to be assessed from the detailed analysis of the high-speed cine films taken at 20 000 fps.

Tension in the textured yarn is expected to vary inversely with the maximum distance between the blown out filaments and the nozzle exit plane, and therefore variations in this distance should reflect fluctuations in tension. This distance, x, as shown in Fig. 5.3, was measured for 100 consecutive frames of high-speed
cine films using an image analyser and Figs. 5.7a and 5.7b show these fluctuations for dry and wet texturing respectively. The other processing parameters were: air pressure $9 \times 10^5 \text{ N m}^{-2} \text{ (abs.)}$; texturing speed $450 \text{ m min}^{-1}$; and overfeed ratio $20\%$. 100 frames of the high-speed film, correspond to a duration of $(1/200) \text{ s}$ of the process which corresponds to $37.5 \text{ mm}$ of the textured yarn.

Fig. 5.7a and 5.7b shows that the frequency of fluctuations of the wet texturing is much higher than that of the dry process with relatively small amplitudes. The maximum average horizontal distance $x$ (see Fig. 5.3) for the wet texturing (1.43 mm) is smaller than that of dry texturing (2.18 mm), thus confirming the observations made in Section 5.1.3 from the high-speed still photographs (see Fig. 5.4).

5.3.2 Average tension

The average tension in the yarns, both in delivery and stabilising zones, were measured by the Rothchild Tensiometer and these are shown in Figs. 5.8-5.10 for varying texturing speed, air pressure, and overfeed ratio respectively. A general observation is that both the effectiveness of the loop formation process, as measured by the average tension in the delivery zone, and the stability of loops, as indicated by the average tension in the stabilising zone, are much higher for wet texturing than for dry texturing conditions, thus confirming the observations obtained by the high-speed cine and still photography techniques.

Fig. 5.8a shows that the yarn tension in the delivery zone reduces with increasing texturing speed, indicating a slight drop in the effectiveness of texturing. At the higher speeds, the decreased tension causes the filaments to be blown well away from the nozzle thereby resulting in unstable texturing and the eventual breakdown of the process. For dry texturing this occurs at comparatively lower production speeds, texturing being impossible at $600 \text{ m min}^{-1}$ although
it was possible for wet texturing. However, Fig. 5.8b shows that the stability of the loops are significantly affected by the texturing speed, and it becomes lower with increasing speeds, as indicated by lower tension in the yarn in the stabilising zone. It can be concluded that, although the effectiveness of texturing is reduced slightly by increasing the texturing speed, loops formed at high speeds are not stable and can be pulled flat under tension applied in the stabilising zone.

Fig. 5.9a shows that the yarn tension in the delivery zone increases with increasing air pressure. This is because the higher the working pressure the higher the air velocity becomes, and consequently filaments travel at higher speeds thereby resulting in more effective texturing. Also due to increased variations in the velocity distributions, longitudinal displacements of the filaments relative to each other are enhanced; this in turn causes effective entanglement and more frequent loop formation leading to increased stability of the loops, as indicated by tension in the stabilising zone (Fig. 5.9b).

Fig. 5.10a shows that the tension reduces with increasing overfeed ratio, indicating a loss in the effectiveness of texturing. This is because of the excessive lengths of the filaments which cause larger loops and a slacker yarn core to be formed, which in turn reduces the yarn stability (Fig. 5.10b). At high overfeed ratios, the process becomes unstable and eventually breaks down, reaching this unsatisfactory stage at comparatively lower ratios for dry texturing.

Fig. 5.10b also shows that the stability of the loops is significantly high at low overfeed ratios and this reduces rapidly for increasing ratios. Although the indicated stability is high at low overfeed ratios, the process fails to produce acceptable textured yarns; the number of loops formed are fewer as was shown by Wray28 because of insufficient excess length of filaments to form such loops. Such yarns produced at low overfeed ratios when tested by
static stability (or instability) tests also show high stability (see Chapter 9). Therefore loop stability tests would give misleading results, giving high stability for the yarns produced at low overfeed ratios, which are not textured effectively.

5.4 Conclusions

From the analysis of high-speed still and cine photographs, together with measurements of filament speeds and yarn tension, it can be concluded that:

i) loop formation occurs at the exit region of the nozzle filaments being open and separated on emergence for effective texturing conditions;

ii) individual emerging filaments may instantaneously travel at a much faster speed than the yarn texturing speed, approximately of the order of 10 times or more;

iii) when left free to travel in the air stream, filaments do not make a right-angled turn on their own due either to pressure variations or to the forces caused by the presence of shock waves;

iv) the tension created in the yarn because of shortening of its length as a result of effective loop formation keeps the filaments closer to the nozzle exit, prevents them being blown away from the nozzle, and pulls and keeps the filaments closer to the nozzle in the take-up direction to make them turn at right angles to the nozzle axis;

v) fluctuations in the tension occur at very high frequencies during texturing indicating the intermittent and instantaneous formation of the loops;
vi) average yarn tensions in the texturing zone (between the nozzle and the delivery roller W2) and in the stabilising zone provide information regarding the effectiveness of texturing and the stability of the loops formed respectively; the effects of varying the production speed, overfeed ratio, and air pressure on these can be monitored to some extent by measuring these tensions;

vii) effectiveness of texturing and the stability of the loops decrease with increasing production speed and overfeed ratio, and increase with increasing air pressure;

viii) stability of the loops, whether measured continuously during texturing or as a static test on the yarns produced, cannot alone provide a direct measure of the yarn quality. Other yarn characteristics such as loop frequency, loop size, linear density and physical bulk, should also be taken into account in order to gain a better assessment of the yarn quality.
TABLE 5.1

Properties of supply yarn which was used in the investigations.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of yarn</td>
<td>Flat polyester</td>
</tr>
<tr>
<td>Source of yarn</td>
<td>ICI fibres Ltd.</td>
</tr>
<tr>
<td>Linear density</td>
<td>175 dtex</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>66</td>
</tr>
<tr>
<td>Breaking load</td>
<td>670 g (683.4 cN)</td>
</tr>
<tr>
<td>Tenacity</td>
<td>3.83 g/dtex (3.91 cN/dtex)</td>
</tr>
<tr>
<td>Breaking elongation</td>
<td>28 %</td>
</tr>
</tbody>
</table>
FIGURE 5.1: High-speed still photographs of the emerging filaments during texturing taken at 400 ns.
FIGURE 5.2: Prints from high-speed cine films showing filaments in (a) stable texturing conditions, and (b) unstable texturing conditions
FIGURE 5.3: Schematic representation of the flow and the separated swirling filaments, showing the distances x, y and d as defined in Section 5.1.3.
FIGURE 5.4: Results of the analyses of 100 high-speed still photographs each for both (a) dry, and (b) wet texturing. x, y, and d are as described in Section 5.1.3, (see also Fig.5.3)
FIGURE 5.5: High-speed still photographs showing the free filament flow from a standard core HemaJet
FIGURE 5.6: Average filament speed in the air flow for varying air pressure
FIGURE 5.7 Variation of distance x as denoted in Fig. 5.3, which indicates tension variations in the delivery zone for 100 consecutive frames.
FIGURE 5.8: Tension variations in the delivery and stabilising zones with the texturing speed
Tension variations in the delivery and stabilising zones with the air pressure

FIGURE 5.9: Tension variations in the delivery and stabilising zones with the air pressure
FIGURE 5.10: Tension variations in the delivery and stabilising zones with the overfeed ratio
CHAPTER 6

FLUID FORCES AND EFFECTS OF FILAMENT CROSS-SECTION

In the air-jet texturing process the forces acting on the filaments are the primary flow forces, \( F_p \), the secondary flow forces, \( F_s \), and the frictional forces, \( F_f \), as shown in Fig. 6.1. Fluid forces due to the primary and secondary air flows in a texturing nozzle, as well as the frictional forces, all affect the resultant force acting on the filaments. In particular frictional forces play an important role in the texturing process (see Chapter 7). In the following analysis of the fluid forces, only primary flow effects will be considered, noting that the approach also applies to the secondary flow.

6.1 Fluid Forces Acting on the Filaments

In order to analyse the fluid forces acting on the filaments, a single fibre in an air flow is considered as shown in Fig. 6.2. This fibre is assumed to be rigid, its motion is two-dimensional i.e., parallel to the xy plane. The resultant forces and moments on the fibre are caused by the relative velocity between the fibre and the surrounding air flow. Velocity components of its centre of mass, \( G \), are \( u_G \) and \( v_G \), and \( V_n \) and \( V_t \) are the relative normal and tangential velocity components respectively at a point on the fibre, where \( u \) and \( v \) are the velocity components of the air flow at the point on the fibre, and \( r \) is the distance from point \( G \) to the point on the fibre. Hence, with reference to Fig. 6.2, \( V_n \) and \( V_t \) can be calculated as follows:

\[
V_n = (u - u_G)\sin\phi + (v - v_G)\cos\phi + r\phi
\]  

\[6.1\]

and

\[
V_t = (u - u_G)\cos\phi - (v - v_G)\sin\phi
\]  

\[6.2\]
Note that $V_n$ and $V_t$ vary from point to point along the fibre because of the spatial variation of $u$ and $v$, and because of $r$.

Fluid forces acting on the filaments can be expressed in terms of the pressure and friction drag forces. The pressure drag $D_p$ is caused by the pressure difference between the two sides of the filament in a cross flow ($V_n$). The drag on an element can be expressed in terms of drag coefficient for a length $dl$ as:

$$dD_p = C_p \rho d_f V_n^2 \, dl/2$$ \hspace{1cm} (6.3)

or integrating:

$$D_p = (1/2) \rho d_f \int_{-L/2}^{L/2} C_p V_n^2 \, dl$$ \hspace{1cm} (6.4)

where:

- $C_p$ is the drag coefficient for pressure drag;
- $\rho$ is the fluid density;
- $d_f$ is fibre diameter; and
- $L$ is the length of the fibre exposed to the flow.

As can be seen from Equation 6.4, the pressure drag is a function of the projected area of the fibre, $A_p = d_f L$.

The friction drag, $D_f$ is caused by the frictional forces between the fibre and tangential air flow ($V_t$), which can be formulated as for the pressure drag, and:

$$D_f = (1/2) \rho d_f \int_{-L/2}^{L/2} C_f V_t^2 \, dl$$ \hspace{1cm} (6.5)

where:

- $C_f$ is the drag coefficient for the friction drag.

Friction drag, as expressed in Equation 6.5, is a function of the fibre surface area, $A_s = \pi d_f L$. 

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Hence, the fluid forces in the x and y directions are

\[ D_x = D_p \sin \phi + D_f \cos \phi \]  
\[ D_y = D_p \cos \phi + D_f \sin \phi \]  

As equations 6.6 and 6.7 indicate, the fluid forces in the x and y directions are functions of the normal and tangential components of the flow velocity, \( v_n \) and \( v_f \), the angle of attack, \( \phi \), of the airflow, and the projected and surface areas \( A_p \) and \( A_s \) of the fibre within the flow.

The resultant force acting on a filament in an air-jet texturing nozzle is determined by the fluid forces acting on the segment of the filament within the nozzle and by the frictional forces due to contacts it makes with the nozzle internal surfaces, \( f_1 \), with the yarns guides, \( f_2 \), and with the wetting unit, \( f_3 \), (see Fig. 6.1).

Since the primary flow is stronger than the secondary flow because of the greater momentum transferred to it from the incoming jets due to the geometry of their inlet bores, the resultant fluid force acting on the filaments is in the direction of the primary flow, i.e., \( F_p > F_s \). Therefore the resultant force acting on a filament is:

\[ F_r = F_p - F_s - F \]  

Effects of friction on the air-jet texturing process are discussed in Chapter 7, and in this chapter factors affecting the fluid forces are analysed.

6.2 Factors Effecting Fluid Forces

The drag force acting on a filament in a given flow conditions is a function of the local air velocity, and of the filament surface
and the projected areas. The air velocity is mainly determined by the air supply pressure, whereas the velocity gradient is determined by the design of the nozzle as discussed in Chapter 4. The surface and projected areas are determined by the diameter (for a circular filament), length of the filament exposed to the air flow, and by the position of the filament across the nozzle.

6.2.1 Filament position

The surface area of a filament is determined by the length of the filament exposed to the flow, and the projected area depends on where the filament is in the nozzle at any instant. Although the surface area of a filament subject to the flow in the nozzle does not vary significantly with its position, its projected area does vary considerably. A filament within the upper part of the nozzle has a greater projected area than a filament within the lower part (Fig. 6.3), and therefore is subject to higher fluid forces. Thus the position of the filament in the nozzle has a significant effect on the fluid forces acting on the filaments.

Therefore, it can be argued that forces acting on the filaments vary considerably with the varying position of them in the nozzle owing to the variations in the local flow velocity and to the varying projected areas subject to pressure drag. Consequently these varying fluid forces acting on the filaments at different positions in the nozzle at any instant cause them to travel at different speeds and hence to be displaced longitudinally relative to each other.

6.2.2 Filament diameter

Filaments with larger diameters will cause the drag forces to rise due to the increase in the projected and the surface areas of the filaments, i.e., \( F_r \) is proportional to \( d_f \). On the other hand, the mass of the filament ( \( m_f \) ) which the fluid forces have to
transport, will increase as a function of the filament cross-sectional area. Therefore the inertial resistance of the filaments to the fluid forces i.e., the momentum required to move these filaments \( \frac{\dot{m}_f}{\rho_f} = \frac{(\pi/4) \rho_f d_f^2 v_f^2}{A} \) is a function of the filament cross-sectional area i.e., proportional to \( d_f^2 \). Therefore an increase in filament diameter causes the fluid forces to increase as a function of filament diameter, and the force required to move this filament will increase as a function of the square of the filament diameter. Consequently an increase in the filament diameter will cause it to be blown out at a relatively slower speed and hence the capability of the nozzle to texture the filaments under given conditions will be reduced. Therefore, it can be concluded that supply yarns which are composed of finer filaments texture into better yarns than the coarser filament yarns.

6.3 Effects of the Filament Cross-section

Area-dependent mechanical properties of the filaments vary with the shape of the cross-sectional areas. This would have an effect on the forces required to deform the filaments when they make a right angle turn as they emerge from the nozzle. The fluid forces acting on the filaments would also vary due to the varying surface and the projected areas caused by different cross-sectional shapes. These may have an effect on the loop formation process.

In order to analyse the effect of the shape of the filament cross-section on the loop formation, filaments with various cross-sectional shape but with the same cross-sectional area (i.e., same linear density) are considered. Hence regardless of the cross-sectional shape of the filaments under consideration, the momentum required to move the filaments remains the same.

The analysis is confined to the comparison of the circular filaments, the most commonly used type, with the elliptic and hollow circular cross-section filaments. The number of examples of cross-
sections can be increased but these three types of filaments are sufficient to demonstrate the effects of filament cross-sections. Some area properties of these cross-sections are given in Table 6.1.

6.3.1 Effects on the drag forces

The total drag force acting on the filaments, as shown in Section 6.1, is dependent on the surface and projected areas of the filaments in the flow. Therefore varying shapes of the filament cross-sections will affect the drag force.

Since an elliptic filament bends about its major diameter under a bending moment its projected area is \( [n^{1/2}] \) times, and its surface area is \( [(n^2 + 1)/2n]^{1/2} \) times larger than those of a circular cross-section of equal area, where "n" is the ratio of the major to minor diameters of an ellipse, i.e., \( n > 1 \) (see Table 6.2). Therefore the drag force acting on an elliptic filament will be larger than that acting on a circular filament of equal fineness. The higher the ratio of major to minor diameter the greater becomes the drag forces. A similar argument is valid for a hollow cross-section (Table 6.2).

Consequently it can be argued that, from the viewpoint of drag forces, elliptic and hollow circular filaments are better suited for the air-jet texturing process than filaments with a solid circular cross-section.

6.3.2 Effects on the mechanical properties

During the texturing process, the filaments emerging from the nozzle make a right angled turn relative to the nozzle exit. Fig. 6.4 shows a model which represents a single filament emerging from the nozzle during the air-jet texturing process which assumes a circular arc outside the nozzle while it makes the right angled turn. The leading end (A) of the filament is instantaneously fixed in the
textured yarn while the fluid forces are assumed to be acting at the trailing end (B) to cause the filament to be blown out of the nozzle. This filament may also be subject to a twisting action, as was observed during the process, due to the swirling effect of the flow, and therefore it is subject to a bending moment and a torque. These will cause instantaneous vertical and horizontal deflection of point B as well as a torsional deflection of the filament.

Basic differential equation that governs the elastic deflection of any beam subject to a bending moment (M) is

\[ \frac{d^2 y}{dx^2} = \frac{M}{EI} \]  

where:
- \( E \) is the modulus of elasticity; and
- \( I \) is the area moment of inertia.

Torsional deflection, i.e., angle of twist (\( \Theta \)) subject to a torque (T) is

\[ \Theta = \frac{TL}{GJ} \]  

where:
- \( L \) is the length of the beam;
- \( G \) is the modulus of elasticity in shear; and
- \( J \) is the polar moment of inertia of area.

Hence bending and torsional deflections are inversely proportional to the area moment of inertia, and polar moment of inertia respectively. The smaller the second moment of areas the smaller becomes the force and torque required to bend and twist the filament.

Table 6.2 shows that both the area moment of inertia and the polar moment of inertia of an ellipse about its major diameter are smaller than those of a circle of equal cross-sectional area. Therefore it may be concluded that a smaller force and torque are
required to deflect a filament which has an elliptic cross-section, and the higher the ratio of the major to minor diameter \( n = a/b \), the smaller becomes the required force and torque to deflect the filament.

In addition to bending and torsion, this filament may also be subject to buckling. Since the critical buckling load is proportional to the smaller principal area moment of inertia of a cross-section, buckling of an elliptic filament occurs about its major axis. Therefore the critical buckling load for an elliptical cross-section is smaller than that for a circular cross-section.

Table 6.2 also shows that the area moment of inertia and the polar moment of inertia of a hollow circular fibre are larger than those for a solid circular fibre of equal fineness. This concludes that larger forces and torques are required to deflect the hollow fibre, than are required for the solid circular fibre.

6.4 Discussion and Conclusions

The model considered in Section 6.4.2 assumes that the filaments make a circular arc and the fluid forces are concentrated at the trailing end of the filament which is usually not the case and the real situation is more complex. Filaments while they make right-angled turn may assume a different shape rather than a circular arc which effects the bending and torsional behaviour of the filaments as well as the fluid forces acting on them. Nevertheless, all the filaments make an eventual right-angled turn with respect to the nozzle axis and they are subject to fluid forces that make them bend, twist and buckle. The following general conclusions derived from the model discussed in Section 6.4.2 are valid in their essence for any texturing conditions.

It can be concluded that the deflection of a filament with increased surface and projected areas and reduced area moment of
inertias, such as an elliptical cross section, require smaller axial forces, bending moments, and torsional moments (torque) than those required to deflect filaments with a solid circular cross-section of equal fineness. In addition fluid forces acting on such filaments become greater because of the increased projected and surface areas. Therefore, from a consideration of both fluid forces and mechanical deformation, elliptical filaments should be more suitable for the air jet-texturing process than are solid circular filaments.

In contrast to the elliptical filaments, forces required to deform the hollow circular filaments become higher while the fluid forces acting on them increase when compared with solid circular filaments of equal fineness (Table 6.2). On the other hand, the hollow circular structure of these filaments might easily collapse under fluid forces when they make the right angled turn as they emerge from the texturing nozzle. This may alter the area-dependent mechanical properties of such filaments and hence reduce their resistance to mechanical deformation. It will also cause a further increase in the fluid forces acting on them due to the increased projected area caused by collapsed structure. Additionally it can be argued that an advantage of hollow filaments in air-jet texturing could be the increased bulk of the textured yarns due to the hollow structure of the filaments.

It can therefore be argued that supply yarns composed of elliptical filaments and probably hollow circular filaments are worth experimental study for use in the air-jet texturing process.
TABLE 6.1

Area properties of circular, elliptic and hollow circular cross-sections.

<table>
<thead>
<tr>
<th></th>
<th>Area moment of inertia, $I$</th>
<th>Polar moment of inertia, $J$</th>
<th>Periphery, $P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>$\pi d^4/64$</td>
<td>$\pi d^4/32$</td>
<td>$\pi d$</td>
</tr>
<tr>
<td>Elliptic</td>
<td>$I_x = \pi ab^3/4$</td>
<td>$\pi ab(a^2+b^2)/4$</td>
<td>$\pi \sqrt{2(a^2+b^2)}$ (approx.)</td>
</tr>
<tr>
<td></td>
<td>$I_y = \pi a^3b/4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hollow Circular</td>
<td>$\pi(d_0^4-d_1^4)/4$</td>
<td>$\pi(d_0^4-d_1^4)/2$</td>
<td>$2\pi d_0$</td>
</tr>
</tbody>
</table>
A comparison of the area moment of inertias and surface and projected areas of circular, elliptic, and hollow circular cross-sectional filaments. where 'n' is the ratio of major to minor diameter for ellipse, and outer to inner diameter for hollow circle, and therefore is always greater than unity ($n > 1$).

<table>
<thead>
<tr>
<th></th>
<th>Area moment of inertia, $I$</th>
<th>Polar moment of inertia, $J$</th>
<th>Surface area, $A_s$</th>
<th>Projected area, $A_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>circle</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ellipse</td>
<td>$1/n$</td>
<td>$2n/(n^2+1)$</td>
<td>$[(n^2+1)/2n]^{1/2}$</td>
<td>$n^{1/2}$</td>
</tr>
<tr>
<td>hollow circle</td>
<td>$(n^2+1)/(n^2-1)$</td>
<td>$(n^2+1)/(n^2-1)$</td>
<td>$n/(n^2-1)^{1/2}$</td>
<td>$n/(n^2-1)^{1/2}$</td>
</tr>
</tbody>
</table>
FIGURE 6.1: Schematic diagram of the texturing zone
\[ V_n = (u-u_G) \sin \phi + (v-v_G) \cos \phi + \rho \dot{\rho} \]
\[ V_t = (u-u_G) \cos \phi + (v-v_G) \sin \phi \]

**FIGURE 6.2:** Model of a textile fibre in an air flow showing the forces acting on it
FIGURE 6.3: Schematic illustration of the variation of the filament projected area with its position in the nozzle.
FIGURE 6.4: Model of filament making a right angle turn on emerging from the nozzle
Modern industrial practice often involves wetting of the filaments during the air-jet texturing process by passing the supply yarn through a water bath, wetting head, or spray unit, either integrated with the texturing nozzle or as a separate wetting system as in Fig. 7.1. Regardless of its application technique, wetting the filaments results in improved process stability (Chapter 5) and consequently in better yarns (see Chapter 9). It should be noted that, although wetting the filaments appears to improve texturing, it may also result in an undesirably high moisture content in the final textured yarn, and cause the spin finish applied to the supply yarn by the fibre manufacturers, and the impurities in the water to be drawn into the nozzle and hence contaminate it. Such side effects reduce the nozzle efficiency, require cleaning of the cycled water for re-use or for disposal, and cause stoppages of the process for cleaning the contaminated nozzles.

7.1 Previous Works

There is no published information regarding how wetting of the filaments improves the effectiveness of the texturing process and the resultant yarn quality. Fischer, although offering no evidence for his explanations, claimed that the effect of wetting as a means of reducing the interfibre friction was limited. By referring to earlier investigations into flow conditions, generally in supersonic nozzles, which had demonstrated that humidity increases the strength of so-called "condensation shocks", he postulated that in the air-jet texturing process, filaments are deflected towards the jet axis after such a condensation shock, a phenomenon which he claimed might assist the "interlacing" of the filaments. Later Bock and Lünenschloss surmised that wetting the filaments could alter the flow and thereby
improve the yarn quality. They also referred to possible condensation effects which the damp air could cause but, like Fischer\textsuperscript{58}, they offered no experimental evidence.

7.2 Effects of Water on the Air Flow

Filaments passing through the wetting head (Fig. 7.1) carry water along with them until they reach the nozzle where the secondary air flow causes some amount of the water to be sprayed away so that only a fraction of the total quantity of the water used is dragged along with the filaments into the nozzle. This water, when it meets the incoming jets from the inlet bores at sonic speeds, will be blown off the filaments and broken down into very small particles of water which are then blown out with the primary flow. These water particles will obviously have some effect on the primary flow.

The effect of entrained water on the flow properties can be determined by considering the flow of a gas-particle mixture. The homogeneous equilibrium flow theory as summarised in Appendix D, gives the properties of the pseudo gas, containing particles, in terms of the properties of the air and particle components in the flow. Since the water is mixed into the air in the form of water particles, it can be assumed that this two-phase (gas-particle mixture) flow consist of air and homogeneously suspended water particles. Hence, homogeneous equilibrium flow theory can be applied to the air-particle mixture in the texturing nozzles and the effects of water on the flow properties can be calculated.

This approach was applied both to converging-diverging and cylindrical type texturing nozzles. For the converging-diverging nozzle a throat diameter of 2 mm and a diverging section which gives a complete expansion is assumed for the calculations. The flow velocities at the exit plane of the nozzles for air only, and for air-water mixtures containing 0.2, 0.5, and 1.0 l hr\textsuperscript{-1} of water are compared in Table 7.1a for varying operating pressures. Similarly,
Table 7.1b shows the effects of same amount of water on the flow velocity in a cylindrical nozzle (nozzle specifications as shown in Fig. 3.3).

Contrary to the previous claims by Fischer\(^5\), and Bock and Lünenschloss\(^4\), these theoretical calculations show that wetting the filaments has only a very slight effect on the flow exit velocity, depending on the amount of water mixed into the air, and may tend to produce a reduction, which in turn would have an adverse effect on the texturing process.

7.3 Significance of the Quantity of Water Used

Bock and Lünenschloss\(^4\) applied water to the supply yarn over the range 0 to 1.5 l hr\(^{-1}\) but only at less than 0.1 l hr\(^{-1}\) did it have significant effects on the instability, number of loops, and tensile strength of the textured yarn. Water consumption rates higher than this did not affect the properties of textured yarns. Similarly Artunc's work\(^43\) on humidity of textured yarns showed that the quantity of water is only critical at consumption rates of less than 0.2 l hr\(^{-1}\). It appears therefore that only a small amount of water is needed to have an effect on the texturing process, and the resultant yarn properties.

In order to observe the effects of the quantity of water used during the process a simple experiment was devised, such that the yarn tension in the feed zone (see also Section 7.6) was measured while the water consumption rate is gradually increased. It was observed that the tension that occurs in dry texturing went up to the level of the tension that was previously observed in wet texturing, as soon as the water is turned on. Further increases in the water consumption rates did not affect the tension in the yarn. This provides further evidence that only a small amount of water is required to impart the desired effects of wet texturing.
7.4 Quantity of the Water Entrained into the Nozzle

To quantify the amount of water entrained into the nozzle, the standard one-chamber nozzle enclosure unit (Fig. 7.2a) was modified to convert it to a two-chamber nozzle enclosure unit, as shown in Fig. 7.2b. A vertical wall in the middle divides the nozzle enclosure unit into two separate chambers, the nozzle housing being fitted into a cutout in this separating wall. These two chambers are sealed so that no air and water can escape from one chamber to another. In this way, the water blown away by the secondary flow can be kept in chamber two, while the water that is entrained into the primary flow is kept in chamber one.

The intention was to collect the cycled water separately from both chambers and determine their ratios with respect to the total amount of water used, which is measured by a rotameter. It was observed that no measurable amount of water was entrained into chamber one. Therefore it can be concluded that the amount of water entrained into the primary flow is insignificant and the postulations of Fischer\textsuperscript{58}, and Bock and Lüenschloss\textsuperscript{40} which claim that wetting alters the flow characteristics is also invalid on the basis of the negligible amount of water mixed into the primary flow; consequently the significant improvements observed in the properties of wet textured yarns (Chapter 9) could be due to frictional effects as will be discussed in Sections 7.5 to 7.9.

7.5 Frictional Behaviour of Textile Fibres

In most textile processes, textile yarns or fibres pass over yarn guides and rub against the guide surfaces. In such applications textile lubricants are used to reduce the friction. In the air-jet texturing process it is likely that wetting the filaments may have some lubrication effects similar to those of lubricants used in textile processes. In this section a review of literature regarding the frictional properties of the textile fibres and yarns is given.
Hansen and Tabor\textsuperscript{60} showed that the frictional behaviour of the textile fibres and yarns passing over cylinders is dominated by hydrodynamic factors. Fig. 7.3 shows a typical frictional behaviour to be expected from textile fibres and yarns making contact with solid-surfaces (after Hanson and Tabor\textsuperscript{60}, and Olsen\textsuperscript{61}), and it can be seen that the crucial factors which determine the frictional behaviour are the yarn speed, \( V \), lubricant viscosity, \( \mu \), and the normal force, \( N \), applied to the yarn. As it can be seen from these figures, increasing yarn speed, fluid viscosity, and decreasing normal force will cause the friction to increase. Hansen and Tabor\textsuperscript{60} claim that the viscosity of the spin finish as applied to the filaments by the manufacturers also play an important role in the frictional behaviour of the filaments. The surface roughness of both the yarn and the contacting surface also have some effect on the frictional properties and it is also discussed in this section.

Schick\textsuperscript{62} showed that the friction in the hydrodynamic region increases with the increasing yarn speed as shown in Fig. 7.4 for a typical textile yarn, (Nylon 66, 200/f34). As the speed increases, friction increases steeply initially and then the rate of increase in the friction becomes much slower at higher yarn speeds, i.e., above 500 m min\(^{-1}\) for the particular yarn and conditions illustrated. Schick\textsuperscript{63} also observed that the friction in the hydrodynamic region is highly dependent on the viscosity of the lubricant and it increases with increasing viscosity.

Increases in the friction due to higher yarn speed and lubricant viscosity are both attributed to the increase in shear stress in the continuous liquid film separating the two surfaces, where the shear stress is a function of both these properties, i.e., \( \tau = \mu (\delta v / \delta n) \).

Schick\textsuperscript{65} also showed that the friction increases with the increasing surface pressure, i.e., the normal load between the surfaces making mutual contact and this was attributed to the increase in the area of contact under higher pressures. He also showed that other factors which increase this area of contact, such
as higher linear density and high contact angle, also increase the friction.

The effects of surface roughness were investigated by Olsen and Schick. They both observed that the friction between the lubricated yarn and the yarn guide in the hydrodynamic region, initially decreases with increasing surface roughness of the guide between 0.1-0.5 μm and then remains essentially constant until the surface roughness reaches a certain value, and Olsen claimed that this value is about 5 μm. Yarn guides with surface roughness greater than this value cause high localised pressures which disrupt the lubricant film and consequently cause the friction to rise. Schick showed that the friction in the hydrodynamic region was higher for smooth feeder yarn than for a rougher surfaced textured yarn. Thus he concluded that the effect of surface roughness at the fibre/solid-surface interface is independent of whether the guide or the yarn is contributing to the increase of the surface roughness.

Schick also concluded that there is apparently no significant difference between the frictional behaviour of fibres contacting solid surfaces and that of fibres contacting other fibres i.e., the fibre/solid-surface mode of friction is governed by principles equally applicable to the fibre/fibre mode.

7.6 Friction in the Air-jet Texturing Process

In the texturing zone, as illustrated in Fig. 7.1, filaments make contacts with the internal surface of the wetting unit and the yarn guides preceding nozzle where they are in further contact with the nozzle's internal surface. As Wray showed, longitudinal displacements of the filaments occur relative to each other (see Section 5.2) and these cause the filaments to rub against each other. Therefore fibre/solid-surface and fibre/fibre modes of the friction both occur during the air-jet texturing process, and these are well in the hydrodynamic range. Friction between the filaments and the
contacting surfaces will oppose the motion of the filaments along their path whereas the friction between the filaments themselves will oppose their longitudinal displacements during texturing.

The group of parameters, \((\mu V/N)\), which determine the frictional behaviour of the textile fibres and yarns are, in the case of air-jet texturing process, the viscosity of the water, the speed of the filaments \((V_f)\), and the normal forces due to the pressure between the filaments themselves and between them and the contacting surfaces, e.g. the nozzle.

The fluid forces, which blow the filaments out of the nozzle, act so as to create a tension in the segment of the filaments in the feed zone, i.e., between the feed rollers \(W1.1\) and the nozzle. The frictional forces acting on the filaments will cause this tension to reduce. The resultant force acting on the filaments will be determined by the fluid and the frictional forces. If the fluid forces are kept constant any changes that may occur in the tension in the filaments within this zone can be taken as an indication of changes in the frictional forces acting on the filaments and hence the effects of wetting the filaments on the friction during the air-jet texturing process can be analysed by such tension measurements.

7.7 Effects of Wetting on Friction in Air-jet Texturing

Fig. 7.5 shows the results of experiments conducted with the conventional texturing arrangement of the nozzle and the yarn feed system (see Fig. 7.1), and the supply yarn specified in Table 5.1 was used in these experiments. In this conventional arrangement, the supply yarn is guided through the wetting unit and passes over a yarn guide prior to its entry to the nozzle where further yarn/surface contact occurs, all of which cause yarn/solid-surface friction. A water consumption rate of \(1.0 \text{ hr}^{-1}\) was used when wet textured.
The effects of the varying texturing speed and overfeed ratio can be analysed from Figs. 7.5a and b respectively, for both dry and wet texturing conditions. Since the fluid forces acting on the filaments did not change, because the working pressure was kept constant during these experiments, the changes that occur in the tension are due to the frictional changes alone.

For both dry and wet texturing, the rate of increase in the friction with increasing texturing speed is small, as indicated by slight decreases in the tension, as shown in Fig. 7.5a. In Section 5.4 it was shown that the actual speeds of the filaments, \( V_f \), are determined by the fluid forces, and these were shown to be much higher than typical yarn texturing speed. Therefore increasing the texturing speed does not have a direct effect on the actual speed of the filaments, but this causes the flow rate of the filaments to increase. Consequently increased texturing speeds cause only a slight rise in friction. Fig. 7.5b shows no significant change in the tensions with increasing overfeed ratio, because changing the overfeed ratio does not affect the determining parameters, \( \mu V_f / P \).

The rates of increase in tension with increasing air pressure are significant and these show approximately a linear relation, for both dry and wet texturing, as shown in Fig. 7.5c. This increase is due to the increased fluid forces obtainable at higher air pressures which act on the filaments.

In general Fig. 7.5 shows that the tensions in the filament when wet textured are substantially higher than those under dry texturing conditions indicating a considerable reduction in the friction. This is because of the lubrication effects of the water. Consequently, since it was shown that (Sections 7.2-7.4) water used in wet texturing has a negligible effect on the air flow and this is to cause a reduction in the flow velocity, it can be argued that the substantial increase in tension in wet texturing arises from the reduction in the frictional forces caused by the lubrication effects of the water used, and not from the changes in flow properties as suggested by
7.8 Realignment of the Yarn Path to Reduce Friction

Another set of experiments was devised to reduce the friction between the filaments and the contacting solid surfaces. As shown in Fig. 7.6 the feed rollers, wetting unit, and the texturing nozzle were realigned to reduce their contact with the supply yarn, and the yarn guide preceding the nozzle was removed so that the filaments assumed a straight path between the feed roller W1.1 and the nozzle. On emergence from the nozzle they were externally forced to deflect at right angles (which is an essential requirement of effective texturing as will be discussed in Chapter 8) by use of an additional yarn guide. Since this yarn guide is situated after the nozzle, it does not affect the tension in the part of the filaments between the feed rollers W1.1 and the nozzle.

The results of the tension measurements with the realigned yarn path arrangement are given in Figs. 7.7a, b, and c for varying texturing speed, overfeed ratio and air pressure respectively. These show that the tensions for both dry and wet texturing with the new arrangement are higher than the corresponding tensions obtained with the conventional texturing arrangement and suggest that the reduced frictional contact in the new arrangement is a factor causing the resultant forces acting on the filaments to increase.

These results also show that the difference between the tensions for both dry and and wet texturing with the realigned path are smaller than those with the conventional yarn path, because of the reduced frictional contacts between the filaments and the contacting parts. This suggests that the scope for improvement by lubricating the filaments with water is reduced for texturing with the realigned yarn path.
7.9 Effects of Wetting on Interfilament Friction

In both wet and dry texturing, with the realigned yarn path, small differences were observed in the tensions in the feed zone. This suggests that similar forces act on the filaments and hence yarns with very similar characteristics would be obtained under both dry and wet texturing conditions. However, as discussed in Section 5.3.2, tension in the yarn in the delivery zone i.e., between the nozzle and the delivery rollers W2, indicates the effectiveness of texturing, and the tension in the stabilising zone, i.e., between the delivery rollers W2, and the take-up rollers W3, gives a comparative measure of the loop stability, and therefore analyses of these should indicate the difference between the yarns textured by both dry and wet texturing conditions with the new texturing arrangement.

Figs. 7.8a and b show the yarn tensions in the delivery and stabilising zones respectively, for varying air pressure. Yarn tensions in these zones for varying overfeed ratio and texturing speed are also shown in Table 7.2.

Fig. 7.8a shows significant difference for dry and wet texturing indicating that a better texturing effect is achieved by wet texturing. Tension in stabilising zone, as shown in Fig. 7.8b, indicates that loop stability is also substantially higher for wet textured yarns than dry textured. Similar results were obtained for varying overfeed ratio and texturing speed, as shown in Table 7.2. Despite the similar fluid and frictional forces acting on the filaments both in dry and wet texturing conditions (Fig. 7.8), poor loop formation and hence inferior textured yarns are obtained by dry texturing.

Although the frictional forces in dry texturing with the realigned yarn path are small due to reduced contact between the filaments and the contacting surfaces, the interfilament friction still remains at the same high level corresponding to that of the conventional texturing arrangement, because the new arrangement does
not alter the state of the interfilament contact. This high friction between the filaments in dry texturing will resist their longitudinal displacements relative to each other, resulting in inferior texturing conditions.

As Skelton discussed, the coefficient of friction of textile fibres decreases when immersed in water due to its lubrication effects. In the wet texturing process, the part of the filaments between the wetting unit and the nozzle is virtually surrounded by water, (see Figs. 7.1 and 7.5) and the filament portions within the nozzle remain wet. This reduces the interfilament friction and makes for easier longitudinal displacement of the filaments under the applied fluid forces, and hence creates better texturing conditions.

In essence the loop formation process is an entanglement of filaments as they emerge from the nozzle. Therefore reduced filament to filament friction, as a result of wetting, could make the entanglement process more effective and also contribute to improvements in loop formation.

Therefore, it can be argued that wetting the filaments not only reduces the tension between the filaments and the contacting surfaces but also reduces the friction between the filaments themselves, thereby enhancing their relative longitudinal displacements and assisting their entanglement on emerging from the nozzle, consequently resulting in better texturing conditions.

7.10 Conclusions

Wet texturing improves the texturing process and results in better textured yarns. Only a small amount of water is sufficient to impart the desired effects of wetting to the textured yarns. Water used in the wet texturing process does not cause any significant changes in the flow velocity, which is the determining factor for the fluid forces acting on the filaments. Friction between the filaments
themselves, and between them and the contacting surfaces, each play important roles in the texturing process, and serve to reduce the resultant forces acting on the filaments.

Wetting of the filaments in the air-jet texturing process produces a lubrication effect to reduce the friction between the filaments and the contacting parts, such as texturing nozzle, wetting unit, and associated yarn guides, causing an increase in the resultant force acting on the filaments. This in turn results in yarns with improved properties. Wetting also reduces the friction between the filaments themselves which enhance the longitudinal displacement of the filaments relative to each other, which is a desired action for improved textured yarns. Reduced interfilament friction also assists the entanglement of the filaments during loop formation on their emergence from the nozzle.

By realigning the feed rollers, wetting unit and the texturing nozzle a further substantial reduction in the filament to solid-surface friction can be obtained. This arrangement does not appear to affect the interfilament friction. Therefore it can be concluded that, wetting is a required and significant parameter in the air-jet texturing process in order to reduce the fibre/solid-surface and fibre/fibre friction.
TABLE 7.1

A comparison of the free air flow velocities with those of the flows of air-water mixture for varying pressure, and varying amount of water contents in the air flow.

<table>
<thead>
<tr>
<th>Working pressure $10^5$ N m$^{-2}$</th>
<th>Axial velocity at the exit plane (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air only</td>
</tr>
<tr>
<td>(a) Converging-diverging nozzles:</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>529</td>
</tr>
<tr>
<td>9</td>
<td>520</td>
</tr>
<tr>
<td>8</td>
<td>510</td>
</tr>
<tr>
<td>7</td>
<td>497</td>
</tr>
<tr>
<td>6</td>
<td>482</td>
</tr>
<tr>
<td>5</td>
<td>462</td>
</tr>
<tr>
<td>4</td>
<td>435</td>
</tr>
<tr>
<td>(b) Cylindrical nozzles:</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>524</td>
</tr>
<tr>
<td>9</td>
<td>503</td>
</tr>
<tr>
<td>8</td>
<td>479</td>
</tr>
<tr>
<td>7</td>
<td>451</td>
</tr>
<tr>
<td>6</td>
<td>417</td>
</tr>
<tr>
<td>5</td>
<td>375</td>
</tr>
<tr>
<td>4</td>
<td>324</td>
</tr>
</tbody>
</table>
TABLE 7.2

A comparison of yarn tensions in texturing and stabilising zones for the realigned yarn path arrangement with corresponding tensions for the conventional arrangement (shown in brackets).

(a) varying overfeed ratio

<table>
<thead>
<tr>
<th>Overfeed ratio</th>
<th>Delivery zone</th>
<th>Stabilising zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.10</td>
<td>7.0 (3.3)</td>
<td>9.6 (4.9)</td>
</tr>
<tr>
<td>1.15</td>
<td>5.8 (2.5)</td>
<td>8.9 (4.3)</td>
</tr>
<tr>
<td>1.20</td>
<td>4.8 (1.9)</td>
<td>8.3 (3.9)</td>
</tr>
<tr>
<td>1.25</td>
<td>4.2 (1.4)</td>
<td>7.7 (3.6)</td>
</tr>
<tr>
<td>1.30</td>
<td>3.8 (1.0)</td>
<td>7.3 (3.3)</td>
</tr>
</tbody>
</table>

(b) varying texturing speed

<table>
<thead>
<tr>
<th>Texturing speed m min⁻¹</th>
<th>Delivery zone</th>
<th>Stabilising zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>5.3 (2.4)</td>
<td>9.3 (4.1)</td>
</tr>
<tr>
<td>300</td>
<td>5.3 (2.2)</td>
<td>8.8 (4.0)</td>
</tr>
<tr>
<td>400</td>
<td>4.7 (2.0)</td>
<td>8.5 (3.9)</td>
</tr>
<tr>
<td>500</td>
<td>4.0 (1.7)</td>
<td>8.1 (3.8)</td>
</tr>
<tr>
<td>600</td>
<td>2.5 (1.3)</td>
<td>7.6 (3.6)</td>
</tr>
</tbody>
</table>
FIGURE 7.1: Schematic diagram of the feed and delivery zone showing the wetting unit, feed and delivery rollers, and primary and secondary flows.
FIGURE 7.2: Nozzle enclosure units: (a) one-chamber unit, and (b) modified two-chamber unit
Where $f$ = coefficient of friction  
$V$ = yarn speed  
$\mu$ = lubricant viscosity  
$N$ = normal force

FIGURE 7.3: Typical frictional behaviour of textile fibres and yarns (after Hansen and Tabor, and Olsen, Refs. 60 and 61)

FIGURE 7.4: Typical variation in the friction with the yarn speed (after Schick, Ref. 62)
FIGURE 7.5 (continued)
FIGURE 7.5: Variation of tension in feed zone with the conventional arrangement for varying:

(a) texturing speed;
(b) overfeed ratio; and
(c) air pressure
FIGURE 7.6: Realigned texturing arrangement to reduce friction between the filaments and the contacting surfaces.
FIGURE 7.7 (continued)
FIGURE 7.7: Variation of tension in the feed zone with the realigned yarn path arrangement for varying:

(a) texturing speed;
(b) overfeed ratio; and
(c) air pressure
FIGURE 7.8: Tension in the delivery and stabilising zones with the realigned yarn path arrangement for varying air pressure:

(a) in the delivery zone; and
(b) in the stabilising zone
8.1 Summary of the Results and Conclusions

The findings and the conclusions of the theoretical and experimental investigations can be summarised as follows:

Flow from the texturing nozzles, at the usual texturing pressures, is supersonic, turbulent, slightly asymmetric and of a non-uniform profile. The mean velocity of the flow and the degree of non-uniformity increases with increasing texturing pressures. A modified cylindrical nozzle, with curved diverging exit (trumpet-shaped) appears to exaggerate non-uniformity in the velocity profile, while nozzles with longitudinally staggered air inlet bores impart swirl into the flow. Asymmetry of the flow is most pronounced in planes close to the air inlets but diminishes with distance towards the nozzle exit.

Shock waves occur in the flow, the strength of which varies depending upon the type of the nozzle. These shocks are at least partially destroyed by the presence of the filaments in the nozzle during the texturing process; and nozzles providing varying degrees of shock strength are equally effective in the texturing process. Therefore the effect of shock waves on the filament motion is negligible and the loop formation mechanism based on the shock waves is invalid.

Intensive turbulence has the effect of separating and scattering the filaments across the nozzle cross-section. During texturing, the filaments are pulled down to the lower part of the nozzle (for downward delivery) due to the tension created in the yarn as a result of texturing itself. Shock waves appear to play no role in changing the direction of the filaments when they are left free to be dragged.
along with the air stream.

The filament segments within the nozzle travel at much faster speeds than the typical yarn texturing speeds. Since the flow velocity distribution is non-uniform and the fluid forces acting on the filaments are a function of the local air velocity, filaments that are separated and scattered across the nozzle are under the action of different driving forces and therefore move at different speeds. This in turn causes longitudinal displacements of the filaments relative to each other. Friction between the filaments and the solid surfaces plays a significant role in affecting the resultant force acting on the filaments, and counteracts the effects of the fluid forces.

Wetting of the filaments, which is known to improve the quality of the textured yarns, has a lubricating effect on the filaments; this in turn reduces the friction between the filaments and the solid surfaces, thereby resulting in increased forces acting on the filaments. Moreover, wetting also reduces the friction between the filaments themselves and hence enhances their longitudinal displacements and assists entanglement as they emerge from the nozzle. Consequently, all these factors improve the texturing process.

The amount of water required to create the desired effects of wetting is only a small fraction of the total amount used in the process, because most of it is blown away by the secondary flow allowing only a small fraction to be entrained into the nozzle. Therefore the possible effects of water particles on the primary flow are insignificant; nevertheless, these effects act so as to cause a reduction in flow velocity. This small yet adverse effect of water particles on the air flow rules out the claims which state that water alters the flow properties such as to improve the texturing conditions and the resultant yarn quality.
Filaments with different cross-sectional areas and with different cross-sectional shapes behave differently in the air stream. For a circular cross-section, while the drag forces that act on the filament increase in proportion to the filament diameter, the mass and the inertial resistance of the filament to these fluid forces will increase as a function of the square of the diameter. This will cause coarser filaments to travel more slowly in given flow conditions, and therefore will result in inferior conditions. Filaments with equal fineness but with smaller area and polar moments of inertia and with increased surface areas, such as elliptical cross-sections, are more suitable for air-jet texturing than are the solid circular filaments.

8.2 The Mechanism of Loop Formation

Usually there are many filaments in a supply yarn, but in order to explain the loop formation mechanism, it is simpler to consider only a few filaments emerging from the nozzle as shown in Fig. 8.1. At any instant some of these 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 displacements is effected by local drag and frictional forces instantaneously acting on the filaments and also by the overfeed ratio.

The textured yarn is delivered from the nozzle at right-angles to the nozzle axis and travels at the yarn texturing speed. Since the filaments are converted into loops the resultant textured yarn is shortened and a tension is created of a magnitude determined by the effectiveness of the texturing. Thus on the one hand the emerging filaments are blown out of the nozzle along the direction of the air stream at much faster speeds than the yarn texturing speed; on the other hand the tension created in the yarn, as a result of texturing,
pulls the "leading ends" of the emerging filaments in the direction of the yarn delivery, i.e., at right-angles to the nozzle axis. While the "trailing ends" of the filaments in the nozzle are blown out at very high speeds (see Section 5.2), the "leading ends" of the filaments are held within the core of the much slower moving textured yarn and these are pulled downward and kept close to the nozzle exit; therefore, the filaments are forcibly bent into bows and arcs by the fluid forces acting on them. These are then entangled with other emerging filaments which are formed into fixed stable loops within the textured yarn.

Lengths of such filaments, as they form loops, are fixed in the core of the textured yarn, become shorter and consequently the tension in them increases. The increased tension resulting from loop formation and subsequent entanglement causes loop forming filaments to migrate towards the lower part of the nozzle since they will assume the shortest possible path between the "trailing" and the "leading ends". An instant later the tension in the segments following these entangled filaments may be relieved on account of the overfeed ratio, and these filaments may be blown out by the air stream and its associated turbulence to form new loops. Therefore every filament goes through this process at different instants and the cycle repeats itself randomly.

This can be illustrated in Fig. 8.1 which is a simplified schematic diagram with only a few filaments representing the behaviour of a more complex multi-filament yarn. In Fig. 8.1a filament 1 is the fastest moving filament having the greatest longitudinal displacement relative to the others and is blown furthest out of the nozzle to form a loose bow or arc. An instant later, in Fig. 8.1b, it is formed into a fixed loop L1 within the textured yarn as a result of mutual entanglement of the filaments under the action of the air stream. This newly formed fixed loop L1 increases the tension in filament 1 thereby causing a change in its position and also contributing to the total yarn tension which is pulling the yarn down closely to the nozzle. Meanwhile filament 2
comes under the action of a greater drag force as a result of changes in the positions of the filaments across the nozzle due to the turbulence and varying tension in the individual filaments, and this now becomes a faster moving filament so causing it to be blown out and displaced longitudinally relative to the others to form a loose bow or arc. Immediately afterwards (Fig. 8.1c,) whilst filament 2 is being similarly entangled into a fixed loop L2, a further filament 3 commences a similar loop formation process.

Since there are many filaments in the actual supply yarn rather than the five illustrated in Fig. 8.1, several loops are formed at any particular instant and these help each other to be fixed and locked within the yarn structure by mutual entanglement. Other filaments, although they do not form visible loops on the surface of the yarn, have their originally closely packed parallel structure changed into a tangled, voluminous structure with increased bulk and linear density.

This description of the mechanism of loop formation is valid for all types of texturing nozzles, despite detailed differences in their design, because the underlying requirement to create a supersonic, turbulent, asymmetric, and non-uniform flow is common to all satisfactory texturing.

8.3 Factors Affecting Loop Formation

To be able to analyse the effects of various parameters on the loop formation mechanism, a filament emerging from the texturing nozzle is considered, as shown in Fig. 8.2a.

Point A on the filament is the "trailing end" of the filament which makes a bow on emerging from the nozzle and moves at a speed dictated by the air flow, i.e., filament speed, \( V_f \). Point B is the leading end of the filament and moves downwards at the texturing speed, i.e., at the speed of the textured yarn, \( V_y \). The ratio of
these two speeds is estimated to be of the order of 10, i.e., \( \frac{V_f}{V_y} > 10 \).

In unit time, points A and B will move to positions A' and B' respectively, as illustrated in Fig. 8.2b. The length of filament L which is blown out in this unit time is determined by the filament speed, \( V_f \), and by the excess free length of filament as provided by the overfeed ratio, whereas the length BB' is determined by the texturing speed, \( V_y \). The filament length \( L_0 \) between point A and B will become \( (L_0 + L) \).

The effects of any changes in the texturing conditions on this filament will be analysed in the light of the described mechanism of loop formation, and by reference to illustrations Figs. 8.2a to d.

### 8.3.1 Effects of air pressure

When the air pressure is increased, the speed of a filament will also increase as a result of increased air velocity, and therefore point A will move more rapidly, and the time taken to blow out the free length of the filament will become shorter. High air pressure will also enhance the differences between the forces acting on the filaments and cause greater relative longitudinal displacements. Since the loop formation is an intermittent process, the increased filament speed could increase the frequency of the loop formation and the entanglement process could then become more effective in flows with high velocities and intensified turbulence. Therefore more effective texturing is likely to be achieved by increasing the air pressure.

### 8.3.2 Effects of overfeed ratio

When the overfeed ratio is increased a relatively longer filament will be blown out in unit time (i.e., \( L' > L \)), as illustrated
in Fig. 8. 2c. Since the yarn texturing speed is not changed point B will not move very far and the longer filament between A and B' will form a larger loop or several smaller loops in this unit time. Therefore increasing the overfeed ratio will result in an increase in loop size and loop frequency which in turn causes an increase in the linear density and a decrease in the yarn stability, because the higher the number of loops the higher becomes the chance of these loops being pulled out under applied loads.

When the overfeed ratio is excessively high, the bow formed by the filament becomes very large, and will consequently reduce the tension in the yarn, causing the filament and the textured yarn to be blown away from the nozzle, as schematically shown in Fig. 8.3. This will result in a failure in the loop formation process.

8.3.3 Effects of texturing speed

Increasing the texturing speed will cause point B to move faster and in turn cause the distance BB' to increase in a given unit time (Fig. 8.2d). Since the length of the filament L that can be blown out in this unit time is not changed, increased yarn speed will cause the filament between points A and B' to form a flatter bow. This bow is unlikely to form into a stable loop and will be removed under applied loads. Therefore the number of stable loops formed will be reduced, the tension in the yarn will drop, and the filaments will be blown away from the nozzle, causing failures in the continuity of the texturing process.

In order, at least partially to counteract the adverse effects of increased texturing speeds, the flow velocity could be increased, which may cause the process to become more effective. This requires very high operating pressures which makes the process uneconomical. Therefore the scope of increasing the productivity by increasing the production speed is very limited.
8.3.4 Effects of other parameters

Wetting, as discussed in Chapter 7, will reduce the friction between the filaments themselves, and between them and other solid surfaces. This will cause an increase in the resultant fluid forces acting on them and the texturing process will become more effective, and hence more stable loops will be formed.

The impact element is unlikely to have a major effect on the flow inside the nozzle, since the element is usually situated at a distance of about one nozzle diameter from the nozzle exit, and is thus remote from the immediate nozzle exit region, where the loop formation process takes place. One minor influence concerns the role of the impact element as a physical barrier to those filaments which are blown away from the nozzle.

8.3.5 Effects of the supply yarn properties

Increased numbers of filaments increases the likelihood of mutual entanglement, and thus may be expected to improve the effectiveness of the texturing process and the resultant yarn quality. The linear density of the individual filaments is also a significant factor, as discussed in Chapter 6, as a consequence of reduced inertial resistance opposing fluid forces acting on the finer filaments. Finer filaments have reduced stiffness which makes bending and other forms of deformation of the individual filaments much easier during the loop formation process, which in turn causes better textured yarns to be produced. The cross-sectional shape of the filaments may also have considerable effect upon the loop formation process as, for instance a thin elliptical section will have a preferred bending axis which leads to reduced stiffness of the filament, while the extended surface and projected areas will tend to increase the fluid forces.
FIGURE 8.1: Schematic illustration of the loop formation as the filaments emerge from the nozzle.
FIGURE 8.2: Schematic illustration of the effects of process parameters on a filament on emerging from the nozzle.
FIGURE 8.3: Schematic illustration of the unstable filaments showing their failure in loop formation
CHAPTER 9

EFFECTS OF PROCESSING PARAMETERS ON YARN PROPERTIES

Properties of the air-jet textured yarns are affected by both the supply yarn properties and the process parameters. The effects of process parameters have been investigated by many researchers but in most of these investigations pretwisted supply yarns were used. Today's modern texturing technology allows for the use of no-twist supply yarns and therefore further investigations of the effects of process parameters on the textured yarn properties are required. Only one type of yarn was used in the tests in order to eliminate the effects of the supply yarn properties.

Tests were restricted to measurements of tensile properties, linear density, and instability. Bulkiness tests were omitted because such test methods have not been firmly established and clearly defined. Loop size and loop frequency tests demand the counting and measuring of individual loops under a microscope or a microprojector, tedious jobs even for laboratory purposes. Instability tests were based on the load-elongation curves, rather than weight-hanging methods.

9.1 Factors Effecting Textured Yarn Properties

The physical characteristics of single end air-jet textured yarns are affected both by the properties of the supply yarn and by the processing parameters. Properties of the supply yarn comprise:

a) type of yarn (including spin finish);
b) linear density per filament;
c) number of filaments in the yarn; and
d) geometry of the filament cross section.
Since the air-jet texturing technology has advanced to enable the industry to avoid using pretwisted supply yarns, pretwist is not considered among the supply yarn properties.

The process parameters comprise:

a) overfeed ratio;

b) air pressure;

c) production speed;

d) wet or dry processing; and

e) use of an impact element.

It has been shown by Rozmarynowska and Godek\textsuperscript{48} that the process of air-jet texturing causes no significant changes in the properties of individual filaments; any changes in the yarn properties result only from the formation of the bulked (textured) structure as determined by the processing parameters and the properties of the supply yarns. Consequently no attempt has been made to determine the properties of the individual filaments after texturing and all the changes in the yarn properties are believed to be the result of the texturing process only.

9.2 Test Plan

For the present investigation, a supply yarn, as detailed in Table 5.1, was used to verify the effects of processing parameters on the textured yarns. These yarns were produced by using Heberlein's standard core HemaJet on the single-head texturing machine as described in Appendix A. The process variables were:

- overfeed ratio varying from 1.10 to 1.30 by increments of 0.05;
- production speed varying from 200 m min\(^{-1}\) to 600 m min\(^{-1}\) by increments of 100 m min\(^{-1}\); and
- varying air pressure from 5x10\(^5\) N m\(^{-2}\) to 9x10\(^5\) N m\(^{-2}\) (gauge) by increments of 1x10\(^5\) N m\(^{-2}\).
Processing conditions of 1.20 overfeed ratio, 400 m min\(^{-1}\) production speed, and 8x10\(^5\) N m\(^{-2}\) (gauge) air pressure were chosen as standard parameters. Whenever one of the parameters was varied the others were kept at their standard conditions. The first set of tests supply yarn was wetted during texturing and the impact element was not used with the nozzle. Two other sets of yarns were produced to verify both the effects of using an impact element and the effects of dry processing on the yarn properties. These further tests were performed only at varying overfeed ratio in order to keep the testing programme to within reasonable time limits.

9.3 Test Methods

The facilities of a textile testing laboratory were not available for the author to carry out the tests planned. An Instron tensile testing apparatus designed for the tensile tests of engineering materials was adapted for use of textile yarns with the aid of a special load cell and pneumatic grips. Load-elongation curves were obtained from which breaking load and breaking elongation and hence tenacity of the yarns can be obtained. Linear density of the yarn was also measured by measuring a certain length and weighing it. Load-elongation curves from the Instron machine were also used to determine the instability of the yarns.

Instability is defined as a measure of the tendency for loops to be removed by applying tension to the yarn\(^2^8\). Conventional instability tests depend on hanging weights on a skein of yarn specimen and measuring the extension after a certain time has elapsed. These tests depend on the duration of the applied loads, and human errors in the test results are inevitable. An alternative test method was used for the present work, in which Instron load-elongation curves were obtained and elongations under loads corresponding to those normally used in other instability tests were calculated. The loads used were 0.01 cN dtex\(^{-1}\) (lower limit) and 0.5 cN dtex\(^{-1}\) (upper limit). The difference in elongations corresponding
to these loads gives the instability of the yarn and this method reduces duration dependence and human errors inherent in the weight hanging methods.

Different test methods have been suggested to assess the physical bulk of the textured yarn, e.g., a package density method, a water absorption test, and a test described to measure the apparent volume of a skein of yarns and comparing it with the theoretical volume. Each has its own disadvantages and there is no unique method which has a wide acceptance. For the present work, therefore, no attempt was made to measure the physical bulk of the yarn.

Other important properties are the surface properties of the textured yarn such as loop size and loop frequency. The measurements of these properties involves the tedious work of counting the loops, measuring the size of them, and measuring the overall and core diameters of the yarn. The present research has, to date, been confined to a visual impression of yarns obtained after wrapping the yarn on a blackboard, although more accurate methods are still required.

### 9.4 Results and Discussions

Test results for tenacity, breaking elongation, linear density and instability for varying process parameters are shown in Fig. 9.1. In general these show that the strength and extensibility of the textured yarn are reduced when compared to those of the raw supply yarn (see Table 5.1), and its linear density is increased as expected. Visual inspection of the experimental yarns showed a substantial increase in yarn voluminosity (bulk). Instability of the textured yarn is in reality a measure of loop stability, and therefore cannot be compared for the flat supply yarn with no loops. Test results showed that textured yarns with more loops are more unstable than those having fewer loops.
The strength of the air-jet textured yarn is reduced because loops in the yarn do not contribute to the carrying of applied loads; such loads are mainly borne by the straight filaments usually located in the core of the yarn. Therefore yarns with higher numbers of loops are generally weaker and less extensible.

9.4.1 Effects of overfeed ratio

Figs. 9.1 and 9.2 show that tenacity and breaking elongation decreases with increasing overfeed ratio and air pressure. At high overfeed ratios, because there are sufficient extra lengths of filaments available for loop formation, the number of loops formed becomes higher as the size of the loops becomes enlarged, as is evidenced by visual inspection. Therefore the tenacity and the breaking elongation of the yarn is reduced as the overfeed ratio is increased.

Fig. 9.3 shows that, as expected the linear density of the textured yarn increases with the increasing overfeed ratio because the overfed excess lengths of the filaments are formed into loops. Not all of these loops are firmly fixed in the yarn core, as indicated by increasing yarn instability with increasing overfeed ratio (see Fig. 9.4). This is due to the increased number of loops at high overfeed ratios; this in turn increases the probability of some of these loops being removed and consequently gives rise to the instability of the yarn. Therefore the rate of increase in the linear density of the yarn is smaller than the overfeed ratio.

9.4.2 Effects of air pressure

Effects of the air pressure on the tenacity and breaking elongation, as shown in Figs. 9.1 and 9.2 are similar to those of the overfeed ratio. As the pressure increases, then air velocity at the
exit, the degree of non-uniformity in the velocity distribution, and the turbulence all increase, the filament separation and their longitudinal displacement with respect to each other become more effective, and filaments travel and displace their positions at a greater rate. Hence a better loop formation and texturing can be achieved, this resulting in lower tenacities and breaking elongations.

At increased air pressures, for a constant overfeed ratio, the linear density of the textured yarn increases (Fig. 9.3) although the excess lengths of the filaments are unchanged. This is due to the more effective entanglement of the filaments which causes more loops to become fixed in the core of the yarn; such loops stand a greater chance of staying intact under stabilising tension. Fig. 9.4 also shows that the yarn instability increases slightly with the increasing air pressure again due to increased numbers of loops.

9.4.3 Effects of texturing speed

The effect of texturing speed on the tenacity and breaking elongation shows different characteristics. Since it is known that a better texturing is obtained at lower texturing speeds and that this reduces the strength of the yarn, it is expected that the strength should gradually increase with increasing texturing speed. Contrary to this expectation, tenacity and breaking elongation do not increase with increasing texturing speed at the lower end of the speed range (Fig. 9.1 and 2), but decrease to a minimum and then begin to increase. This minimum is determined by other processing parameters as well as by the properties of the supply yarn; for the particular yarn used in the tests the minimum speed was about 350 m min\(^{-1}\) when textured under the chosen standard processing conditions.

The texturing speed affects the bulkiness of the yarn and its structure becomes closely packed at low speeds. The interfilament friction in the core of such yarns becomes higher than those of less closely packed yarns. This increased interfilament friction,
therefore contributes to the strength of the yarn as analogous to the interfibre friction in spun yarns and accounts for the higher strength and extensibility of the yarns textured at low texturing speeds. As the texturing speed is increased, the yarn structure becomes less compact and consequently interfilament friction is reduced, causing the yarn strength to drop. As the texturing speed continues to increase, then further reductions in interfilament friction occur due to the less compact structure of the yarn and texturing gradually becomes less effective; therefore, the strength and extensibility of the yarn begins to increase.

Fig. 9.5 shows both high speed photographs taken during texturing at various texturing speeds and scanning electron microscope photographs of the corresponding yarns produced under the respective texturing conditions. These depict that the yarns produced at lower texturing speeds have very dense, closely packed structures with smaller overall diameters and smaller loops. An inspection of Fig. 9.1 shows that yarns textured at about 150 m min⁻¹ and 600 m min⁻¹ exhibit similar tenacity (strength) although the structures of these two yarns are much different. For the former speed this strength is attributed to the increased interfilament friction whereas for the latter it is attributed to the reduced numbers of loops due to less effective texturing.

At high texturing speeds, for a fixed overfeed ratio, the linear density of the textured yarn reduces because of the poor loop formation (Fig. 9.3); such loops are liable to be removed under stabilising tension.

Fig. 9.4 shows that yarn instability increases slightly with increasing texturing speed. This is due to the open and less compact structure of the yarn because of poor loop formation, which causes most of the formed loops to be removed under applied stabilising tension. Its effect is not severe because the loop frequency is not too high.
9.4.4 Effects of impact element and dry texturing

Test results for varying overfeed ratio are shown in Figs. 9.6 to 9.9; these enable the effects of using an impact element at wet texturing conditions to be examined and the difference between the effects of wet and dry processing to be compared. Fig. 9.6 shows that the tenacity of the yarn is not affected essentially by using an impact ball except at high overfeed ratios; however it is increased considerably for dry processing conditions due to the less effective loop formation. As shown in Fig. 9.7, dry texturing also has a similar effect on breaking elongation, whereas the use of an impact ball results in approximately constant breaking elongation for the range of overfeed ratios tested.

Figs. 9.8 and 9.9 show that the linear density and instability of the textured yarn are slightly increased by using an impact element, but they are affected considerably by dry texturing, again due to less effective loop formation.

It can be concluded that the inferior textured yarns produced by dry texturing are caused by the poor texturing conditions due to high friction between the filaments themselves and between the filaments and the contacting parts. Wet texturing substantially improves the texturing conditions. Use of an impact element has a slight effect on the textured yarn properties, and this occurs particularly at high overfeed ratios.

9.5 Conclusions

The results of the yarn tests, in general, showed that the effects of process parameters on the yarn properties vary as predicted by the postulated loop formation mechanism, which was described in Chapter 8.
Although these test results may give some indication of the yarn properties, they afford only a limited indication of the textured yarn's suitability for particular end-uses. Among the examined properties, surface characteristics, such as loop size, loop frequency and physical bulk have still to be assessed and simple, quick and accurate methods for these tests have yet to be developed.
FIGURE 9.1: Tenacity at varying processing parameters

FIGURE 9.2: Breaking elongation at varying processing parameters
FIGURE 9.3: Linear density at varying processing parameters

FIGURE 9.4: Yarn instability at varying processing parameters
FIGURE 9.5: High-speed photographs of the filaments during texturing at varying texturing speed and corresponding yarns produced under respective texturing conditions.
FIGURE 9.6: Comparison of wet and dry processing and use of an impact ball on breaking elongation at varying overfeed ratio

FIGURE 9.7: Comparison of wet and dry processing and use of an impact ball on tenacity at varying overfeed ratio
FIGURE 9.8: Comparison of wet and dry processing and use of an impact ball on linear density at varying overfeed ratio

FIGURE 9.9: Comparison of wet and dry processing and use of an impact ball on yarn instability at varying overfeed ratio
CHAPTER 10

IMPROVEMENTS IN THE NOZZLE DESIGN

10.1 Desirable Characteristics of a Texturing Nozzle

In the light of the theoretical and experimental investigations, the desired characteristics of a texturing nozzle required for effective texturing can be summarised as follows:

An effective texturing nozzle should produce a supersonic, turbulent, asymmetric flow with a non-uniform velocity profile. Supersonic flow is required because the speeds of the filaments are mainly determined by the fluid forces acting on them; the faster the speed of the filaments, the more effective becomes the texturing process. An asymmetric and non-uniform velocity profile is required to provide differences between the forces acting on the filaments that are situated at different locations across the nozzle at any instant. This will enhance the relative longitudinal displacement of the filaments, which is an essential requirement of the loop formation process. Intense turbulence is also required, because it plays an important role in causing the filaments to change their positions across the nozzle.

The trumpet-shaped diverging exit contributes to the non-uniform distribution of the velocity at the exit plane of the nozzle by causing a central depression in the velocity distribution. This therefore enhances the variations between the forces acting on the filaments.

Shock waves, as discussed appear to have no effect on the filaments, and therefore are not essential requirements of the flow from a texturing nozzle; however they occur as a consequence of the supersonic flow.
The secondary flow reduces the effects of the primary flow; however it has a useful function of blowing the water away and preventing most of it being entrained into the nozzle. Therefore it is desirable to have it, but its flow rate and flow velocity should be kept at optimum levels to minimise its adverse effects on the primary flow.

The swirl observed in the flow in a standard core HemaJet appeared to cause the filaments to change their positions across the nozzle by rotating during the process. Therefore it should be among the factors that are considered in the nozzle design.

Friction between the filaments and any solid surfaces should be kept at a minimum level because it plays an important and yet undesirable role in counteracting the fluid forces acting on the filaments.

Separation of the filaments in the nozzle is another desired effect that should be created by a texturing nozzle, because this separation enhances the variations in the forces acting on them caused by a non-uniform flow velocity profile.

In the design and development of texturing nozzles one of the factors that should be considered is the compressed air consumption, the major contributor to the cost of the texturing process. Therefore in the attempts to design nozzles the goal was to reduce the compressed air consumption, without causing any reductions in its texturing effect.

10.2 Nozzle No.1: Asymmetric Double Inlet Nozzle

A greater asymmetry and non-uniformity in the velocity distribution was one of the objectives. Figs. 10.1a and b show the velocity distribution of the flows at the exit plane of the triple inlet cylindrical nozzle and the same nozzle with a trumpet-shaped
exit respectively. A comparison of these velocity distributions shows that trumpet-shaped exit contributes to the non-uniformity of the velocity distribution.

Figs. 10.2a and b show velocity distributions of the flows at the exit plane of a single and double inlet cylindrical nozzles nozzles respectively. These velocity distributions show that asymmetry and non-uniformity in the flow can be increased by an asymmetric configuration of the inlet bores, such as a single inlet nozzle. It also appears that the double inlet nozzle has also an increased non-uniformity when compared with the triple inlet nozzle.

These experiments with large scale nozzles showed that a texturing nozzle with asymmetric air inlet configuration with a trumpet shaped exit can produce the desired effects of texturing nozzles. Therefore the obvious choice appears to be a single inlet nozzle. On the other hand, filaments in such nozzles will be impinged on by an air-jet emerging from a single air inlet bore situated on one side of the texturing nozzle, and this may press the filaments against the opposite wall of the nozzle. Consequently the friction between the filaments and the nozzle internal surface may be increased. Therefore, a texturing nozzle with two inlet bores situated opposite to each other, and with different diameters to create the required asymmetry was thought to be an alternative solution. In addition, two opposing flows, when they impinge on the filaments, may contribute to the better separation of the filaments and reduce the friction.

Bearing in mind that the trumpet-shaped diverging exit exaggerates the non-uniformity in the flow, a nozzle having double inlet bores with different diameters and with a trumpet-shaped exit, was designed, as detailed in Fig. 10.3. This and two other nozzles (see Sections 10.3 and 10.4) designed by the author were made by the Heberlein Machine Works of Switzerland, for the present research. The exact geometry of the curved diverging exit, angle of inclination of the inlet bores, and their longitudinal positioning were made
identical to those of the HemaJet of the Heberlein. The compressed air consumption of this nozzle was $10 \, \text{m}^3 \, \text{hr}^{-1}$, a one sixth reduction over that of standard HemaJet; this was obtained by reduced area of inlet bores. The ratio of the inlet bore areas to the main flow duct area was kept similar to that of the HemaJet, hence a similar range of exit velocities was expected, as predicted by the mathematical model.

10.3 Nozzle No.2: High-swirl Nozzle

A limited swirl is imparted to the flow by the longitudinally staggered configuration of the standard HemaJet, and this caused the yarn to rotate during the process as observed by the high-speed cine-films. This swirl appeared to contribute to the movements of the filaments to change their positions in the nozzle which is a desired effect for effective texturing. A second nozzle, similar to Nozzle No.1 was designed specially to exaggerate this swirl by means of two air inlets of equal diameters but with an eccentricity as shown in Fig. 10.4 to test this hypothesis.

10.4 Nozzle No.3: Diverging Nozzle

Cylindrical texturing nozzles, having a straight uniform main flow duct with air inlets opening into it at an angle, are not the most efficient nozzles from the viewpoint of losses because of the sudden expansion of the flow to the wider main flow duct from the inlet bores. Converging-diverging nozzles with critical conditions at the throat (i.e., $M=1$) cause the flow to accelerate in the diverging part and hence supersonic flows ($M>1$) can be obtained. These nozzles when designed for complete expansion of the flow give the maximum velocity obtainable. On the other hand, cylindrical type texturing nozzles, despite their low efficiencies, may have positive effects in the texturing process owing to the configuration of the air inlets. Flows from these types of nozzle impinge on the
filaments and may cause them to separate, whereas the flow in a converging-diverging texturing nozzle does not possess this feature.

In the cylindrical texturing nozzles, the expansion of the flow in the main duct, is treated as an abrupt enlargement in the mathematical model which results in the predicted velocities as shown in Table 10.1 for varying pressure. If the flows from the inlet bores open to a duct where the primary flow area before expansion is equal to the duct cross-sectional area and the downstream part of the duct is in the form of diverging nozzle, as shown in Fig. 10.5, flow conditions that occur in a converging-diverging nozzle may be simulated. This assumes that the critical conditions reached at the throat of the inlet bores are not changed when several inlet jets are intermixed, as assumed in the mathematical model for cylindrical nozzles, and hence the primary flow accelerates in the diverging part from the critical conditions at the throat to create a supersonic flow. This nozzle, not only has the advantage of the inlet jets impinging on the filaments, but also has the additional merit of increased efficiency due to the reduced losses.

The mathematical model was modified to enable the exit velocities from such nozzles possessing a tapered diverging exit to be computed; and the results are compared in Table 10.1 with the corresponding velocities from cylindrical nozzles. The steady one-dimensional isentropic flow equations were employed and a complete expansion of the flow in the diverging part was assumed in these calculations. This comparison shows that higher velocities can be obtained with this diverging nozzle, particularly at lower pressures.

The complete expansion assumed in the theoretical calculations is obtainable at a particular pressure ratio, i.e., the ratio of the stagnation to the critical pressure, for a certain area ratio, which is also given in Table 10.1. Therefore a texturing nozzle designed to be used over a varying range of working pressures can give maximum efficiency at only one particular pressure. However, in practice this is very difficult to achieve because of the high precision.
required in the manufacture of such miniature nozzles to the
dimensions determined by the theoretical analyses. In addition,
filaments present in the nozzle during the texturing process may
alter the nozzle cross-sectional area and hence the correct area
ratio and consequently the complete expansion to give maximum
efficiency may not be achieved. By taking these factors into
account, the diameter of the main duct was made slightly larger than
that dictated by the throat areas, i.e., d=1.5 mm, as shown in Fig.
10.5.

A 3° (inclusive) conical diverging duct, without trumpet-shaped
exit, gives an area ratio of 1.9, which normally provides complete
expansion at about $10 \times 10^5$ N m$^{-2}$ when the critical flow condition is
reached at the throat. But the usual trumpet-shaped exit alters the
area ratio considered in the design analyses. However, this
introduces the desired effects of enhanced non-uniformity in the
velocity profile at the exit plane. Other design features are
similar to the previous designs. Furthermore this nozzle was
designed to give an air flow rate of $8 \text{ m}^3 \text{ hr}^{-1}$ providing a further
reduction in the air consumption, i.e., by one third when compared
with the standard HemaJet.

10.5 Testing of the Nozzles

Since the manufacture of such nozzles requires high precision
and specialised machine tools and skills, the workshop of the
Mechanical Engineering Department did not have this specialised
facility, hence these three nozzles were specifically made for the
use of the author by the Heberlein of Switzerland, and these
prototypes are shown in Fig. 10.6. Other designs were also
considered, such as: (i) a double inlet nozzle with different inlet
bore diameters and one of the air inlet bores nearer to the nozzle
exit in order to increase the asymmetry; (ii) a nozzle with smaller
inclination of the air inlet bores for a greater momentum in the
direction of the primary flow; and (iii) a single inlet bore nozzle
with a slight eccentricity to impart a small swirl into the flow. The high cost of manufacture of these prototype nozzles prevented the manufacture of all but 3 nozzles provided by Heberlein.

Preliminary tests showed that the high swirl nozzle (Nozzle No.2), with eccentric inlet holes to impart enhanced swirl into the flow, failed to texture because of the excessive twist inserted into the filaments.

Due to the lack of the specialised facilities of a textile laboratory, and time scale involved in the yarn tests, the other two nozzles were employed in trials of yarn tension measurements in the feed, delivery, and take-up zones since these indicate the level of the fluid forces acting on the filaments, the effectiveness of the texturing, and the stability of the loops, as defined in Section 5.3 respectively. These measurements were conducted with wetting at varying overfeed ratios; air pressure and texturing speed being $8 \times 10^5$ N m$^{-2}$ (gauge) and 400 m min$^{-1}$ respectively. The results of these measurements are compared with those of standard core HemaJet and with recently obtained single inlet HemaJet nozzle, as shown in Figs. 10.7 to 10.9. Compressed air consumptions of all four nozzles are also shown in Table 10.2.

Fig 10.7 shows that fluid forces acting on the filaments, as indicated by the tension in the feed zone, are higher for both asymmetric double inlet nozzle (No.1) and diverging nozzle (No.3) than the standard triple inlet HemaJet, despite the fact that these prototype nozzles consume less compressed air. The single inlet HemaJet exerts the least force on the filaments, but on the other hand it has the advantage of consuming the least compressed air among the four nozzles tested.

Fig. 10.8 shows that Nozzle No.1 and Nozzle No.3 compares favourably with both HemaJet nozzles from the viewpoint of the effectiveness of texturing, as indicated by the tension in the delivery zone. Similar results were also obtained in the stabilising
zone (Fig. 10.9), except the stability of the loops as produced by the standard core HemaJet are slightly higher than those produced by Nozzle No. 3.

10.6 Discussion and Conclusions

These trials with the specified 175 dtex 66 filament polyester yarn (Table 5.1), in general, indicate that the prototype nozzles, with reduced compressed air consumptions, produce yarns comparable with those produced by standard HemaJet. Trials also indicate that both of the prototype nozzles are also considerably superior to the single inlet HemaJet. An extensive study of the properties of the yarns produced by these nozzles could provide useful information for the better comparison of these nozzles.

The trials with the prototype nozzles proved that the compressed air consumption of the texturing nozzles can be reduced without deteriorating their efficiency in texturing. Hence, reduced compressed air consumption results in reductions in the cost of yarn texturing, thereby causing the productivity of the process to rise. The design of these nozzles can be further improved in the light of the findings of the investigations and the knowledge gained with the trials of the prototype nozzles.
### TABLE 10.1

Comparison of the cylindrical and diverging nozzle velocities as predicted by the mathematical model.

<table>
<thead>
<tr>
<th>Stagnation pressure (abs) $10^5$ N m$^{-2}$</th>
<th>Axial velocity at the nozzle exit plane, (m s$^{-1}$)</th>
<th>Area ratio (diverging)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cylindrical</td>
<td>Diverging</td>
</tr>
<tr>
<td>10</td>
<td>524</td>
<td>529</td>
</tr>
<tr>
<td>9</td>
<td>503</td>
<td>520</td>
</tr>
<tr>
<td>8</td>
<td>479</td>
<td>510</td>
</tr>
<tr>
<td>7</td>
<td>451</td>
<td>479</td>
</tr>
<tr>
<td>6</td>
<td>417</td>
<td>482</td>
</tr>
<tr>
<td>5</td>
<td>375</td>
<td>462</td>
</tr>
<tr>
<td>4</td>
<td>324</td>
<td>435</td>
</tr>
</tbody>
</table>

### TABLE 10.2

Comparison of the compressed air consumptions of the prototype nozzles with those of the HemaJet nozzles.

<table>
<thead>
<tr>
<th>Nozzle type:</th>
<th>Compressed air consumption:</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1: asymmetric double inlet</td>
<td>10 m$^3$ hr$^{-1}$</td>
</tr>
<tr>
<td>No.2: diverging</td>
<td>8 m$^3$ hr$^{-1}$</td>
</tr>
<tr>
<td>HemaJet (standard core)</td>
<td>12 m$^3$ hr$^{-1}$</td>
</tr>
<tr>
<td>HemaJet single inlet</td>
<td>6 m$^3$ hr$^{-1}$</td>
</tr>
</tbody>
</table>
FIGURE 10.1: Velocity distribution of the flow at $6 \times 10^5 \text{ N m}^{-2}$ (abs) at the exit plane of (a) the triple inlet cylindrical nozzle; and (b) the same nozzle with a trumpet-shaped exit.
FIGURE 10.2: Velocity distribution of the flow at $6 \times 10^5$ N m$^{-2}$ (abs) at the exit plane of (a) the double inlet cylindrical nozzle; and (b) single inlet cylindrical nozzle.
FIGURE 10.3: Nozzle No. 1: Asymmetric cylindrical nozzle having double inlet bores with different diameters.

Scale: 5:1
All dimensions in mm.
Scale: 5:1
All dimensions in mm.

FIGURE 10.4: Nozzle No. 2: High-swirl nozzle having eccentric double inlet bores with equal diameter
FIGURE 10.5: Nozzle No. 3: Texturing nozzle possessing a conical diverging exit and double inlet bores with different diameters.

Scale: 5:1
All dimensions in mm.
FIGURE 10.6: Prototype texturing nozzles
FIGURE 10.7: Comparison of tension in the feed zone indicating the drag force acting on the filaments: (a) Nozzle No. 1; (b) Nozzle No. 3; (c) Standard HemaJet; (d) Single inlet HemaJet
DELIVERY ZONE:
- Nozzle No.1: asymmetric double inlet
- Nozzle NO.3: diverging
- HemaJet (standard core)
- HemaJet single inlet

FIGURE 10.8: Comparison of tension in the delivery zone indicating the effectiveness of

texturing: (a) Nozzle No. 1; (b) Nozzle No. 3; (c) Standard HemaJet;
(d) Single inlet HemaJet
FIGURE 10.9: Comparison of tension in the stabilising zone indicating the stability of the loops: (a) Nozzle No. 1; (b) Nozzle No. 3; (c) Standard HemaJet; (d) Single inlet HemaJet.
CHAPTER 11

SUGGESTIONS FOR FURTHER WORK

11.1 Nozzle Design

Of the three nozzles designed and tested on the texturing machine, two proved to be successful in producing yarn and in reducing compressed air consumption to about 8 m³ hr⁻¹. A more comprehensive range of test of the yarns produced by these nozzles should be undertaken in a textile testing laboratory.

Trials of a wider range of texturing nozzles (see Section 10.5) were hindered by the lack of facilities in the Mechanical Engineering workshops to manufacture prototype nozzles and the costs involved in having them manufactured externally. In the light of the theoretical and experimental investigations, and with the knowledge gained from the nozzles that were manufactured even more efficient nozzles could be designed which might be produced with the co-operation of an external manufacturing organisation. The author suggests that such collaboration between the university and industry should be encouraged by both parties.

11.2 Further Investigations of the Air Flow

Compressed air available in the Mechanical Engineering laboratories made it possible to conduct experiments with the scaled-up models up to a pressure of 7×10⁵ N m⁻² (abs). Further experiments could be conducted at higher pressures if this can be made available.

It was theoretically shown that effects of wetting the filaments during the texturing played a negligible role in affecting the flow properties (Chapter 7). Additional experiments are required to
verify the theoretical predictions. This would require the design and construction of a special test rig to facilitate flow measurements in simulated wet texturing conditions.

The existence of the filaments in the texturing nozzle may reduce the flow velocity and increase the turbulence level, as discussed in Section 4.8. Experiments with the filaments inside the nozzle have so far failed to produce results. An investigation of the effects of the filaments on the air flow could also be undertaken on a specially designed experimental rig to simulate the existence of the filaments in the nozzle.

11.3 High-speed Photography

High-speed cine films taken at 20 000 fps, provided useful information about the stability of the process and the effects of wet texturing, but failed to freeze the motion of the filaments. The motion can be analysed with high-speed image convertor cameras, such as the Imacon 790 (Hadland Photonics Limited, UK) which is capable of producing 16 consecutive frames at speeds of up to $2 \times 10^7$ pictures per second.

Behaviour of the filaments inside the nozzle could not have been observed. A study into the techniques to make this investigation feasible could be a useful contribution to the understanding of the effects of impinging jets on the filaments and of their behaviour inside the nozzle.

11.4 Realigned Yarn Path

A new texturing arrangement involving realigning the yarn path, as discussed in Chapter 7, to reduce the friction between the filaments and the solid surfaces, enabled considerable improvements in the texturing process to be achieved as indicated by the tension
measurements in the feed, delivery, and stabilising zones. Extensive yarn tests should be undertaken in a textile testing laboratory to study the improvements that this arrangements could bring to the texturing process.

11.5 Wetting the Filaments

Only a small amount of water needed is in the texturing process, as discussed in Sections 7.2 to 7.4, to impart the desired effects of wetting. The resultant properties of yarns textured under such minimal wetting conditions could be usefully analysed and compared with those of the yarns made by the higher amounts of water, typical of current industrial practice. In addition, a reduction in total water consumption could also reduce the inherent undesirable effects of wetting. Effects of wetting agents mixed into the water and wetting with other liquids could also be studied.

Trials with the two-chamber nozzle-enclosure showed that most of the water remained in chamber 2 at the yarn feed side of the nozzle causing a relatively dry environment in the texturing side, chamber 1, as discussed in Chapter 7. Hence the proportion of the water absorbed by the yarn is likely to be reduced, however a detailed examination of moisture in the produced textured yarn had yet to be undertaken. This also could be investigated extensively in a textile testing laboratory equipped with air conditioned atmosphere and moisture analyser.

11.6 Filament Properties

It has been suggested that filaments with elliptical and hollow circular cross-sections might be more suitable for the air-jet texturing process (Chapter 6), however such yarns were not available in quantities for texturing. The work was constrained to just one yarn type and the effects of the properties of other types supply
yarn, for example the number of filaments and the filament linear density on the properties of the resultant yarn should be analysed with a collaboration between a textile research institution and a major fibre producer company.

Early research\(^4^8\) into the properties of the filaments resulting from being textured at speeds of about 50 m min\(^{-1}\) and at low pressures, by using relatively coarse filaments, showed that the individual filament properties were not affected by the texturing process. In today's modern texturing technology finer filaments are used at higher texturing speeds in the region of 500 m min\(^{-1}\). Current texturing nozzles has seen considerable improvement to provide a more violent air stream. Research should be conducted to analyse the physical properties of the individual filaments when subject to the aggressive conditions of modern texturing.

### 11.7 Yarn Surface Characteristics

The surface characteristics of the air-jet textured yarns, including loop frequency and loop size are significant factors in determining the yarn quality. Test methods to determine such properties are dependent on the visual inspections or on counting and measuring the loops under a microscope, which is a tedious work even for laboratory investigations. A quick but reliable method to determine the surface characteristics of air-jet textured yarns needs to be developed and, for this purpose, an SERC supported project was commenced in November 1983 in the Department of Mechanical Engineering, Loughborough University of Technology.

Test to measure the yarn instability, which is a measure of tendency for loops to be pulled out under applied tension, may give very high stability for the yarns with very few loops which are not acceptable for most textile end uses. Loop instability gives a misleading measure of yarn quality and, therefore, methods of relating the loop frequency and loop frequency to the instability...
should be developed for a better assessment of the yarn quality for specific end-uses.
APPENDIX A

THE EXPERIMENTAL SINGLE-HEAD TEXTURING MACHINE

Fig. A1 shows the single-head texturing research machine (see also Fig. 2.2) that the author designed and developed according to the principles described in Section 2.1. The intended research programme requires a machine to the following specifications:

i) it should be capable of higher running speeds than today's practical texturing speeds, and facilitate experimentation at these high speeds;

ii) its texturing speed should be adjusted by stepless variable speed controls;

iii) the speeds of each of its feed, delivery, and take-up rollers, as well as that of the take-up unit should be adjustable individually in order to give a greater versatility to the speed ratios;

iv) it should be capable of texturing single, parallel, and core and effect yarns; and

v) it should be usable with any type of texturing nozzle.

A variable speed motor/controller unit is used to drive the machine which enables it to run at any texturing speed up to 750 m min⁻¹. Individual cone-drum type gear boxes are used for the feed and take-up rollers and for the take-up unit, but the delivery roller W2 is driven directly by gearing from the motor and this determine the texturing speed. Gear boxes provide adjustments of speed ratios i.e., overfeed ratios up to 50% for the feed rollers W1.1 and W1.2, and ±25% for the take-up rollers W3 and the take-up unit WW. An electronic tachometer unit with digital displays is used to measure
the speeds of each delivery roller and take-up unit as well as to display the ratios of their relative speeds to the texturing speed. Hence, the two possible overfeed ratios and stabilising ratio can be read directly from this unit.

A compressor which is capable of delivering the required volume of air, up to 16.6 m$^3$ hr$^{-1}$, at a maximum pressure of $10 \times 10^5$ N m$^{-2}$ (gauge) is used to supply compressed air to the texturing nozzle. This air is first passed through an air dryer unit to reduce the water content and then through filters to remove any particles larger than 0.01 micron. The air pressure is controlled and monitored by means of pressure regulators and gauges before it is fed into the nozzle. The amount of air used is measured by a rotameter.

Clean water from the cooling plant is used to wet the filaments, the amount of which is also measured by a rotameter.
FIGURE A1: Purpose built experimental single-head air-jet texturing machine
APPENDIX B

LISTING OF THE COMPUTER PROGRAM FOR THE MATHEMATICAL MODEL

The following programme was written in Apple Soft Basic to run on a 48K Apple/II Computer and deals with the mathematical model for the cylindrical nozzles developed in Chapter 3. It also includes the theory to cover the nozzles with conical diverging exit, as discussed in Chapter 10.

The nomenclature adopted in this routine varies slightly from that adopted in the main theory on account of the limited variable descriptors available in this language, but where possible, original variables have been used.

The programme is laid out as a set of consecutive segments each dealing with a separate aspect of the model which is described in the remark statements preceding each section.

Four levels of flow complexity are considered, and stagnation conditions for each situation are input to the routine in an interactive manner. The main parameters of the model are displayed during the course of the calculation which results in the flow properties at the nozzle exit planes for both the primary and the secondary flows.
100 PI = 4 * ATN (1)
500 REM *****************************************************
502 REM REM PROPERTIES OF AIR
504 REM 508 REM *****************************************************
510 REM 515 RR = 287.04: REM "RR" IS GAS CONSTANT
520 GA = 1.4: REM "GA" IS SPECIFIC HEAT RATIO FOR AIR
525 GA = GA / (GA - 1)
530 CP = GP * RR: REM "CP" IS SPECIFIC HEAT RATIO AT CONSTANT PRESSURE
535 CV = CP / GA: REM "CV" IS SPECIFIC HEAT RATIO AT CONSTANT VOLUME
540 REM 544 REM *****************************************************
546 REM REM PROPERTIES OF WATER
548 REM 550 REM *****************************************************
550 CS = 1863.1: REM "CS" IS SPECIFIC HEAT FOR WATER
559 REM 560 REM *****************************************************
562 REM REM NOZZLE GEOMETRY
564 REM 566 REM *****************************************************
566 DC = 0.9E - 3: REM "DC" IS THROAT DIA. OF INLET BORES IN "MM"
570 CA = PI * DC ^ 2 / 4
575 DN = 2E - 3: REM "DN" IS NOZILE MAIN DUCT DIA. IN "M"
580 NA = PI * DN ^ 2 / 4
585 TH = 48: REM "TH" IS ANGLE OF INLET BORES IN "DEGREES"
590 NI = 3: REM "NI" IS NO. OF INLET BORES
595 GNI = NI * DC ^ 2
600 IF (GNI > NA) THEN END
604 REM *****************************************************
608 REM REM ATMOSPHERIC (AMBIENT)
610 REM 615 DC = 0.9E - 3:
617 REM "DC" IS THROAT DIA. OF INLET BORES IN "MM"
620 CA = PI * DC ^ 2 / 4
625 DN = 2E - 3: REM "DN" IS NOZILE MAIN DUCT DIA. IN "M"
630 NA = PI * DN ^ 2 / 4
635 TH = 48: REM "TH" IS ANGLE OF INLET BORES IN "DEGREES"
640 NI = 3: REM "NI" IS NO. OF INLET BORES
645 GNI = NI * DC ^ 2
650 IF (GNI > NA) THEN END
659 REM *****************************************************
663 REM REM STAGNATION CONDITIONS
667 REM 670 PA = 1.0133E5: REM "PA" IS AMBIENT PRESSURE IN "N/M^2"
675 TA = 293: REM "TA" IS AMBIENT TEMP. IN "K"
680 RA = PA / (RR * TA): REM "RA" IS DENSITY OF AMBIENT AIR, IN "KG/M^3"
685 REM 690 REM *****************************************************
694 REM REM STAGNATION CONDITIONS
698 REM 702 REM *****************************************************
706 REM 707 REM *****************************************************
710 PA = 1.0133E5: REM "PA" IS AMBIENT PRESSURE IN "N/M^2"
715 TA = 293: REM "TA" IS AMBIENT TEMP. IN "K"
720 RA = PA / (RR * TA): REM "RA" IS DENSITY OF AMBIENT AIR, IN "KG/M^3"
725 REM 730 REM *****************************************************
734 REM REM STAGNATION CONDITIONS
738 REM 746 REM *****************************************************
748 REM 752 REM *****************************************************
756 REM 760 REM *****************************************************
764 REM 772 REM *****************************************************
776 REM 780 REM *****************************************************
784 REM 792 REM *****************************************************
796 REM 800 REM *****************************************************
808 REM 816 REM *****************************************************
824 REM 832 REM *****************************************************
840 REM 848 REM *****************************************************
856 REM 864 REM *****************************************************
872 REM 880 REM *****************************************************
782 \( \text{A0} = \sqrt{\text{QR}} (\text{GA} \times \text{RR} \times \text{T0}) \)
785 PRINT
786 PRINT "-----------------------------"
788 PRINT "STAGNATION CONDITIONS:
790 PRINT "-----------------------------"
792 PRINT "P0 = \text{P0} / 1E5" BAR (ABS.)"
795 PRINT "T0 = \text{T0} " K", \text{R0} = \text{R0}" KG/M^3"
800 GOSUB 2000
900 PRINT "ENTER A NUMBER BETWEEN 0 AND 3"
922 PRINT 
904 PRINT 
905 PRINT " 0 : FOR AIR ONLY"
910 PRINT " 1 : FOR AIR-WATER MIXTURE"
915 PRINT " 2 : FOR AIR-FILAMENTS MIXTURE"
925 INPUT 
930 \text{ON IS GOSUB 3500,4000,4500 }
950 GOSUB 3000
965 \text{B1 = NA / AP}
970 \text{B2 = NA / AS}
975 \text{M} = 1
990 REM "SUBROUTINE THROAT"
1000 PRINT "ENTER 1 OR 2"
1005 PRINT "**********************"
1010 PRINT "1 : FOR TUBULAR"
1020 PRINT "NOZZLES": PRINT
1030 PRINT "2 : FOR DIVERGING"
1040 PRINT "EXIT"
1050 INPUT " IS IN IN GOSUB 5000,7000
1195 END
1998 REM "**********************"
2000 REM "SUBROUTINE THROAT"
2001 REM "C.V.1"
2002 REM "**********************"
2005 REM "PCR = (2 / (GA + 1)) * SQR(2 * \text{SQR})" + \text{SQR}
2020 \text{TCR} = (2 / (GA + 1)) \times \text{T0}
2030 \text{RCR} = (2 / (GA + 1)) \times (1 / (GA - 1)) \times \text{R0}
2050 \text{ACR} = \text{A0} \times SQR(2 / (GA + 1))
2060 \text{VCR} = \text{ACR}
2070 \text{WCR} = \text{ACR} \times \text{CA} \times \text{VCR}
2080 \text{QCR} = \text{WCR} / \text{RA}
2092 PRINT "-----------------------------"
2095 PRINT "CRITICAL CONDITIONS:": PRINT "-----------------------------"
2096 PRINT "VC="VC" M/S"
2097 PRINT "PC="PC" / 1E5" BAR"
2100 PRINT "RC="RC" KG/M^3"
2105 PRINT "TC="TC" K"
2110 REM "\text{WCR} IS MASS FLOW RATE FOR ONE INLET JET IN KG/S"
2120 \text{TW} = \text{NI} \times \text{WCR}: \text{REM} "\text{TW} IS TOTAL MASS FLOW RATE IN KG/S"
2130 REM "\text{QCR} IS VOLUME FLOW RATE FOR ONE INLET JET IN M^3/S"
2140 \text{TO} = \text{NI} \times \text{OCR}: \text{REM} "\text{TO} IS TOTAL VOLUME FLOW RATE IN M^3/S"
2150 DHR = TO * 3600
2200 PRINT "TW="TW" KG/S"
2210 PRINT "TO="TO" M^3/S"
2220 PRINT "DHR="DHR" M^3/HR"
2250 PRINT
2900 RETURN
2998 REM ****************************
2999 REM
3000 REM SUBROUTINE INCmix
3001 REM
3002 REM C.V.2
3003 REM
3005 REM ****************************
3010 AP = (NI / 2) * CA * (1 + COS (PI * TH / 180))
3015 REM "AP" IS PRIMARY JET AREA
3020 AS = (NI / 2) * CA * (1 - COS (PI * TH / 180))
3025 REM "AS" IS SECONDARY JET AREA
3030 PRT = AP / (NI * CA)
3032 REM "PRT" IS RATIO OF PRIMARY AREA TO THE TOTAL AREA OF INCOMING JETS (I LET BORES)
3035 SRT = AS / (NI * CA)
3037 REM "SRT" IS RATIO OF SECONDARY AREA TO THE TOTAL AREA OF INCOMING JETS
3040 WP = PRT * TW
3045 WS = SRT * TW
3047 REM "WP" AND "WS" ARE MASS FLOW RATE OF PRIMARY AND SECONDARY FLOWS RESPECTIVELY
3049 PRINT "--------------------"
3050 PRINT "JET MIXING (C.V.2):"; PRINT "--------------------"
3055 PRINT
3500 REM SUBROUTINE WATER
3502 REM EFF ECTS
3505 REM
3510 REM ****************************
3515 REM
3550 INPUT "ENTER WATER FLOW RATE IN (KG/HR)";WS
3555 REM "TW" IS THE MASS FLOW RATE IN (KG/S)
3560 REM "WR" IS THE RATIO OF WATER MASS TO AIR MASS FLOW RATE
3570 WR = WS / (TW * 3600)
3580 RR = RR / (1 + WR)
3590 GA = (CP + WR + CS) / (CV + WR + CS)
3595 GF = GA / (GA - 1)
3600 REM SUBROUTINE FILAMENT EFFECTS
4000 REM
4005 REM "WF" IS THE MASS FLOW RATE OF THE FILAMENTS
4010 REM ENTER THE OVERFEED RATIO IN (%)": OF
4020 INPUT "ENTER THE YARN LINEAR DENSITY IN (TEX, 'G/KM')":TX
4120 WF = ((1 + OF) * SP * TX / 60) * 1E - 3
4140 WR = WF / (TW * 1E3)
4150 RR = RR / (1 + WR)
4200 RETURN
4500 REM SUBROUTINE WATER+FIL'S COMBINED EFFECT
4550 GOSUB 3500
4555 GOSUB 4000
4600 RETURN
4998 REM *************
4999 REM
5000 REM SUBROUTINE ABR.ENL.
5001 REM C.V.3
5002 REM
5003 REM ************
5004 PRINT
5050 PRINT "PROPERTIES OF PRIMARY AND SECONDARY FLOW"
5055 PRINT "-----------------------------------------
5060 PRINT "MP IS = "MP
5065 PRINT "MS IS = "MS
5070 PRINT "TP = "TP,"TS = "TS
5075 PRINT "PP = "PP,"PS = "PS
5085 PRINT
5110 F11 = AP / NA
5120 F2I = AS / NA
5130 MP = 1.01
5140 MD = MP
5150 GS = SQR ((2 + (GA - 1) * MP ^ 2) / (2 + (GA - 1) * M ^ 2))
5160 MP = (PC / PA) * F11 * M / GS
5170 IF ABS (MD - MP) < 1E - 3 GOTO 5190
5180 GOTO 5140
5190 PRINT ; PRINT "MP IS = "MP
5200 MS = 1.01
5210 MD = MS
5220 GS = SQR ((2 + (GA - 1) * MS ^ 2) / (2 + (GA - 1) * M ^ 2))
5230 MS = (PC / PA) * F2I * M / GS
5240 IF ABS (MD - MS) < 1E - 3 GOTO 5270
5250 GOTO 5210
5270 PRINT "MS IS = "MS
5310 X = 2 + (GA - 1) * M ^ 2
5320 X = 2 + (GA - 1) * M ^ 2
5330 X = 2 + (GA - 1) * MS ^ 2
5340 TP = (XC / XP) * TC
5350 TS = (XC / XS) * TC
5355 PRINT
5360 PRINT "TP = "TP,"TS = "TS
5370 PP = (1 / G1) * (M / MP) * (XC / XP) * PC
5375 PP = PA
5380 PS = (1 / G2) * (M / MS) * (XC / XS) * PC
5385 PS = PA
5390 PRINT "PP = "PP,"PS = "PS / 1E5
5400 VP = MP * SQR (GA * RR * TP)
5410 VS = MS * SQR (GA * RR * TS)
5420 PRINT "VP = "VP,"VS = "VS
5430 RP = (PP / PC) * (TC / TP) * RC
5440 RS = (PS / PC) * (TC / TS) * RC
5450 PRINT "RP = "RP,"RS = "RS
5460 A1 = SQR (GA * RR * TP)
5470 A2 = SQR (GA * RR * TS)
5490 PRINT
5500 K1 = (F11 / (1 - F11)) * SQR (1 + GA)
5510 K1 = (F2I / (1 - F2I)) * SQR (1 + GA)
5520 K2 = 1 + GA * MP ^ 2
5530 L2 = 1 + GA * MS ^ 2
5540 K3 = MP * SQR (2 + (GA - 1) * MP ^ 2)
5550 L3 = MS * SQR (2 + (GA - 1) * MS ^ 2)
K4 = SQR (1 + GA)
L4 = K4
R1 = K1 * (K2 / K3 - K4)
R2 = L1 * (L2 / L3 - L4)

PRINT "SUPERCRITICAL RATIO:": PRINT "---------------------"
PRINT "SCRP=" R1, "SCRS=" R2
PRINT "STEP LOSS:": PRINT "---------------------"
PRINT "RTOTP1=" LP; "RTOTP2=" LS
RETURN

REM SUBROUTINE LAVAL
PR = PA
PP = PA

VP = ((2 * GA * RR * T0 / (GA - 1)) * (1 - PR)^((GA - 1) / GA))^0.5
MP = ((2 / (GA - 1)) * ((1 / PR)^((GA - 1) / GA) - 1))^0.5

AP = VP / MP
TP = T0 * AP^2 / A0^2

RETURN

PR = PA / (RR * TP)

PRINT "TP="TP
PRINT "PP="PP / 1E5
PRINT "VP="VP
PRINT "ROF="RP
PRINT "AP="AP
PRINT "AREA RATIO="EP
PRINT "NOZZLE RATIO PRIMARY="E1
PRINT "NOZZLE RATIO SECONDARY="E2
RETURN
APPENDIX C

CALCULATION OF THE FLOW VELOCITY BY USING PITOT TUBES IN SUBSONIC AND SUPERSONIC FLOWS

Stagnation pressures as measured by pitot tubes in subsonic and supersonic flows can be used to calculate flow velocities in the axial direction, as discussed by Massey. The process by which the fluid is brought to rest at the nose of a pitot tube is assumed to be frictionless and adiabatic. For subsonic flows (Fig. C1) then:

\[ \frac{v_2}{2} = C_p (T_o - T) = C_p T_o \left[ 1 - \frac{(p/p_o)}{(\gamma - 1)/\gamma} \right] \quad (C.1) \]

where the suffix 'o' refers to stagnation conditions.

If \( T_o \) and ratio \( (p/p_o) \) of static to stagnation pressures are both known, then the velocity of the stream may be determined.

For supersonic flows, a shock wave forms ahead of the pitot tube (Fig. C2). If the axis of the pitot tube is parallel to the oncoming flow, the shock wave may be assumed normal to the stream line leading to the stagnation point, then the pressure rise across the shock is given by:

\[ \frac{(P_o)_2}{P_1} = \left[ \frac{(\gamma + 1)\gamma/((2\gamma M_1^2 - \gamma + 1))}{[M_1^2]} \right] (\gamma - 1) \quad (C.2) \]

This equation enables the upstream Mach number, \( M_1 \), to be calculated from the ratio of downstream stagnation pressure \( (P_o)_2 \) to the upstream static pressure \( (p_1) \). Since the stagnation temperature does not change across the shock wave, then:
Thus $V_1$ may also be calculated if $T_0$ is known. Therefore the downstream stagnation pressure, $(P_0)_2'$, stagnation temperature, $T_0'$, and upstream static pressure, $p_1'$, are required to be measured.

In the application of this method to a free jet, when it is not practicable to measure the static pressure, it can be assumed that the static pressure is atmospheric.

\[ C_p T_0 = C_p T_1 + V_1^2/2 = C_p \left( V_1^2/R M_1^2 \right) + V_1^2/2 \quad (C.3) \]

FIGURE C1: Pitot tube in a subsonic flow

FIGURE C2: Pitot tube in a supersonic flow
Homogeneous flow theory, as discussed by Wallis\textsuperscript{58}, provides a technique for analysing steady one dimensional flow involving a gas carrying suspended particles, either solid or liquid, or both. Suitable average properties are determined and the mixture is treated as a pseudo-fluid that obeys the usual laws of a single-component flow. All of the standard methods of fluid mechanics can then be applied. The average properties which are required are velocity, thermodynamic properties, e.g., temperature and density, and transport properties, e.g., viscosity.

The following assumptions are applicable to a steady one dimensional gas flow carrying suspended condensed particles:

i) flow is steady and one dimensional;
ii) there is no heat, mass, and momentum transfer with the nozzle walls;
iii) there is no phase change and chemical reaction;
iv) the effect of gravity is negligible;
v) particles occupy negligible volume and are discrete, i.e., they do not interact with each other;
vi) particles have a uniform internal temperature and are incompressible;
vii) variations in particle size and shape are negligible.

Differences in velocity and temperature between the phases will promote mutual momentum and heat transfer. Often these processes proceed very rapidly, particularly when one phase is finally dispersed in the other, and it can be assumed that equilibrium is reached. For a homogeneous equilibrium flow, the average values of velocity and temperature are the same as the values for each component, i.e.,
\[ v_p = v_g = v \]
\[ T_p = T_g = T \]

where \( s \) and \( g \) denote particles and gas respectively.

The mixture behaves as a pseudo-gas with the following weighed average properties in terms of the relative mass fraction of the particles:

\[ R' = \frac{R_g}{1 + m_s} \]

\[ C = \frac{C_{pg} + m_s C_s}{1 + m_s} \]

\[ \gamma' = \frac{C_{pg} + m_s C_s}{C_{vg} + m_s C_s} \]

where

- \( R' \): gas constant for the mixture
- \( R_g \): gas constant for the specific gas
- \( m_s \): mass ratio of the particle to the gas
- \( C_{pg} \): specific heat of the gas at constant pressure
- \( C_{vg} \): specific heat of the gas at constant volume
- \( C_s \): specific heat of the particles
- \( C' \): specific heat of the mixture at constant pressure
- \( \gamma' \): specific heat ratio of the mixture

All of the conventional one-dimensional compressible flow equations apply provided that the above parameters are inserted in place of the gas properties. The sonic velocity is

\[ a = (\gamma' R' T)^{1/2} \]

and is less than the sound velocity in the gas alone.
REFERENCES


