Supersonic jet texturing of yarns (76th Thomas Hawksley Lecture)

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Supersonic jet texturing of yarns

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Almost all aspects of textile production increasingly feature the application of fluid jets and this paper reviews some of these in connection with the specific field of synthetic filament processing, for example the mingling or interlacing of false-twist textured yarns and the hot fluid texturing process for carpet pile yarns. Particular attention is then given to the texturing of filaments by cold air jets operating at supersonic speeds in view of the two authors' considerable advancements of knowledge in this growingly significant field of application for the man-made fibres.

1 PREFACE
Thomas Hawksley FRS, born in Nottingham in 1807, was President of the Institution of Mechanical Engineers in 1876 and the first Thomas Hawksley Memorial Lecture was presented at the Institution in 1913. Since then 75 Lectures have covered a wide diversity of subjects which have amplified the ever-continuing changes in mechanical engineering and its underlying science. It is fitting to remember that Thomas Hawksley had the width of vision of a true engineer in that he was responsible for the evolution and management of major projects that helped to create wealth. His greatest contribution was concerned with the adequate supply of water to most of this country's growing industrial regions, but particularly to the cities of Liverpool, Sheffield and Leicester. The supply of pure water has topical relevance today with the current trends of changes of ownership and the higher environmental requirements in order to meet EC standards. Water is, of course, fundamental to all life and has also seen many industrial applications. The other fluid in this category is air and, therefore, the authors consider it a great honour to be invited to give this lecture in commemoration of this notable engineer of the last century.

2 INTRODUCTION
Fluid jets play a highly significant role in many aspects of textile production and find specialized applications in almost all yarn and fabric manufacturing processes. For instance, they are used in such modern developments as synthetic yarn manufacture, automatic winding machines, air-jet spinning, fluid-jet weaving, weft knitting, multi-filament mingling (interlacing), yarn splicing, fabric dyeing and finishing machines, and the air-jet texturing of filament yarns.

The air-jet texturing process, which has evolved over the past 30 years, is a purely mechanical yarn texturing technique that is used to convert the parallelly arranged continuous multi-filament yarns, not suitable for most textile manufacturing processes, into much more acceptable yarn structures with enhanced visual and tactile qualities, such as higher insulation, greater covering power, increased comfort and improved texture. The process therefore has high relevance in the international textile industry. Most other existing texturing techniques are based on the good thermoplastic properties of synthetic yarns, such as polyamides, polyesters, polycrylenes and acrylics, whereas the air-jet texturing process is not so restricted by the yarn material and can therefore also be used with an almost limitless variety of multi-filament yarns, including glass, rayons and all other regenerated filament yarn types.

The mechanical nature of the process, together with the complicated supersonic airflow, has made its study an important and challenging project. This lecture will briefly describe the various texturing processes that use fluid-jets and will then summarize the ongoing air-jet texturing research undertaken by Dr Acar at Loughborough University of Technology during the 1980s, which was a continuation of Professor Wray's pioneering researches at UMIST some thirty years earlier.

The authors have tackled their joint researches in various stages. Initially, an extensive study of flow measurements with scaled-up nozzles and sample nozzles from industry was carried out to establish an understanding of the flows in such texturing jets. A flow visualization laser shadowgraph technique was used to study the nature of the flow. High-speed still- and cine-photography techniques were also used to analyse the airflow-filament interactions. A mathematical model of the flow was then developed as a tool to be used in further nozzle designs. Indeed, based on the results obtained from these research findings, the energy losses during the expansion of the flows in the nozzles were reduced and more effective nozzles, which can achieve higher air velocities at lower operating pressures, have been designed and are in current industrial use.

3 THE REASONS FOR THE DEVELOPMENT OF TEXTURED YARNS
Textile manufacture was the first mechanized industry. Consequently, it was not surprising that by the middle of the nineteenth century the machines for processing cotton and wool staples had achieved a high degree of efficiency. It is true to say that they have shown very little change in principle over the subsequent years—for
example, the machinery for performing the basic operations of opening, carding, combing, drafting and twisting have altered only in detail during the last century. Nevertheless, the exciting developments that have occurred during this century in the field of man-made fibres have heralded great changes in yarn production techniques which have made them more effective as competitors with the conventionally spun yarns from the natural staples. The elimination of opening, carding and combing processes is now an established reality in certain types of tow conversion machinery. Moreover, the process of texturing, that is the simulation of a spun yarn by a modified filament structure, has given a new impetus to all sections of the industry. Such developments have been very rapid and modern yarn production is no longer constrained by the traditional methods of the past.

When the first regenerated cellulosic filaments, that is the viscose, acetate and cuprammonium rayons, were introduced some hundred years ago, they were in continuous filament form; the only natural fibre that was expected to feel any competition was silk and hence their early designation by the generic term 'artificial silks'. By virtue of their lower cost, the rayons won a substantial share of silk's markets, particularly in the fields of fine hose and underwear. In addition, they made new markets by creating a popular demand among those who had never been able to afford the beautiful but expensive garments and fabrics made from the natural filament. Nevertheless, the smooth, lustrous filament rayons were unable to replace the hairier, warmer and less transparent yarns spun from the natural staples, such as cotton, wool and flax, until the early 1930s when rayon staples were introduced in lengths cut suitably for processing into yarns of conventional spun construction on machines used for processing the natural staple fibres. Although it now may seem to have been an entirely illogical step to constrain such clean, parallel fibres to machinery designed originally to suit a particular type of natural staple fibre with inherent uncontrollable properties such as fixed length and fineness, and high impurity contamination, the decision was obviously made on the grounds of convenience and expediency. The existence of ready-made machinery for treating staples enabled the characteristics of the spun rayon yarns to become known and appreciated and also offered the possibility of blends with the natural fibres. Later, when the truly synthetic fibres (such as nylon and polyester) made their entrance around the time of World War II, they followed rayon's precedent by being made available in both filament and staple form but their unique characteristics further accentuated the trend towards completely new methods of yarn manufacture. Most modern synthetic fibres have thermoplastic properties, and this is a feature that offers the greatest scope for most of the new texturing techniques.

The wide differences in the properties and appearances between filament yarns and spun yarns at first prevented the former from competing effectively in most fields, but the texturing or 'bulking' of the filament structure by simple mechanical or chemical distortion has enabled a staple spun yarn to be simulated such that these textured yarns are regularly knitted and woven into fabrics and garments that were hitherto considered to be unsuitable structures for filament yarns. In addition, some of their properties are completely original in the textile field and have found their own 'customer appeal' in new areas where the natural fibres find it difficult to compete. Admittedly the early textured filament yarns possessed many limitations and imperfections that are common to many innovations but they are still very much in their infancy when compared with traditionally spun yarns and have quickly improved over their short existence of some thirty years; their rapid rate of growth indicates how the man-made fibres have established their own systems of processing to exploit their unique characteristics. These characteristics include the high elasticity of the heat-set stretch yarns and the loftiness of air textured yarns, as will be discussed in subsequent sections of this paper.

The term 'texture' may be related to both surface and internal effects. Surface texture consists of irregularities on the face of the yarn which determines the appearance and handle of the end product which is usually a fabric or garment. Internal texture is determined by the relative positioning of the constituent fibres which affects the bulk of the material, that is the amount of air trapped between the fibres. Thermal insulation, handle, natural texture, absorbency, strength, elasticity and attractive appearance are some of the characteristics to be desired from all textile yarns. Flat, continuous, synthetic filament yarns certainly do not possess many of these qualities, but they are often stronger and much more uniform than spun staple fibre yarns such as cotton and wool. When producing textile yarns from synthetic filaments, it would be ideal to combine the desired properties of both natural and synthetic fibres, but this is an impossible task to achieve. Thus, the primary objective of all synthetic yarn conversion processes is to imitate the 'comfortable wearing' features of the spun natural fibre yarns while maintaining the desirable properties of synthetic fibres. The oldest method of achieving this is to crimp and cut (or break) the continuous filaments into staple fibres and then process them into the more usual spun yarn form using conventional spinning methods. This is a long and protracted process although it can be shortened somewhat by using what are known as 'tow conversion techniques' whereby the early opening and carding processes are eliminated because the inherent parallel arrangement of the 'tow' of filaments is maintained up to the drawing, spinning and twisting stages. Alternatively, continuous filaments can be converted into textured filament yarns in one single operation by various 'texturing methods' without any cutting, breaking, drawing or spinning operations being used. This makes for many process economies. 'Yarn texturing' can therefore be generally defined as a single-process operation whereby closely packed parallel arrangements of continuous synthetic multifilament yarns are changed into more open, voluminous structures to increase their textile usability.

4 TEXTURING TECHNIQUES

Textured yarns can thus be considered from two distinct standpoints: firstly, as a class they simulate spun yarns in that they have soft open structures without the processes of opening, carding, drawing, reducing and
spinning being employed; secondly, each of the textured
yarns, insofar as the spun yarn structure is not accu-
ratesly copied, possesses distinctive properties, and thus
becomes a new type of yarn structure in its own right.

Several texturing techniques have been developed
over the last 30 years to impart bulk and stretch and to
change the texture of the continuous filament yarns.
Such yarn texturing processes are often based on the
good thermoplastic properties of synthetic continuous
multi-filament yarns. Most of these consist of mechani-
cal deformation (usually by torsion, compression or
bending) of regularly packed thermoplastic continuous
filament yarns by heating them to a semi-plastic condi-
tion and setting this deformation by cooling to ambient
conditions. Thus, permanent crimps are imparted by the
yarn being ‘set’ when it returns to the normal physical
state at ambient conditions, such crimping being due to
reforming of the molecular crosslinks while the fila-
ments are in their distorted shape. Because synthetic fil-
aments are conveniently plasticized by heating in either
dry air or steam, nylon and polyester filaments have
been the obvious choices for most of the heat-set tex-
tured yarns. The process can be compared with the per-
manent waving of human hair, although in yarn
texturing the permanent crimping is performed on a
continuously running yarn. Because hair is an animal
fibre, and therefore not easily set by heat alone, per-
manent waving is normally performed by chemical
setting methods; similarly, if it is desired to texture
fibres that are not able to be thermally set, e.g. viscose,
rayon or cotton, it would be necessary to resort to
chemical treatments. This is expensive compared with
the simple ‘heat, deform and cool’ methods used in the
continuous texturing of thermoplastic filaments.

There are various texturing techniques based on this
heat-set principle, such as (a) false-twist (torsion), (b)
stuffr-box (compression) and (c) ‘knit-deknit’ pro-
cessing, gear crimping and edge crimping (bending).
However, the most common is the false-twist technique
(Section 5) which accounts for about three-quarters of
the world’s total textured yarn production. Such yarns
have characteristics that may or may not be desirable
depending on the intended end uses.

Fluid-jets are also being increasingly used for the tex-
turing of yarns. The hot-fluid texturing process, used
in the production of BCF (bulkur continuous filament)
yarns, uses pressurized hot air or steam to crimp and
heat set the filament yarn (Section 7). On the other
hand, cold-fluid texturing, commonly known as air-jet
texturing (Section 8), does not rely upon the use of fil-
aments possessing good thermoplastic properties. In con-
trast to false-twist texturing, the air-jet texturing process
is a unique, purely mechanical method that uses a
supersonic cold air stream to produce entangled bulked
yarns with low extensibility characteristics. It involves
the ‘overfeed’ principle, whereby the supply yarn is fed
via feed rollers into the texturing nozzle at a greater rate
than it is taken away from it by delivery rollers. The
overfed filaments are rearranged as a looped and entan-
gled yarn structure by the effect of a supersonic air
stream without requiring any heat treatment.

An intermittently operating technique known as min-
gling (see Section 6), which makes use of a totally differ-
ent kind of air-jet, is often used in association with the
false-twist process to impart greater fibre-to-fibre cohe-
sion to the highly opened multi-filament yarn struc-
tures.

Both mingling and air-jet texturing are discussed in
some detail in the following sections of this paper,
which also includes some reference to the BCF process.
First it is necessary to describe the false-twist texturing
process, not only because of its extensive use of min-
gling jets but also because false-twist textured yarns are
the most common; therefore it must be compared with the
air-jet textured yarn process which is the principal
subject of this lecture.

5 FALSE-TWIST TEXTURING

The false-twist texturing technique is actually a more
productive single-process version of a now obsolescent
protracted system of making torsionally crimped syn-
thetic filament yarns, namely, the twist—set—untwist
method, which consisted of inserting a high twist of the
order of 70–100 turns/in (2800–4000 turns/m) by twist-
ing, followed by a heat-setting treatment to set the
twisted yarn structure while on the wound package, and
finally untwisting at the same rate in the opposite direc-
tion to remove the yarn twist. This used to involve up
to ten separate production stages and was therefore
very costly. Because the filaments were heat-set whilst in
their twisted state, they did not regain their original
parallel form by such de-twisting and they therefore
extended but becoming a bulky mass of snarled fila-
maments when allowed to go slack. In singles form, such
yarns were very lively because of the high unbalanced
torsional forces present. Consequently, yarns of
opposite twist direction had to be plied together to give
a balance of twist in the yarns, or, alternatively, single
yarns of opposite twist needed to be knitted in alternate
courses to produce a finer yet stable fabric.

For economic reasons, almost all torsionally crimped
yarns are now produced by simultaneously false-
twisting and heat-setting the yarn in one continuous
operation. Before explaining this technique in any
greater detail, it would be appropriate to describe the
action of a false-twist spindle. This is normally a simple
tube with a bar which contacts the yarn by means of
coil friction and forces it to rotate as it passes longitudi-
nally through the tube. The twist spindle is rotated con-
 tinuously by an external drive so that both the yarn and the
tube are revolved simultaneously. Thus it can be
visualized that if a stationary multi-filament yarn is held
at both ends and twisted in the centre by a suitable
false-twist tube, then equal amounts of twist are imparted
on each side of the tube as shown in Fig. 1a. Never-
theless, if either half of the yarn is considered separately
it is observed that the twist is real although the alge-
braic sum of twist throughout the whole yarn is zero;
therefore such twisting is called false-twisting.

With the false-twist tube rotating continuously, but
with the yarn passing forward, the system reaches a
state of equilibrium where no twist exists after the yarn
has passed through the tube, because of the canceling
out of twist on the delivery side of the tube, as shown in
Fig. 1b. Thus the resultant effect is for the yarn to be
twisted on the feed-in side of the tube and to be
untwisted on the delivery side. A fuller treatment of the
action of the false-twist spindle, which of course has been used in textile machinery long before the advent of textured yarns, was given by one of the present authors in reference (1).

By interposing a heater on the intake side of the rotating tube and allowing enough space for cooling to take place before the twisted yarn passes through the tube, the three basic stages of twisting, heat-setting and untwisting are carried out continuously on one machine. Figure 2 schematically illustrates the basic principle of manufacture of crimped yarns by the false-twist method. The yarn is taken from the supply package and fed at controlled tension over the heater, through the false-twist spindle, and wound onto a take-up package. The twist between the feed rollers and the spindle is heat-set and allowed to cool before escaping on the exit side of the spindle. Therefore, on leaving the false-twist spindle, where a twistless state exists, and after the tension has been removed, the filaments are observed to be distorted similarly to those in the yarns made by the protracted sequence of processes described above. In the twisted state the multi-filament yarn is in a helical configuration, but each filament is twisted about its axis within the yarn bundle. Heat-setting relieves the filaments from torsional stress so that each filament is in fact torque-free although lying in a helical configuration in the twisted structure of the yarn. The subsequent untwisting effect removes this helical configuration, but each individual filament is then twisted in the opposite direction. This bulked yarn type has been described as 'a twist free bundle of twist-lively filaments, which has considerable retractive power derived from the snarling tendency of each filament' (2). A typical false-twist textured yarn structure is to be seen in Fig. 3 alongside a typical cotton staple spun yarn and an air-jet textured yarn.

Heating was initially performed by electrically heated elements but, as production speeds increased, vapour-phased close condensation heating systems were used. A low heater temperature causes the filaments to be insufficiently plasticized and a stringy yarn possessing poor crimp results; a firmer crimp is obtained as the heater temperature is increased but, when this is so high that the yarn begins to soften, fusing of the filament occurs yielding a lean weak yarn (3). Obviously the important criterion is the yarn temperature, and this will depend not only on the heater temperature but also on the tension and speed of the yarn as it passes through the heating zone. Production speeds have increased by well over a hundredfold during the short time that false-twist textured yarns have been manufactured, and consequently heaters have needed to be so designed that the yarn path through the heating zone has become progressively longer.

The reason for the massive production speed increases mentioned above is that false-twist spindle speeds have increased remarkably since the 30 000 r/min simple roller-bearing supported types typically used around the late 1950s. The rapid developments of high-speed spindles had one thing in common in that they all avoided the concept of supporting the yarn in a tube mounted directly in bearings. Some mounted the yarn in a very small diameter tube supported either magnetically or by pulleys against a moving drive member which was usually a more slowly rotating pulley or belt as shown in Fig. 4a. Soon afterwards the EPI spindle, which was developed by British Nylon Spinners Limited some 30 years ago, used the ingenious friction twisting principle shown in Fig. 4b whereby the yarn’s peripheral surface was directly driven by frictional contact with the inside walls of a relatively slower rotating rubber-lined driving bush (4). The speed of twisting was increased by a ratio determined by the relative diameters of the bush (16 mm) and the very fine yarn. The principle was somewhat similar to the method of ‘centreless grinding’ where the circular ground rod is driven by pairs of grinding wheels.

Modern friction twist spindles, using exactly the same principle as the EPI spindle mentioned above, have been employed for the false-twisting of fine denier yarns, and these achieve twisting rates of some 7 million turns per minute in daily production! Friction twisting may
be accomplished in hollow tubes, between rotating surfaces or against crossed belts, as shown in Fig. 4b, c and d respectively. For multi-filament yarns having linear densities* of 50 denier (55 dtex) and higher, false-twist spindles that assure positive contact are usually preferred over such friction twist devices. However, in day-to-day industrial false-twist texturing, ladies’ hosiery yarns of 15 denier (17 dtex) are regularly produced at linear speeds of 1200 m/min with the surface speed of the discs of belts providing rotational yarn speeds of 720000 r/min. One wonders where else in manufacturing does one see mass production of quality products being produced 'round the clock' at speeds of 120 000 revolutions per second!

The stretch and recovery characteristics of false-twist yarns are well suited to some end uses, such as ladies' stockings and tights, children's and men's socks, knitted outerwear, sportswear and upholstery fabrics where high extensibility characteristics are required. In this respect they have created new markets and fostered higher consumer demands. The range of the most common false-twist textured yarns is between 10 and 350 dtex.

The false-twisting process produces yarns that are not always desirable for many end uses because of their extremely high stretch properties. These can be reduced somewhat by overfeeding the yarns into a second heat-treatment zone whereby they are reset in a partially extended condition. Nevertheless, it is totally impossible to eliminate this extensibility and, therefore, all the heat-set textured yarns mentioned in Section 4 are, in fact, poor competitors with spun staple yarns for most of the common end uses usually associated with the natural fibres, e.g. mens' suitings, shirts, overcoats, carpets, towels, sewing threads etc. Consequently, yarns textured by the false-twist technique, having the largely undesirable characteristic of high extensibility under quite low loads, makes them less suitable than air-jet textured yarns as competitors for such traditional markets.

6 MINGLING (INTERLACING) JETS FOR FILAMENT YARNS

Inter-fibre friction, attributed to the twist imparted to the spun staple yarns, is the main cohesive force that holds staple fibres together to form a yarn. Untextured continuous multi-filament yarns, however, do not possess this essential cohesive force due to the parallel arrangement of the constituent filaments, and the yarns textured by the false-twist process still lack inter-filament cohesion. Moreover, the filaments can be 'snatched' and broken by the overlapping layers and this creates tension irregularities during the unwinding process. The filaments of false-twist textured yarns are sometimes trapped by the latch needles of very fine gauge knitting machines and hence filament breakages occur. Similarly, loose filaments can be caught by the warp yarns while an uncompact false-twist textured weft yarn is travelling through the narrow warp shed of a weaving loom and thus create irregularities in woven fabrics.

Several solutions have been used to overcome such problems. True twisting and yarn sizing of the filaments are expensive ways of compacting them. The requirements of a cost-conscious modern industry tend to favour a process that can be carried out during the yarn texturing stage itself and therefore the mingling process has been evolved.

Mingling is an on-line processing operation whereby a loose bundle of continuous filament yarn is instantaneously subjected to a turbulent cold air-jet impinging upon it, normally to its axis. This opens up sections of the filaments such that, in the immediate vicinity of an opened-up section, adjacent filaments will be inter-twined and mingled with each other to form compact

* The yarn linear density (mass per unit length) for silk and other filaments has, for centuries, been known as the denier, which is the mass (grams) of 9000 m of yarn. The consistent SI unit for linear density is the tex, which is the mass (grams) of 1000 m of yarn. For synthetic filaments a more convenient measure is the decitex (dtex). Therefore,

\[
dtex = \frac{\text{denier}}{0.9}
\]

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Fig. 3 A visual comparison of: (a) a cotton yarn, (b) a false-twist yarn and (c) an air-jet textured yarn
sections known as 'nips'. If the yarn travels in the direction of its axis while the air-jet is stationary, the 'open' and 'mingled' sections will alternatively follow sequentially since the jet fails to open up a section that has already been mingled (Fig. 5). This cohesion is imparted to an originally loose yarn. Although the filaments' relative spatial positions are altered, the overall structural properties do not change appreciably in that a flat yarn is still flat and a conventionally textured yarn is still stretchable.

Flat continuous filament yarns are mingled in such a way that no visible nips are imparted, and the number of nips per unit length is quite low. This so-called 'continuous mingling' is achieved by relatively simple nozzle designs and at low air pressures. It is applied either immediately after the extrusion stage or at subsequent drawing or warping. False-twist textured yarns, however, are mingled to form visible nips and open places. This is due to the stretch characteristics of the yarns. When tension is low, the filaments tend to assume the minimum energy level which is in the highly

![Diagram](image-url)

**Fig. 4** Various friction-twist spindles in which the yarn's periphery acts as the driven member

![Diagram](image-url)

**Fig. 5** Schematic illustration of a mingling nozzle and its effect on a false-twist textured yarn
crimped form and the open sections become bulkier than the mingled sections. By applying a slight tension, the mingled yarn is stretched, and the differences between the nips and the open filaments become barely visible. This compact and cohesive structure is more suitable for further textile processes.

On a false-twist texturing machine, the mingling process is carried out by simply positioning a nozzle at one of the alternative positions shown in Fig. 6. Position 1 is not widely used, and at this location mingling is applied to the flat yarn prior to its entering the primary heater and false-twisting zones with a view to more effective heat transfer in the heater and better twisting at the twisting unit. Position 2 is where mingling nozzles are usually located and, in the case of single heater machines this is the only possible option. However, dual heater machines have two options: either before or after the secondary heater (positions 2 and 3 respectively). Both options are widely used, depending on the original machine design. In these positions, the mingling nozzles operate to impart regular nips to the textured yarn for the purposes already mentioned.

In its simplest form, a mingling nozzle consists of a main yarn channel and a jet of air impinging perpendicular to the yarn as it travels through the channel. Therefore, a length of cylindrical tube with an air entry midway along the tube conforms with these requirements and, indeed, may perform the task in a limited sense. Following from the first mingling nozzle patent in the early 1960s, the international textile industry has been seeking more effective mingling by experimenting with a wide variety of nozzle designs and configurations, as summarized in Fig. 7. Since mingling is an on-line operation with other textile processes, threading of the yarn through the nozzle without stopping the machine is highly important. So-called ‘open’ nozzles with a ‘slot-in’ threading facility are, therefore, essential for rapid processing operations such as false-twisting and yarn extrusion. Conversely, ‘closed’ nozzles, which can only be threaded by means of a needle or by a yarn

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**Fig. 6** Possible locations of intermingling nozzles on a false-twist texturing machine

**Fig. 7** Classification of mingling nozzles
end, could also find applications in slower processing operations such as draw-warping. Existing designs of slot-in threading facilities vary from a thin slot in the wall of the yarn channel to spring-loaded flaps that close the main channel.

The cross-sectional shapes of the main yarn channel vary from circular, semi-circular, quarter-circular, triangular, rectangular, pentagonal to irregular undefined shapes. The shape of the yarn channel may also vary in the longitudinal direction. A curved yarn path is a common feature in most applications. This is achieved either by a curved channel or by offsetting the position of the yarn guides before and after the nozzle. Most nozzles possess only one air inlet to give favourable air consumption rates and the working pressure may be as high as 6 bar (gauge). The yarn processing speeds can be as high as 1000 m/min, but the mingling density and frequency decreases with increasing yarn speeds.

The authors and their colleagues at Loughborough University of Technology are currently receiving SERC and industrial financial support from Rieter-Scragg Limited for research investigations of the mingling process with the objective of improving nozzle efficiency.

**7 THE BCF PROCESS FOR HOT FLUID TEXTURING**

BCF (bulked continuous filament) yarn systems are used in the carpet industry to give texture and added bulk. The current capacity of polypropylene BCF yarns is approximately 100 million kg/annum, and this accounts for only 20 per cent of the total usage, with the remainder being mainly nylon. Therefore, this is a major industrial process with an impressive growth record.

Hot fluid texturing, which evolved from mechanical stuffer-box texturing, has become the dominant process for producing BCF yarns intended for carpet piles. A typical hot-air nozzle used in the production of BCF yarns is shown in Fig. 8. The preheated yarn enters the nozzle at a temperature just below the plasticizing point. Compressed hot air or steam is introduced just after the entry; this heats up the yarn further and conveys it into the stuffer chamber of the nozzle by means of pressure. In the stuffer chamber, pressure is released by removing hot air or steam so that the yarn, which is opened up into its individual filaments, forms a plug in the lower part of the chamber, and this plug is propelled through the chamber by the remaining compressed gas pressure. Three-dimensional crimp is obtained by impacting the yarn onto the plug which is cooled as it leaves the chamber.

The intensity of the plug, and, therefore, the texturing effect, is controllable by the type of pressure release and the design of the stuffer chamber itself. Other parameters that affect the crimp level are: (a) temperature, (b) pressure of the hot fluid and (c) speed of the delivery roller.

Mingling jets (Section 6) are often needed with BCF yarns in order to achieve the filament cohesion required in subsequent processing of the yarn.

**8 AIR-JET TEXTURING (USING COLD AIR)**

The textured yarns produced by cold air-jets are greatly different from all the above-mentioned heat-set types in that they more closely simulate spun staple fibre yarn structures, both in appearance and physical characteristics. Whereas the bulkiness of false-twist textured stretch yarns decreases with the degree of imposed tension, the geometric form of air-jet textured yarns can be made to remain virtually unchanged at loads corresponding to those normally imposed in fabric production and during wear; this is due to the entangled core and 'locked-in' loop structure attributed to air-jet textured yarns. The air-jet texturing process is unique in that a flat synthetic multi-filament yarn is given a spun-like structure with a compact core and with surface loops occurring frequently in irregular intervals along its length. Therefore, air-jet textured yarns more closely resemble conventionally staple fibre spun yarns in that the yarn surface is covered with fixed resilient loops, and these serve the same purpose as the protruding hairs in spun yarns by forming an insulating layer of entrapped, still air between neighbouring garments.
The heart of the air-jet texturing process is the nozzle. This may vary in design and detail, as will be discussed in this section, but it serves the same purpose of creating a supersonic, turbulent and non-uniform flow to entangle filaments and form them into loops to generate stable textured yarns.

Following the announcement of the first nozzle patent in 1952, which described a jet used by the Du Pont Company for the manufacture of 'Taslan' textured yarns from pretwisted filaments, the air-jet texturizing process has experienced many developments and improvements and seen many variations in the detailed nozzle design. The progressive development in nozzle design since the early 1950s has considerably improved the productivity of the nozzles and has led to: (a) elimination of the necessity for pretwisted supply yarns, (b) increased texturing speeds, (c) reduced compression air consumption, (d) reduced energy consumption, (e) reduced water consumption, (f) improved yarn quality and (g) a wider range of products. Today, many texturizing nozzles are available to be fitted to modern purpose-made air-texturizing machines. These nozzles are basically of two kinds: Taslan-type nozzles and HemaJet-type nozzles.

Contemporary Taslan nozzles allow the supply yarn to enter a needle with the airflow passing through a uniform gap around the needle circumference or through an inlet hole displaced to one side. These nozzles may have impact elements of cylindrical, spherical or flat shapes situated at the exit to impact with the flow and the emerging yarn, as shown in Fig. 10. These impact elements are believed to improve the process stability and yarn quality in texturing the finer yarn types. These Du Pont nozzles were basically made with a so-called 'venturi', which is a converging-diverging nozzle, to create the required, highly turbulent, supersonic flow, and a 'feed needle' to guide the supply yarn into this violent airflow. Both parts were assembled in a nozzle housing. The annular gap between the nozzle and venturi was required to be precisely adjusted to obtain the optimum nozzle efficiency and to maintain the air-jets but also to collect the used water and chemical spin-finishes washed off the filaments during the process.

A single supply yarn, or two or more yarns of the same or different types, can be textured at the same speed (parallel-end texturing) or can be co-textured at different speeds (core and effect texturing) by the use of separate feed rollers, as schematically indicated in Fig. 9, hence facilitating the blending of different types of yarns during processing.

The air-jet texturing process is by far the most versatile continuous texturing method in that it can blend filaments together during processing and the supply yarns need not be restricted to the synthetics, since the process does not depend on good thermoplastic properties. This permits the texturing of non-thermoplastic yarns such as glass and the production of blends from thermoplastic materials, all of which react very differently to heat treatment. This greater versatility offers the yarn texturizer a potential for developing hundreds of different types of yarns.

9 TEXTURING NOZZLES

The heart of the air-jet texturing process is the nozzle. Figure 3 compares a typical air-jet textured yarn with a typical cotton fibre spun yarn and a false-twist textured yarn.

The spun-yarn look and the non-stretch feature, achieved through their entangled structures and the loops projecting on the yarn surfaces, are thus the main characteristics of the air-jet textured yarns. Consequently, the air-jet texturing process is becoming very important in the textile industry where the usage of synthetics is approaching tant in the textile industry where the usage of synthetics is approaching.

Figure 3 compares a typical air-jet textured yarn with a typical cotton fibre spun yarn and a false-twist textured yarn.
the nozzle-to-nozzle consistency. This precise setting requirement has been a major disadvantage of such types of nozzles.

In the late 1970s, the Heberlein Company of Switzerland introduced a texturing nozzle under the trade name of 'HemaJet'. The air was fed into the main duct of this 'standard core' nozzle by means of three small inlet bores where it impinged upon the overfed supply yarn from three sides, as shown in Fig. 11. The 'HemaJet' nozzles were made of one solid piece and required no adjustment during operation, which reduced the attention and maintenance required. Nozzle-to-nozzle consistency, which relied on the manufacturing tolerances, was also improved. A spherical impact element (baffle ball) was provided to be used optionally but was particularly recommended for the finer yarns.

In recent years, the Heberlein Company announced several other nozzles, known as the T-series, having the same basic design features but covering a wider supply yarn range from 30 to 5000 dtex. The trumpet-shaped diverging exit of the 'standard core' nozzle was widened, and this became a common feature of all the T-series nozzles. Some of these recent nozzles have considerably reduced the amounts of compressed air required.

These improvements have reduced the conversion costs of air-jet textured yarns to a level comparable with those of the cotton- or wool-spinning process. This has led to a current upsurge of interest in the air-jet texturing process, both in industry and in research institutions, owing to its unique capability to produce textured yarns that closely simulate spun yarns.

10 INVESTIGATIONS INTO THE TEXTURING MECHANISM

There is a scarcity of published knowledge about the texturing mechanism, particularly the relation between the airflow and the mechanism of loop formation. Publications in the 1960s by Wray and Entwistle (6) were followed by Sen (7) and Sivakumar (8) in the early 1970s. The mechanisms claimed by these researchers were all based on the use of pretwisted yarns and therefore are not valid for today's no-twist yarn texturing process. Further research by Bock (9) in the early 1980s claimed that loop formation mainly resulted from the retardation of the filaments by shock waves; this was not entirely new as Sen in 1970 had observed such shock waves and Sivakumar in 1975 had suggested a similar mechanism based on his theoretical work and Sen's experimental findings.

In the 1960s the first researchers to analyse the mechanism of the air-jet texturing process with a Taslan type 9 nozzle (which was designed to operate only with pretwisted filament supply yarns) were Wray and Entwistle (6). They observed the false-untwisting of the filaments during the process with the aid of high-speed photography. They studied the airflow and related the vortex shedding in the flow to the untwisting of the yarn. Their hypothesis presupposed that a vortex-shedding action was occurring in the venturi to cause the observed rotations of the textured yarn.

In 1970 Sen (7), 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 vortices in the wake of the yarn feed needle, as postulated by Wray and Entwistle, 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 was invalid, although the overall principle of texturing by a temporary removal and reassertion of the twist was still applicable.

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 and these photographs have only recently been published more widely (10).

In 1975, Sivakumar (8) 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 the 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 the texturing mechanism on the decelerating effect of the shock waves on the filaments.

All of these hypotheses were based on the assumption that the supply yarns were pretwisted, since this was
then the usual industrial practice. Therefore, without reference to any other aspect of the process, it can be concluded that these hypotheses do not apply to current processing technology where no pretwist is involved.

Some further attempts have been made to improve the understanding of the events that occur during texturing of twistless yarns by modern texturing nozzles. Bock (9) analysed the mechanism of texturing by using a Taslan type 14 nozzle. His research confirmed the findings of Sen and Sivakumar by verifying the occurrence of the shock waves in the free jet from this nozzle by using Schlieren photography. He also gave evidence of asymmetry in the flow which he verified by pressure measurements, as expected from the asymmetric design of the nozzle. By using high-speed photography, Bock showed that the filaments were opened on emergence from the nozzle. Like Wray and Sen, 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, he argued that there is a force within the stream that 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.

The Bock 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 claimed in 1975. The validity of texturing mechanisms attributed to the presence of shock waves is questioned by Acar et al. (10) as a consequence of theoretical and experimental findings to be described in Sections 11 to 13 which have led to an improved understanding of the mechanism as summarized in Section 14.

**11 FURTHER THEORETICAL AND EXPERIMENTAL STUDIES WITH TEXTURING NOZZLES**

In this section an account will be given of further contributions to the understanding of the air-jet texturing process based on the ongoing work at the Loughborough University of Technology.

Texturing nozzles can be categorized in two main groups: (a) converging-diverging-type nozzles, that is Taslan-type nozzles, in which a converging-diverging nozzle is attached to the yarn exit end of the nozzle assembly, and (b) cylindrical nozzles, that is HemaJet-type nozzles, in which one or more air inlets enter at an angle to the cylindrical, straight, uniform main flow duct of the nozzle. The main characteristics of the two types of nozzles are compared in Fig. 12.

In the first group of nozzles, a compressed air supply passes through a passage and an annular gap before it reaches the converging–diverging nozzle attachment, as Fig. 12a illustrates. The cross-sectional areas of the air passages and gaps are larger than the throat area of the converging–diverging nozzle, and therefore, at typical texturing pressures, the airflow reaches critical conditions at the throat. Hence the flow parameters at the exit plane of the nozzle are determined by the well-established theory of compressible flow in a converging–diverging nozzle, and these can be calculated by assuming a frictionless, steady, one-dimensional, isentropic flow and by applying the principle gas dynamic equations. A study of the flow in a Taslan type 14 nozzle was reported by Bock and Lunenschloss (11). Their experimental work showed that the flow in this nozzle was supersonic, turbulent and the total pressure profile at the nozzle exit was non-uniform, probably due to the single air inlet hole on one side of the nozzle. Furthermore, they observed shock waves in the free airflow (undisturbed by the filaments) outside the nozzle by means of Schlieren photography.
The flow in the second group of nozzles is more complex owing to the design of the nozzle. The main flow duct is straight, uniform and cylindrical with a trumpet-shaped diverging exit section as illustrated in Fig. 12b. Usually convergent air inlet bores enter the main flow duct at an angle of about 45 degrees. The number of inlet bores may vary between one and three. Yarn is fed through the central duct and the incoming air-jets are directed to impinge on the yarn. Most of the air leaves the nozzle in the direction of yarn movement (primary flow) but some leaves in the opposite direction (secondary flow), as shown in Fig. 13. No mathematical model was available in the literature for such a complicated flow system, even without the yarn being present. The presence of the moving yarn is a further complication and a rigorous solution for the actual yarn texturing situation is probably not possible.

The authors published a mathematical model which they developed for such nozzles (12) and this is here summarized in the Appendix to this lecture. In that publication they concluded that the predictions of the mathematical model developed for the cylindrical-type texturing nozzles with any number of inclined air inlet bores opening to the main flow duct were shown to be in good agreement with the experimental results. This model was also shown to be valid for nozzles with a trumpet-shaped diverging exit. Therefore, the mathematical model can be used as a useful tool in the design and development of such nozzles in order to reduce the compressed air consumption and hence the overall cost of the texturing process.

The experimental study with a dynamically similar scaled-up model of a cylindrical-type texturing nozzle (13) and later experiments with the actual size texturing nozzles (14) indicated that the undisturbed airflows in such nozzles are supersonic, turbulent and of a non-uniform profile, which are also typical characteristics of the flow from a converging-diverging-type texturing nozzle. The trumpet-shaped diverging exit was found to affect the exit velocity profile to introduce some degree of non-uniformity. The presence of the filaments in the nozzle during the texturing process was expected to affect the flow characteristics, but this was difficult to evaluate experimentally.

The distribution of the air velocity outside the nozzle may vary depending on the design details, but the common feature of all the nozzles is that the velocity distributions are non-uniform, as illustrated in Fig. 14. High-speed photographs of filaments that were left free in the airflow show that these are separated and dispersed across the nozzle due to the effects of the turbulent flow. Figure 15, which is one of many such photographs, clearly indicated that filaments that were left free in the airflow showed no sign of changing their directions at right angles to the jet axis due to any forces existing in the air stream, as had been postulated by Bock (9). It was also evidenced that filaments travel at very high speeds, an order of magnitude higher than the texturing speeds (15).

Observation of shock waves with texturing nozzles goes as far back as Sen's research (7) published in 1970. In these earlier flow visualizations the airflows were free of any interference by the filaments themselves. Naturally, during actual texturing conditions, the filaments are present within the airflow and this would disturb the flow and hence affect the formulation of the shock waves. Acar et al. (16), by using converging-diverging and cylindrical-type nozzles, showed that such shock waves are disturbed and at least partially destroyed by the presence of the filaments in the flow. A later work...
by Bock and Lunenschloss (17) also showed Schlieren photographs of the airflow and filaments inside an experimental nozzle with a rectangular cross-section and glass sides; such operations fail to simulate the circular cross-section of conventional, industrially used converging–diverging texturing nozzles. These photographs also showed that the pattern of shock waves with and without filaments present in the nozzle were not identical. Therefore, the authors' contention is that the validity of the loop formation mechanism based on the deceleration of the filaments by the shock waves and the possibility of changing the direction of the filaments by any forces existing in the flow due to these shock waves, both of which had been previously suggested by Bock (9), are very doubtful, even on close examination of Bock's own subsequently published findings (17). The authors postulate an alternative loop formation mechanism in Section 14.

12 FORCES ACTING ON FILAMENTS

The authors have shown elsewhere (18) that the most important factors in air-jet texturing are the fluid (drag) forces and the frictional forces acting on the filaments, because such forces primarily determine the resultant forces acting on the filaments which not only transport them through the texturing nozzle but also facilitate the entanglement and loop formation process by bending, buckling and twisting of the filaments. It can be argued that the separated filaments at different locations in the nozzle are under the effect of different drag forces due to the non-uniform velocity distribution.

The fluid forces in the form of frictional drag and pressure drag forces acting on a filament under any given flow conditions are functions of the local air velocity, and of the filament surface and projected areas exposed to the flow. The air velocity is primarily determined by the air supply pressure, whereas the jet velocity profile is affected by the design of the nozzle. The surface and projected areas exposed to the flow are determined by the width (diameter for a circular filament) and length of the filament exposed to the airflow, and also by the location of the filament across the nozzle and its orientation. Therefore, forces acting on the individual filaments at different locations in the nozzle may vary and such varying fluid forces acting on the filaments at any instant cause them to travel at different speeds and, hence, cause them to be displaced longitudinally relative to each other. These filaments are more likely to form loops. Since the filaments change their positions because of turbulent flow and filament migration, an individual filament may go through variations in the drag force acting on it as the process continues and may have randomly distributed loops along its length.

Filaments with varying fineness, different cross-sectional shapes and different filament numbers within the yarn bundle behave differently in the airflow. Incidentally, the fact that changes of dimension and shape are readily obtainable with man-made fibres gives them an extra significant advantage over natural fibres such as cotton, wool, silk and flax. Increasing the diameter of a circular filament of a certain length gives rise to a greater drag force acting on it owing to its greater projected and surface areas. On the other hand, its inertial resistance to the fluid forces that transport this filament is a function of the filament cross-sectional area (18). An increase in filament diameter thus causes the fluid forces to increase proportionally to the diameter, but the force required to overcome the inertia and to transport this coarser filament will increase with the square of the diameter. Consequently, coarser filaments will require greater forces than finer filaments to overcome their inertial resistance. Furthermore, filaments with larger diameters have higher bending and torsional stiffnesses, thus requiring increased forces and torques to buckle, bend and twist the filaments to facilitate the convoluted loop formation process. This explains the fact that supply yarns that are composed of finer filaments should texture more satisfactorily than coarser filament yarns.

Filaments with different cross-sectional shapes will require different forces to deflect them as they emerge from the nozzle. The drag forces acting on these filaments will also vary owing to the different surface and projected areas arising from their different cross-sectional shapes. These factors may have an effect on the loop formation process. Circular filaments have been compared with, for example, elliptical cross-sectional filaments in order to illustrate the effects of
different cross-sections. The drag forces acting on elliptical filaments are larger than those acting on a circular filament of equal fineness due to their increased surface and projected areas; therefore such filaments are better suited for the air-jet texturing process from the viewpoint of drag forces. Smaller forces and torques are required to deflect filaments that have elliptical cross-sections because their bending and torsional stiffness about their major axes are smaller than those of circular filaments of equal finenesses. Hence, it can be argued that the elliptical or similar cross-sectional filaments are more suitable for air-jet texturing from the stiffness viewpoint.

13 YARN WETTING DURING TEXTURING

Modern industrial practice usually involves wetting of the supply yarns during the air-jet texturing process by passing them through a wetting system. Regardless of the application technique, wetting improves the process stability and hence the yarn quality, although it may cause the chemical spin finish on the supply yarn and any impurities in the water to contaminate the nozzle. The wetting systems used in the early days of the process simply involved passing the filament yarn through a water bath prior to its entry to the nozzle (Fig. 16). Recent wetting systems, such as the HemaWet system, use separate wetting heads of jet or spray types which can be positioned conveniently prior to the nozzle chamber (Fig. 17). In such systems, fresh clean water is always used and the washed-off spin finish is drained away with the used water, reducing the likelihood of nozzle contamination.

There has not been a satisfactory explanation of how wetting improves the texturing conditions and the resultant textured yarn quality. Results of research at Loughborough University of Technology on the effects of wetting the filament yarn on the air-jet texturing process has been fully reported elsewhere (19) but a summary of the research findings is given here.

The authors' experimental and theoretical studies showed that only a very small fraction of the applied water mixes into the airflow, causing hardly any significant changes in the flow velocity, which is the principal factor determining the fluid forces acting on the filaments. This observation casts doubt upon any suggestions that water alters the airflow properties sufficiently to improve the texturing conditions and the resultant yarn quality.

Friction between the filaments themselves, and between them and the contracting surfaces, both play significant roles in the texturing process, because they reduce the net driving forces acting on the filaments. Experimental studies showed that water acts as a lubricant and reduces the friction between the filaments and the contacting parts, as indicated by the reduced friction between the filaments and yarn guide as shown in Fig. 18. This causes a decrease in frictional forces and, consequently, an increase in the resultant forces acting on the filaments, as indicated in Fig. 19 by the tension in the yarn in the feed zone as defined in Section 8 and Fig. 9. These two sets of results suggest that wet processing, when compared with dry processing, results in significantly improved texturing conditions, as indicated.
Effects of wetting on yarn stability (that is the tension in the stability zone of Fig. 9)

in Fig. 20 by the tension in the yarn in the stabilizing zone.

Wetting also reduces the friction between the filaments themselves which enhances their longitudinal displacements relative to each other, thereby facilitating better loop and entanglement formation and generating improved textured yarns. The authors have also shown that the lubricating capability of the water is slightly enhanced as its temperature is raised and that wetting agents can also have a beneficial effect. Recent wetting units, such as the 'HemaWet Plus', facilitate mixing wetting agents into the water in precisely measured quantities.

It can be concluded that wetting the filament yarn during texturing reduces the inter-filament friction and the friction between the filaments and the machine parts, increasing the net drag forces acting on the filaments and, hence, making for easier longitudinal displacement of the filaments with respect to each other.

This in turn encourages the formation of loops which then become mutually entangled as they emerge from the nozzle. By this mechanism, the wetting of the filaments enhances the texturing process.

Based on these observations, it is possible to postulate a mechanism of loop and entanglement formation.

At any instant some of the filaments in a texturing nozzle will be moving at faster speeds than others due to the relatively greater fluid forces acting on them. The 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 this longitudinal displacement is affected by local forces instantaneously acting on the filaments (including friction) and by the overfeed ratio. The textured yarn is delivered at right angles to the nozzle axis and travels at the final yarn production speed (that is texturing speed). Since the yarn length is shortened as a result of loop formation, this creates a tension in the yarn 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 airflow at much faster speeds than the yarn texturing speed; on the other hand, the tension in the yarn pulls the 'leading ends' of the emerging filaments in the direction of the yarn delivery (that is at right angles to the nozzle axis). Since the 'trailing ends' of the filaments are held within the nozzle, these filaments are forcibly bent into bows and loops. These are then entangled with other instantaneously emerging filaments and become fixed stable loops within the textured yarn structure.

The filaments continually change their position across the nozzle due to the dual effect of the turbulent airflow and the tension induced by the loop formation process itself. Therefore different filaments go through this process at different instants and the cycle repeats itself randomly.

This can be illustrated in Fig. 21, which is a simplified schematic diagram with only a few filaments representing the behaviour of a more complex multi-filament yarn. In Fig. 21a, filament 1 is the fastest moving filament having the greatest longitudinal displacement with respect to all others and is blown furthest out of the nozzle.
nozzle to form a loose bow or loop. An instant later, in Fig. 21b, it is formed into a fixed loop L1 within the textured yarn as a result of mutual entanglement of the filaments. 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 swirl, and this now becomes the fastest moving filament so causing it to be blown out and displaced longitudinally with respect to others to form a loose bow or loop. Immediately afterwards, whilst filament 2 is being similarly entangled into a fixed loop L2, a further filament 3 commences a similar loop-formation process (Fig. 21c). Since there are many filaments in an actual supply yarn rather than the five illustrated in Fig. 21, 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.

This postulated mechanism of loop formation is valid for all types of texturing nozzles, despite detailed differences in their design, because the underlying requirement to create supersonic, asymmetric, turbulent and nonuniform flow is essential for satisfactory texturing.

15 APPLICATIONS OF AIR-JET TEXTURED YARNS

The above-mentioned advancements have reduced the conversion costs of air-jet textured yarns to levels that make them highly competitive with conventional fibre spinning processes. This, together with a unique capability to produce yarns that closely simulate spun yarns, has led to the current upsurge of interest in the air-jet texturing process. The process has become the most versatile in existence in terms of the range of yarns that can be produced, varying from 70 dtex nylon to 18 000 dtex glass.

Most end uses are still based on a wide range of woven fabrics. The ranking by end use would certainly show home furnishings as still the largest, followed by automotive, industrial and apparel fabrics. Furnishings have long been the primary market for air-jet textured yarns, having started with nylon and acetate filaments. The superior fabric performance in most cases combined with attractive aesthetics opens up many fields of application such as wear-resistant automobile upholstery. Currently, the majority of European car seat and interior fabrics are being made of air-jet textured yarns.

A 'wool-like' handle in apparel fabrics is one of the most popular characteristics of air-jet textured yarns. Consequently, apparel end uses include suiting and trousers, dress-wear, ski-wear, sports-wear and workwear. Also, because of their high level of uniformity and strength, air-jet textured yarns find a related garment application field in sewing threads.

Since glass fibre is not thermoplastic and cannot be textured by the conventional techniques, the air-jet texturing process is also used for the conversion of glass filaments into textured yarns for industrial applications, such as fire blankets. Textured glass yarns also find uses in domestic curtains and drapes that are very easily washed and dried.

The entangled structures of the air-jet textured yarns and their protruding loops enable extremely stable fabrics to be produced which find applications in many technical end uses, including coated and laminated fabrics; this is due to the protruding loops providing much improved adhesion and bonding for a lower fabric weight.

The authors contend that the potential application areas for air-jet textured yarns are far greater than have yet been realized. They are capable of extending into many other markets due to the unrivalled unique blending capabilities and the versatility of the multi-end texturing techniques that are possible with this unique filament yarn texturing process.

REFERENCES


APPENDIX

A mathematical model for the flow in cylindrical-type texturing nozzles

The construction of cylindrical-type nozzles is such that the sum of the air inlet bore cross-sectional areas is smaller than the main flow duct cross-sectional area. The flow is considered to have reached critical conditions in these inlet bores and the total flowrate is thus determined by the sum of the individual flowrates. In the case of more than one inlet bore the emerging air streams collide with each other and mix together in the main flow duct where they are divided into flows in opposite directions (the primary and secondary flows as seen in Fig. 13); these flows then immediately expand and leave the nozzle as fully or partially expanded flows, depending on the upstream and ambient pressures.

For the purpose of theoretical analysis the whole flow system was defined by dividing the nozzle into three parts (or control volumes), as illustrated in Fig. 22. To simplify the mathematical treatment of the flow undisturbed by the filaments, it was assumed that the flow was isentropic and one-dimensional in each control volume, the velocity profiles across both primary and secondary flow exit planes were uniform and the exit pressures of both primary and secondary flows are atmospheric.

Control volume 1 applies to the air inlet bores, which usually have the form of converging nozzles. Since the conventional operating pressures are much higher than the critical pressures, it is possible to apply the classical steady one-dimensional gas dynamic equations to calculate the critical flow conditions at the throat of these converging inlet bores as follows:

\[
 p'_i = p^* = \left( \frac{2}{\gamma + 1} \right)^{\gamma/(\gamma - 1)} P_o
\]

\[
 T'_i = T^* = \left( \frac{2}{\gamma + 1} \right) T_o
\]

In control volume 2 the flows from the inlet bores mix together, and outgoing flows occur in the primary and secondary directions as shown in Fig. 22. The flow properties in the core of a free jet are known to be unchanged up to approximately six diameters away from the throat, for example as shown by Gaunter et al. (20). Therefore, the critical conditions achieved at the throat of the converging nozzles (control volume 1) can be considered to be unchanged at the inlet boundary of the control volume 2, which is adjacent to the outlet boundary of the control volume 1. Hence the input data to control volume 2 is that corresponding to the critical conditions (that is \( M = 1 \)) achieved at the throat (exit) of control volume 1.

One of the constructional constraints of the cylindrical nozzles (as stated earlier) is that the total throat area of the inlet bores is smaller than the cross-sectional area of the main duct. This implies that, for an incompressible flow, the cross-sectional areas of the primary and secondary flows after collision and mixing in control volume 2 would also be smaller than the main duct cross-sectional area. Since the flow in question is a compressible one, both primary and secondary flows will immediately expand to the wider physical boundary of the main duct of the texturing nozzle. Since this expansion is taken into account in control volume 3, it is assumed that no expansion takes place within control volume 2 (that is the fluid is assumed incompressible) and that the properties of the outgoing flows are the same as those of the incoming flows. This assumption enables us to apply the theory for the incompressible collision, and mixing of two jets, as described by Gurevich (21), can be applied to control volume 2 to calculate the mass flow division into primary and secondary flows. The areas of both primary and secondary flows and hence the mass flowrates can thus be calculated by extending the theory of collision of two jets to any
number of jets colliding at the same point of the axis of the texturing nozzle.

The concept of continuity states that the total mass flow of the incoming jets is equal to the sum of the primary and secondary mass flows. Thus, if \( n \) incoming jets are used,

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

(4)

Since the density and velocity of the incoming and outgoing flows were assumed to be the same, equation (4) becomes

\[
\sum_{i=1}^{n} A_i = A_p + A_s
\]  

(5)

Similarly, applying the concept of momentum change in the \( x \) direction:

\[
\sum_{i=1}^{n} (\rho AV^2 \cos \alpha)_i - (\rho AV^2)_p - (\rho AV^2)_s = 0
\]  

(6)

Equation (6) can similarly be simplified to

\[
\sum_{i=1}^{n} A_i \cos \alpha_i - A_p + A_s = 0
\]  

(7)

In this equation \( \alpha_i \) is the angle made by the \( i \)th inlet jet with the \( x \) axis. When all jets are at the same angle, then

\[
A_p = \frac{1}{2} \sum_{i=1}^{n} A_i (1 + \cos \alpha)
\]  

(8)

and

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

(9)

Thus, the primary and secondary flowrates, applying the concept of continuity, are

\[
m_p = (\rho AV)_p
\]  

(10)

and

\[
m_s = (\rho AV)_s
\]  

(11)

where

\[
\rho_s = \rho_p = \rho_t
\]

and

\[
V_p = V_s = (V_{0_{\text{max}}})
\]

The expansion of the outgoing flows from control volume 2 to the nozzle boundary in control volume 3 (Fig. 22) can be treated as a sudden expansion of a flow across an abrupt enlargement as, for example, discussed by Benedict et al. (22). This occurs when \( A_p \) and \( A_s \) are being expanded to \( A_n \) in control volume 3, where \( A_n \) is the cross-sectional area of the main duct. For such abrupt enlargements the static pressure ratio is given by

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

(12)

where \( \phi = A_1/A_2 \) and the suffixes 1 and 2 apply to the situations before and after expansion through an abrupt enlargement.

It was assumed that the static pressure at the exit of both the primary and secondary flows is atmospheric and therefore \( M_2 \) can be calculated by using equation (12). 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,

\[
V_2 = M_2 a_2 = M_2 (\gamma RT_2)^{1/2}
\]  

(13)

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

(14)

Fig. 23 Flow profiles from single, double and triple inlet cylindrical nozzles

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\[ p_2 = \left( \frac{p_2}{p_1} \right) \left( \frac{T_2}{T_1} \right) p_1 \]

Equations (12) to (15) are applicable to both primary and secondary flows.

A comparison of predicted and measured velocities

A typical industrial nozzle of cylindrical type with a trumpet-shaped diverging exit section has a typical main flow duct diameter of 2 mm with air inlet bore diameters of less than 1 mm, the total length of the nozzle being approximately 25 mm. It was very difficult to measure the flow from a nozzle of such a minute size, because even the smallest practicable flow measuring probe was thought to interfere with the flow from such a small nozzle and might cause significant disturbances in the flow. Thus, three experimental nozzles of larger size with single, double and triple inlet bores and a dynamically similar, scaled-up model of an industrial nozzle were constructed. These were designed to give the same flowrate. The main difference between the industrial texturing nozzles and experimental nozzles is that the latter did not have the trumpet-shaped diverging exit. All the experimental data presented were obtained from these larger nozzles.

Constant temperature anemometers (CTA) with hot wire and hot film probes were first considered for the axial velocity measurements, but these had to be abandoned due to the lack of mechanical strength of the wire or the film-coated elements in supersonic and intensely turbulent flows achievable with such nozzles. Consequently, a special pitot tube, designed and constructed in compliance with the standards, was used to measure the axial velocity profile at the nozzle outlet.

Experimental results were compared with those predicted by the mathematical model. These showed that the velocity distributions at the primary flow exit plane were approximately uniform for all three nozzles (Fig. 23), as was assumed by the mathematical model, and demonstrated close agreement with the theoretical predictions (12).

In order to investigate the effect of a trumpet-shaped diverging exit, the triple inlet nozzle used in the experiments was modified to give it a similar exit shape. Experiments with this modified nozzle showed that the axial flow velocity profile was no longer uniform (Fig. 23) and it had a depression in the centre. Since all other conditions were the same, this non-uniformity in the velocity profile is attributed to the modification of the exit shape of the nozzle.