A basic understanding of the air flow in texturing nozzles

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1. Introduction

In the USA, pioneer work has been done in the field of air-jet texturing since the early 1950's; Du Pont, for example, supplies 'Taslan' texturing nozzles to licensed users. These are of the converging-diverging type i.e. de Laval type nozzles. There are also other manufacturers who produce texturing nozzles very similar to the Taslan nozzles, but these share only a small fraction of the market.

Although the Heberlein Company of Switzerland is comparatively new in the market, it became a major texturing nozzle manufacturer in the mid 1980's. Heberlein's nozzles are of cylindrical type and are known by the trade name 'HemaJet'. Du Pont and Heberlein have each been producing different variations of their nozzle types, while keeping the main features of them unchanged. For example, Du Pont's range includes Taslan IX [1], X [2], XI [3], XIV [4], XV [5] and most recently XX [6]; Heberlein started with its 'Standard-core' HemaJet [7] and continued with other types such as T100, T300, T341 etc. [8]. The main structural features of the HemaJet and Taslan nozzles are compared in Fig. 1. The compressed air is admitted to the straight main channel of the HemaJet nozzle, where it is divided into primary and secondary flows, whereas in a Taslan nozzle air flows into the venturi through a circumferential gap and is then divided into primary and secondary flows. The choked flow in the throat of the Taslan nozzles is subsequently accelerated by the diverging section of the venturi, but no such controlled acceleration takes place in the HemaJet nozzles.

![Fig. 1 Structural comparison of the Taslan and HemaJet nozzles](image-url)
Investigation of the air flow in the Taslan nozzles was left outside the scope of this research mainly for two reasons; the Taslan nozzles utilise a very common supersonic nozzle configuration, i.e., converging-diverging nozzle, to which a well-known and proven flow theory is applicable, and many research workers [9, 10, 11-16] have already investigated this type of texturing nozzle in detail. HemaJet nozzles, however, are relatively recent and have not been investigated thoroughly. Apart from Acar’s prominent work [17] on these nozzles, very little published work exists. However, these nozzles are increasingly being used in today’s textile industry. Therefore, this chapter is devoted to a detailed and more thorough investigation of the cylindrical type, i.e., HemaJet nozzles. In this research, primarily the T100-type HemaJet with one inlet hole has been studied, since it typifies the whole range of HemaJet nozzles and the same principles of investigation apply to all cylindrical nozzles whether they have a single hole or three inlet holes.

In this paper, only the undisturbed air flow flowing through the mentioned nozzle is studied. Although it has been proven by Acar et al [18] that the presence of the filaments affects the flow to a large extent, a comprehensive understanding of air flow in the absence of filaments is first required. This investigation has led to the design of more efficient texturing nozzles [19].

2. Description of cylindrical texturing nozzles

The commercial texturing nozzles in this category consist of a cylindrical main duct into which one inlet hole or three inlet holes of smaller diameter are obliquely opened. The compressed air is admitted into the main duct through this (these) inlet hole(s), while the yarn follows a straight path in the nozzle as shown in Fig. 2. The yarn inlet section of the cylindrical duct is called the secondary flow section and the other end of the duct is the primary flow section usually with a trumpet-shaped divergent exit. In the early types of the HemaJets (e.g. the obsolete 'Standard-core'), this divergent exit had a smaller radius (small trumpet). However, all the recent HemaJets have trumpet-shaped exits with larger radii. A comparison of exit shapes of early and recent HemaJets is also seen in Fig. 2.

The major difference between various different HemaJets is the number of inlet holes and, with the exception of 'Standard-core', these are designated according to the number of inlet holes they possess [8]. The three inlet holes of the Standard-core HemaJet are not only radially equispaced but are also longitudinally slightly staggered. This configuration is said to impart a swirl to the air flow [20]. However, the recent HemaJet nozzles with three inlet holes, e.g. T 341, appear to have inlet holes on the same circumferential line, i.e., the staggered configuration has been eliminated. The two most common features of all cylindrical nozzles are that the ratio of the sum of inlet hole areas to the main duct area is always less than unity and the inclination of the inlet hole(s) to the main duct is at the same angle. These two features of HemaJet nozzles, together with other geometrical parameters, are broadly studied in Demir’s work [19]. Through this investigation their optimum values (from the air flow standpoint) are sought.

The research reported in this paper has been mostly undertaken experimentally, e.g. velocity measurement by use of pilot tubes, visualisation of flow by means of laser shadowgraphy and air mass flow rate measurement by rotameter.
Fig. 2 the HemaJet (a) Standard-core, (b) T100

Full-size cylindrical texturing nozzles, i.e., Standard-core, T100 and T341 HemaJets, have been used where possible. However, scaled-up nozzles have also been used to justify the experimental results obtained from the full-size nozzles.

Fig. 3 shows a HemaJet nozzle mounted in nozzle housing. It can be said that the compressed air that flows through the inlet holes is divided into two streams in the main duct. The primary flow, which has the largest momentum due to the inclination of the inlet hole, flows vigorously and creates a supersonic, asymmetric, non-uniform and turbulent air jet, as claimed by Acar et al [21]. The secondary flow having smaller momentum, flows in the opposite direction to the primary flow and is always subsonic and uniform. This description of the flow is insufficient, however correct, for the objectives of this paper. Therefore, the flow field will be divided into sub-sections and investigated in detail with a step by step approach. This subdivision, as dictated by the geometry of the nozzle, can be defined as follows:

a. The inlet hole
   1. convergent section
   2. sonic section
   3. abrupt enlargement and backward deflection

b. The main duct
   1. oblique impingement and division of the flow
   2. primary flow
   3. secondary flow

c. The jets
   1. primary jet (supersonic jet)
   2. secondary jet (subsonic jet)
3. **The inlet hole**

The experimental investigation of the air flow through the inlet hole has been done on a simplified scaled-up model as shown in Fig. 4. The first simplification is that the jet created by this model is assumed to expand into an infinitely large area at atmospheric conditions, although the cross-sectional area of the main duct of the texturing nozzles is finite and pressure builds up due to the static pressure recovery in the main duct. As the second simplification, the originally circular main duct is assumed to be rectangular. This facilitates visualisation of the flow at the very intersection of the inlet hole with the main duct. Furthermore, in order to facilitate the explanations which follow, the inlet hole is divided into three subsections as seen in Fig. 4.
3.1 Convergent section

The theory for compressed air flow in converging channels can be applied to the converging section of the inlet hole. It will be seen from the isentropic flow theory that if the reservoir pressure is above the critical value, the flow chokes at the throat of the converging section and delivers only the critical mass flow rate, the flow velocity being sonic. Since the working pressures of the texturing process are well above the critical value, texturing nozzles operate under choking conditions. Hence, at a given pressure, a nozzle delivers only the critical mass flow rate.

3.2 Sonic section

The sonic section (Fig. 4) is a cylindrical channel which continues from the throat of the convergent section. Since the length of this channel is short and no area change is observed, the flow conditions are assumed to remain constant throughout this section.

3.3 Abrupt enlargement and backward flow deflection

The total cross-sectional area of the inlet holes is always less than the cross-sectional area of the main duct. An abrupt enlargement of the sonic flow is, therefore, inevitable. Pressure losses occur there due to the abrupt enlargement of the flow, and therefore pressure energy is not fully converted into kinetic energy. Flow velocity reaches supersonic levels, but some energy is wasted due to the pressure loss.

When a sonic flow passes over a sharp convex corner, the flow accelerates and turns through large angles without separating; such deflection of a flow is termed 'Prandtl-Meyer deflection'. A Prandtl-Meyer deflection occurs at the intersection of the inlet hole and the main duct of the nozzle. The simplified and scaled-up model of the inlet hole, as shown in Fig. 4, is used to visualise this deflection. The shadowgraph of the phenomenon is given in Fig. 5a.

![Fig. 5 Shadowgraphs and line drawings of the jets created by the simplified and scaled-up model of the inlet hole with (a) oblique opening; and (b) square opening](image-url)
Since the intersection is oblique, the flow at point A deflects through a series of expansion waves (an expansion 'fan'), whilst the flow at point B is still sonic and parallel to the axis. The flow at point C, however, also observes the Prandtl-Meyer deflection. Nevertheless, the whole jet deflects 'backward' at point A (See Fig. 5a), because the flow reaches point A well before it reaches point C due to the oblique opening of the inlet hole. Hence the deflection at point A dominates and causes a total 'backward' deflection of the whole jet, whereas a similar model of the inlet hole without any oblique opening creates no flow deflection (See Fig. 5b).

Fig. 6 Variation of the backward flow deflection with increasing reservoir pressure

Shadowgraphs of the jets created by the simplified and scaled-up model of the inlet hole with the oblique opening have revealed that the total 'backward' deflection of the jet is a function of the driving pressure. The variation in this deflection angle with the driving pressure has been measured from the shadowgraphs and is shown in Fig. 6 together with the shadowgraphs of the jets. Fig. 6 shows that the higher the pressure, the more the jet is deflected backward. This backward deflection increases the angle of impingement of the incoming jet with the opposite wall. The secondary flow velocities, therefore, increase. Furthermore, these higher angles of impingement cause more flow losses and in turn create primary flow velocities which are lower than expected. Fig. 7, illustrating the deflection angle and the ratio of the primary flow rate to the total flow rate with varying air pressures, shows that as the backward flow deflection increases, the primary flow rate decreases.
Fig. 7 Variation of the primary flow rate to total flow rate with the reservoir pressure and its relation to the backward flow deflection

4. The main duct

Being a straight cylindrical channel, the main duct is of no aerodynamic significance. However, the impingement and division of the incoming jets occurs in this channel; moreover, the primary jet, which carries out the actual texturing, is formed at the end of the primary flow section of the channel. Although the secondary flow is always seen as a source of energy loss, this flow does contribute to the texturing by blowing off the applied water and the spin-finish constituents from the surfaces of the filaments. Therefore, the main duct will be investigated by dividing it into three sub-sections.

4.1 Oblique impingement and division of the flow

In the case of the T100 HemaJet, only one incoming jet carries the whole mass flow of the air into the main duct. The impingement of this jet on the opposite wall of the main duct, and its division, have been experimentally investigated in this section. In order to be able to visualise this oblique impingement and the reflection of the flow in the main duct, the originally circular duct had to be converted to a square cross-section with transparent walls (Fig. 8).

The investigation of this two-dimensional flat nozzle was made in three steps. In the first step, the opposite wall to which the incoming jet impinges was removed and the incoming jet was visualised by the shadowgraph method. This is a slightly deflected jet conforming to the preceding study in Section 2.3 (Fig. 9a). In the second step, the counterwall was mounted, but no glass walls were used, and the shadowgraph of the impingement was taken (Fig. 9b). This illustrates that the incoming jet creates a normal shock wave obliquely attached to the opposing wall. The flow naturally disperses in all directions due to the absence of side walls. Lastly; the glass side walls of the nozzle were mounted, thus forming a square main duct. When the flow was visualised (Fig. 9c), it was observed that the normal shock wave attached to the wall had become a detached shock wave. The mass of the incoming flow was diverted to the primary flow section of the nozzle after this shock wave. It was also noted that the expansion waves crossed the whole secondary flow section, whereas in the primary flow section they only crossed less than half of the channel. In both directions after the expansion waves, the pressure became less than the upstream pressure. In the secondary flow section, this corresponds to a pressure equal to or less than the atmospheric pressures.
Fig. 8 2.5-times scaled up 2-dimensional nozzle with glass walls

Fig. 9 Shadowgraph of the jet from the transparent flat nozzle: (a) with no counterwall; with counterwall but without glass side-walls; and (c) with both counterwall and glass walls
The entire flow divides into the primary and secondary flows in such a way that the secondary flow momentum flux, (depending on the working pressure), only varies between 15% and 30% of the primary flow momentum flux, as seen in Table 1.

Table 1. Momentum flux division for T100 HemaJet Nozzle

<table>
<thead>
<tr>
<th>Air pressure (bar-gauge)</th>
<th>Primary flow momentum flux kgm/s²</th>
<th>Secondary flow momentum flux kgm/s²</th>
<th>Primary to secondary flow flux ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.522</td>
<td>0.078</td>
<td>14.94</td>
</tr>
<tr>
<td>6</td>
<td>0.644</td>
<td>0.111</td>
<td>17.23</td>
</tr>
<tr>
<td>7</td>
<td>0.713</td>
<td>0.192</td>
<td>26.92</td>
</tr>
<tr>
<td>8</td>
<td>0.799</td>
<td>0.223</td>
<td>27.90</td>
</tr>
<tr>
<td>9</td>
<td>0.860</td>
<td>0.278</td>
<td>32.23</td>
</tr>
</tbody>
</table>

4.2 Primary flow

Due to the inclination of the inlet holes, a greater portion of the incoming flow, despite the backward deflection of the incoming jets, goes to the primary flow section of the nozzle (Table 1). The speed of the flow is supersonic, provided that the reservoir pressure is well above the critical value.

An acceleration or deceleration of a supersonic flow requires an area change. Being a cylindrical channel, the main duct of the nozzle fails to fulfil this requirement. Consequently, no velocity change is observed by the flow, until the divergent section of the duct is reached. As soon as the flow area increases, the speed of the flow increases at the expense of pressure, in other words the flow expands and the flow pressure decreases. The rate of the divergence is so large that the flow cannot follow the full contour of the surface and separates as is seen in Fig. 10 which shows the shadowgraph of the primary flow from the transparent walled square nozzle. Thus a free air-jet is created. Fig. 10 also shows the expansion waves emanating from where the divergence of the main duct starts.

Fig. 10 Shadowgraph of the primary jet showing the beginning of the divergence and the expansion waves
4.3 Secondary flow

The static pressure measurements obtained by Acar et al [21], using wall tappings, and the static pressure measurements which have been carried out by Demir [19] using a centre line static pressure tube, both indicate that the secondary flow pressure is atmospheric. Very little momentum occurs in the secondary flow direction as is noted in Table 1. Therefore, the secondary flow is almost exclusively subsonic for all the working pressures and appears to have no significance.

5. The jets

Both the primary and the secondary flows create free jets when they leave the nozzle walls. Being supersonic, the primary jet possesses many characteristics whilst the secondary jet is fully subsonic and uniform.

5.1 The primary jet (supersonic jet)

A general background study, resorting to the established theory and published works of an axisymmetric supersonic jet, is given in Appendix A.

5.1.1 Experimental investigation

Since the aim of this research was to investigate industrial texturing nozzles, it was most desirable to conduct experiments using them. However, certain characteristics of these nozzles make it difficult, if not impossible, to conduct satisfactory investigations due to difficulties associated with the geometry of the texturing nozzles. As seen in Fig. 11, the jet emerging from the T100 HemaJet can only be visualised much further downstream; however, the most complicated part of the jet is at the very exit of the diverging section of the nozzle as indicated by $L_{sc}$ for the Standard-core and $L_{T100}$ for the T100 nozzles respectively. On the other hand, both the walls of the texturing nozzles’ diverging exit interfere with the flow measurement (pitot) probe, and thus a complete velocity trace across the jet cannot be obtained; the presence of the probe is also likely to block the flow.

![Fig. 11 Jets emerging from: the Standard-core HemaJet; the T100 HemaJet;](image-url)
These shortcomings of the use of texturing nozzle in the supersonic jet investigation suggested another supersonic jet model needed to be devised. The simplest solution to this was thought to be a straight pipe. Although this only produces sonic velocity at the exit, as soon as the sonic flow with a pressure which is higher than the ambient pressure reaches the exit, it suddenly expands and becomes supersonic due to both the pressure difference and the sudden change of area. Such a jet has been utilised in the further experimental research. Fig. 11 also shows that, by using such a pipe, the flow velocities even at the very exit section could be measured without any interference with the solid walls of the pipe, and in addition, the flow could be visualised from the exit plane onwards.

For the jet from such a straight pipe, an ‘average’ shadowgraph, obtained by f (leans of a fairly long light exposure. and an instantaneous shadowgraph, taken by using a high-speed flash, are given in Figs. 12a and b respectively. These two shadowgraphs clearly delineate the expansion fans as white bands and the shock waves as dark bands where the density gradient changes rapidly [22]. The instantaneous shadowgraph also shows the turbulent nature of the jet. These shadowgraphs are reconstructed in Fig. 12c.

By using a fine pilot tube, the total pressures were recorded at 0.2 mm intervals in both the radial and axial directions up to 4 pipe diameters. The measured values are given in Fig. 13a in topographic form. Since the total pressure is related to the local kinetic energy (static pressure being constant as atmospheric pressure), the high and
low velocity regions are shown in this figure. It was thought to be informative to show the distribution of the centre line total pressure and the total pressure distribution across the jet at different distances downstream from the exit plane. Therefore, these are also included in Fig. 13 a, b and c respectively.

![Diagram](image)

Fig. 13 Illustrations of total pressure measurement results for the jet from a straight pipe: (a) total pressure distribution in topographic form; (b) total pressure distribution on the centre-line; and (c) traverse total pressure distributions at different locations downstream from the exit plane

5.1.2 Centre line velocity fluctuations

In order to elaborate further on the behaviour of the supersonic jet emerging from an underexpanded nozzle, the centre line total pressure distribution given in Fig. 13b is repeated on Figs. 12a, and 12b. It is seen from this representation that the flow decelerates up to the point where the intersection of the expansion waves occurs. Having passed this intersection point, the flow recovers rapidly (See Fig. 12), then slows down up to the point where the shock waves have intersected. Further downstream from the jet, these rises and falls of the centre line total pressure are repeated, and they finally fade out due to the viscous and turbulent mixing of the jet into the surrounding atmosphere.

5.1.3 Non-uniform axial velocity distribution

The axial total pressure distribution illustrated in Fig. 13c is not of the same pattern at various distances from the exit plane. It is fairly uniform just at the exit plane, whilst a central deficit is observed in the downstream section of the jet. However, further
downstream where the viscous mixing through a thick boundary layer dissipates the flow, the traverse velocity distribution across the jet becomes bell-shaped.

In order to shed more light on this phenomenon, the plane numbered III in Fig. 13c will be considered in conjunction with the corresponding cross-section AA of Fig. 12c. When the pitot tube (which is parallel to the flow) is held at the point 1, the lowest total pressure is recorded, because the point 1 is on the boundary line. At the point 2 which is at the outer border of the expansion fan, the flow pressure is atmospheric, and the flow passing through the expansion has been accelerated. Therefore, the highest flow velocity is recorded at the point 2. By advancing in the expansion fan from the points 2 to 3, less accelerated flow is observed due to the smaller number of expansion waves through which the flow has passed. As soon as the point 3 is reached, the least flow velocity is recorded, because the streamline at the point 3 is not affected by the expansion waves at all. From points 3 to 4, the flow is uniform and parallel to the nozzle axis. A reversed pattern is recorded when the pilot tube is traversed from the points 4 to 7.

Similar axial velocity distributions are observed at different distances from the exit plane, but the level of the central deficit varies from one point to another due to the formation of expansion and/or compression waves which causes acceleration or deceleration of the flow as seen in Fig. 13c. Finally, further downstream, the central deficit disappears because of the dissipation of the density discontinuities i.e., shock or expansion waves. Thus the velocity profile becomes a bell-shaped. For this reason, the axial velocities measured at the exit plane of the T 100 nozzle (which is located at 4.5D, D being the nozzle diameter further downstream from the beginning of the diverging section where the flow separates) do not show any central deficit. Neither do the centre-line velocities fluctuate, as is seen in Figs. 14a and b.

![Fig. 14 (a) The primary jet traverse velocities at the exit plane of the T100 HemaJet at various driving pressures, (b) the primary jet centre-line velocities of the T100 HemaJet at various driving pressures](image)

5.2 Secondary jet (subsonic jet)

When the secondary flow leaves the nozzle, it creates a secondary jet which is subsonic. The pressure in the jet is atmospheric and no density discontinuities are present. Fig. 15a shows the secondary jet axial velocities at various working pressures for the T100 HemaJet nozzle.
These are all subsonic and of uniform distribution. In addition to this, the centre-line velocities for this nozzle at various pressures are shown in Fig. 15b. The figure shows that the flow velocity remains constant indicating a potential core.

6. Results of flow measurements with the HemaJets

6.1 Axial velocity profiles

At varying air pressures, the axial velocity distributions at the exit plane of the Standard-core, T100 and T341 nozzles are given in Figs. 16a, b, and c respectively. These velocity distributions are also presented in 3-dimensional and topographic form, in Figs. 17a, b, and c for a typical 7-bar supply pressure.

From these figures, the supersonic and non-uniform nature of the flow can be seen. The asymmetric nature of the flow is obvious in the case of the T100 jet (Fig. 16b), whereas the other nozzles more closely approximate to symmetrical air velocity distributions. Some dissimilarities in the axial velocity profile from these three nozzles were observed (See Fig. 16).

6.2 Shock waves and centre-line velocities

Flows from all these nozzles at different pressures were also studied by using a shadowgraph system in order to obtain a better understanding of them. From the shadowgraphs and the centre-line velocity fluctuations (which are also indicators of the occurrence of shock waves) as shown in Figs. 18a, b, and c, it can be concluded that the strengths of the shock waves produced by different nozzles are varying. Since the shock waves are known to affect the velocity distribution as discussed in Section 4.1.3, it is not surprising to see different velocity profiles from different nozzles with varying degrees of shock strengths.
Fig. 16 (a) The air velocity distribution of the jet produced by the Standard-core HemaJet at varying pressures, (b) the air velocity distribution of the jet produced by the T100 HemaJet at varying pressures, (c) The air velocity distribution of the jet produced by the T341 HemaJet at varying pressures

Shock waves are surmised initially to occur at the start of the trumpet-shaped exit part where the flow separates from the wall of the nozzle. This point is 2 nozzle diameters to the exit plane in the Standard-core nozzle, is 4.5 nozzle diameters in the T100 nozzles, and is 3 nozzle diameters in the T341 nozzle. Since the repetitive shock waves will gradually diminish and expand to the ambient atmospheric conditions, waves of relatively lesser strengths are highly unlikely to be observed in the emerging flows from different nozzles with various diverging shape and sizes. For instance, the T341 nozzle, even at high pressures, produces no clearly visible shock waves outside the nozzle, whilst the Standard-core nozzles produce relatively strong shock waves (Fig. 18). Since the strong shock waves do not dissipate in very short distances and repeat themselves periodically in the further downstream of the flow as seen in Fig. 18a, they are expected to be visible (by a flow visualisation technique) outside the nozzle. Therefore it can be argued that different nozzles produce shock waves of different strengths.
Fig. 17 (a) 3-Dimensional and topographic representation of the air velocity distribution of the jet produced by the Standard-core HemaJet at 7 bar pressure, (b) 3-Dimensional and topographic representation of the air velocity distribution of the jet produced by the T100 HemaJet at 7 bar pressure, (c) 3-Dimensional and topographic representation of the air velocity distribution of the jet produced by the T341 HemaJet at 7 bar pressure

Fig. 18 (a) Centre-line velocities and shadowgraphs of the flow from the Standard-core HemaJet at varying pressures, (b) Centre-line velocities and shadowgraphs of the flow from the T100 HemaJet at varying pressures, (c) Centre-line velocities and shadowgraphs of the flow from the T341 HemaJet at varying pressures
6.3 Turbulence

The turbulent nature of the jets created by several nozzles was demonstrated by means of a high-speed shadowgraphy technique. Fig. 19 shows two such photographs obtained from jets created by: (a) a straight pipe at 7 bar supply pressure; (b) the Standard-core HemaJet at 9 bar supply pressure, and (c) a Taslan nozzle XIV at 9 bar supply pressure. It is seen that the instantaneous shadowgraph of the jet from a straight pipe is almost the same as that obtained with long exposure times indicating the less disturbed nature of the flow. However, the other shadowgraph of the jet from the Standard-core HemaJet nozzle illustrates the local density variations caused by the highly turbulent nature of the flow.

Furthermore, by comparing these shadowgraphs, it could be suggested that this higher turbulence is created by the oblique impingement of the incoming jets of the HemaJet nozzles.

7. Interactions between the air-jet and the filaments

In the course of the investigations reported up to this point, all the air jets were free of disturbances from the filaments. During the actual texturing process, however, overfed filaments exist in the nozzle, and they are transported through the nozzle and entangled to form a looped structure by the action of the air flow. It is, therefore, highly likely that a mutual interaction between the filaments and the air flow will take place, and in turn the characteristics of the air flow will change as discussed by Acar et al [18] as well as Bock and Luenenschloss [15]. This interaction has been investigated by means of air velocity measurements, shadowgraph techniques, and high-speed still photography during the actual texturing process.

7.1 Velocity measurements during the texturing process

Using the flow measurement techniques, the velocities of the air flow during the actual texturing process have been measured. In order to avoid any possible interference with the filaments, the pitot tube has been kept at a distance of 1.5 nozzle diameters from the exit plane. The presence of the water droplets in the flow causes ice formation just at the tip of the measuring probe, which consequently made the measurements impossible.

Two different methods were deployed to defrost the probe. The first one involved an external heating of the probe so that the condensed water particles would be evaporated. This was done by focusing an intense light onto the probe and the nozzle. Although the heat released from the light did not affect the texturing process itself, the probe holder expanded due to the intense heat, resulting in the uncontrolled displacement of the probe. This method of defrosting the instrument was, therefore, abandoned.
Fig. 20 (a) Centre-line velocities measured during the texturing process at 5 bar, (b) Centre-line velocities measured during the texturing process at 7 bar, (c) Centre-line velocities measured during the texturing process at 9 bars

Fig. 22 Instantaneous process shadowgraphy with the Standard-core HemaJet at 5 and 9 bars

The second method considered was heating of the water. Before making any attempt to do this, the possible effects of the water temperature on the process itself and the resultant textured yarns is needed to be ascertained. As is disclosed by Demir [19], at the
end of that investigation, it was concluded that the effect of water temperature in the range of 15-65°C was negligible. Having obtained this result, the air velocity measurements were carried out at 65°C water temperature. Unfortunately, at high pressures and low texturing speeds, ice formation still hindered the smooth running of the measurements and cast some doubt over the repeatability and reliability of the results. Some results, however, were obtained, and Figs. 20a, b, and c show the centre-line velocity fluctuations at 5, 7, and 9 bar pressures respectively. Fig. 21 also shows the axial flow velocities at 1.5 D distance from the exit plane in the vertical diameter. These figures clearly indicate that the presence of the filaments in the nozzle reduces the flow velocity and makes the shock waves weaker. The degree of the velocity deceleration due to the filaments is almost equal for all the driving pressures used.

![Fig. 21 Axial velocity profile recorded during texturing process](image)

### 7.2 Shadowgraphy during the texturing process

The instantaneous shadowgraphy of the process was performed at different process conditions with the Standard-core Hemajet nozzle because this nozzle produces the strongest shock waves. The shadowgraph given in Fig. 22 illustrates that a substantial change in the characteristics of the jet occurs in that shock waves are partly destroyed and the intensity of turbulence is increased by the presence of the filaments in the flow.

No consistent relation between the shock waves and the turning points of the filaments as claimed by Bock and Luenenschloss [14-16] could be detected.

### 8. Conclusions

In an attempt to describe the flow through HemaJets, the cylindrical type nozzles, the following conclusions have been achieved:

i. The flow is choked at the throat of the inlet hole and delivers only the critical mass flow determined by the reservoir pressure.

ii. Flow in the inlet hole is only sonic and possesses excess pressure again determined by the reservoir pressure.
iii. Due to the sudden opening of the inlet hole into the main duct, abrupt enlargement losses which create energy loss are inevitable.

iv. The oblique opening of the inlet hole deflects the incoming jet backward, and consequently increases the angle of collision to the opposite wall.

v. The oblique collision of the incoming jet is a paramount source of energy loss.

vi. The primary flow is supersonic in the main duct, whereas the secondary flow remains subsonic both in the main duct and in the jet form.

vii. Further acceleration of the primary flow occurs at a place where the divergence of the main duct starts. However, the flow soon separates from the wall of the nozzle because of the large divergence of the trumpet-shaped exit.

viii. Since the supersonic jet has pressures above atmospheric, it creates an underexpanded supersonic jet. The properties of this jet have been investigated by means of another underexpanded jet created by a straight pipe. The results are applicable to the jets created by all the texturing nozzles under consideration.

ix. The axial velocities from a supersonic jet fluctuate on the centre-line due to the semi-periodic expansion and compression of the flow.

x. The non-uniform distribution of the flow velocities is due to the formation of pressure waves and the viscous and turbulent mixing of the flow on the boundary layer.

xi. Being a subsonic jet, the secondary jet has the characteristics of all well-defined subsonic jets.

The current investigation has also shown that the air flows from various texturing nozzles, despite the substantial differences in their geometrical configurations, are supersonic. However, the strength of shock waves created by these supersonic air flows may vary from one nozzle to another, or indeed shock waves may not exist at all. A non-uniform velocity profile, on the other hand, is common to all the texturing nozzles, whereas the axial centre-line velocity fluctuations which are caused by the formation of the shock waves may also vary from one nozzle to another. Turbulence, as visualised by the instantaneous shadowgraph technique, is found to be highly intensive in the flows created by the HemaJets due to the oblique impingement of the incoming jets.

The flow investigations carried out during the texturing process illustrated that the flow velocity is decreased and the shock waves are partially destroyed by the presence of the filaments in the flow. Numerous instantaneous shadowgraphs taken at different texturing conditions did not reveal any obvious correlation between the loop and entanglement formation and the occurrence and position of the shock waves as argued by Bock and Luenenschloss [14-16]. Therefore, it can be concluded, as Acar et al [21] claimed, that the shock waves do not appear to contribute to the loop and entanglement formation. Absence of shock waves in certain nozzles is further evidence that supports this conclusion.
REFERENCES

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