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Main Features of Overexpanded Triple Jets

Gamal H. Moustafa*
Menoufia University, Shbien El-Kom, Egypt

The flowfield of an overexpanded triple free jet has been investigated. The flowfield was generated by three Laval nozzles set in a common end wall with equal spacing in a triangular configuration. Total pressure measurements were made for three exit Mach numbers of 1.5, 2, and 2.5 with the range of stagnation pressure from 2.9 to 4.5 atmospheres. The spacing between the nozzles based on the throat diameter was varied as 2.8, 3.6, 4.4, and 6. The triple jet has been compared to a single jet operating at the same initial flow conditions. It is shown that the triple jet in triangular configuration undergoes a transformation in its shape and axis orientation. The triple jet spreads at the base side more than at the top side. The differential spreading rate generates more flow disturbance and, therefore, enhances the mixing process.

Introduction

THE mixing of supersonic multijet flows has application in a wide variety of fields. It is used, for example, in jet engine/rocket combustors and the thrust augmenting ejectors for VTOL/STOL aircraft and industrial gas burners. In fact, such flows are quite complex, involving turbulent flow mixing, compression and expansion waves/shear layer interaction, acoustic coupling between neighboring jets, and mutual interaction between the jets. In view of these complexities and to achieve proper combustion, thrust development, and reduction in the noise level, it is often desirable to control the intermixing between the jets and also the entrainment of the surrounding atmosphere. This, in turn, requires a detailed study of the behavior of high-speed jets in multijet configuration. The situation of interest here is an array of three Laval nozzles set in a common end wall with equal spacing in a triangular configuration (Fig. 1). The reason why this particular configuration has been chosen is that it promotes bending of the jet axes toward each other, thus leading to greater mixing.

There have been a number of experimental investigations over the past few decades directed toward the measurement of flowfields of single jets. The main concerns of the available literature on multijet flows are with the turbulence characteristics of incompressible jets and the acoustic behavior of compressible jets. Turbulent incompressible jet flows have been studied by Sforza et al.,[1] Tanaka and Nakata,[2] Krothapalli et al.,[3] and Quinn.[4,5] These authors have performed mean flow and turbulence measurements and have analyzed the effects of nonaxisymmetric nozzle geometries. The results obtained lead to the conclusion that low-speed jets originating from nonaxisymmetric orifices decay to form axisymmetric jets far downstream. Asymmetric jets (elliptic, triangular, rectangular, etc.) have also shown to be capable of entraining large amounts of surrounding fluid relative to those entrained by circular jets. As observed by Quinn,[5] these jets spread in the minor axis plane more than in the major axis plane, resulting in axis switching.

Moreover, the near acoustic field and shock cell structure of noncircular supersonic jets have been investigated by Krothapalli et al.,[6] Schadow et al.,[7] and Gutmark et al.,[8,9] while the noise generation mechanisms of high-speed multiple jets have been studied by Raghunathan and Reid[10] and Krothapalli et al.[11] Some investigators have used the acoustic feedback mechanisms (sound reflectors near the nozzle exit[12]) or fingers or slots added to the nozzle exit[13] to alter the mixing and noise characteristics of the underexpanded jets. Improved mixing and absence of screech tone were observed. Also, the flow and acoustic features of supersonic tapered nozzles have been investigated by Gutmark et al.[14] Krothapalli et al.[11] have studied the edge tones in high-speed flows and their effect on multiple jet mixing. Improved mixing of the multiple jet occurred when a wedge was placed in one of them. Furthermore, supersonic jet interactions have been considered by Wlezien[15] and Gamal.[16] The mean and turbulent velocity characteristics of incompressible round jets impinging through a cross flow have been studied by Barata et al.[17] In their investigation, the flowfield was generated by two jets in line and three jets in a triangular configuration. No investigations have so far been reported regarding the behavior and development of compressible triple jet configurations. In the present study, experiments have been conducted to investigate the effect of exit Mach number, stagnation pressure ratio, and nozzle spacing on the mean flow characteristics of compressible jets in triangular configuration. The individual flow features of the vertex top jet and the base twin jet are analyzed, and their contributions to the overall triple jet behavior are highlighted. Comparison with a single jet is provided.

Experimental Setup and Procedure

Compressed dry air was passed through the gate valve and pressure regulating valve into the settling chamber, Fig. 1. It was then accelerated through an array of round nozzles and released into the ambient atmosphere in the form of free jets. Mesh wire screens were inserted inside the settling chamber to produce a uniform flow at the nozzle exit. Three models of Laval nozzles with design Mach numbers M_e of 1.5, 2, and 2.5 were used. The throat diameter d_t was 5 mm for all of the nozzles, whereas the exit diameter and the nozzle length were varied according to the design Mach number. The spacing between the nozzles ($S = s/d_t$) was chosen as 2.8, 3.6, 4.4, and 6. The pressure ratio p_0/p_a was varied from 2.9 to 4.5. The Reynolds number based on the nozzle exit diameter, for the present range of exit Mach number and pressure ratio, was varied from 4.2×10^4 to 2.7×10^5. The distribution of the total pressure in the jet was measured by a pitot tube of 0.5-mm i.d. Time averaged (mean) values of total pressure were measured at several X, Y, and Z locations downstream of the nozzle exit. The nozzles were held horizontal and were aligned parallel to the X axis of the three-dimensional traversing system. The traversing system had a uniform pitch of 0.5 mm in all three directions. The distance between the nozzle axes and the floor was kept sufficiently large to ignore the wall effects in the present experiment. The stagnation pressure p_0 was maintained with an accuracy of ± 1.7% whereas the total pressure reading (pitot pressure p_t) across the jet was uniform within ± 0.6%. The uncertainty in the nozzle spacing was ± 1.6% and in the nozzle throat and exit diameters was ± 1.2%. Also, the uncertainty in the dimensionless measuring spacings x/d_t, y/d_t, and z/d_t was ± 0.006. Throughout the paper, measurements were made along the three mentioned planes shown in Fig. 1.

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*Lecturer, Department of Power Mechanical Engineering, College of Engineering & Technology.

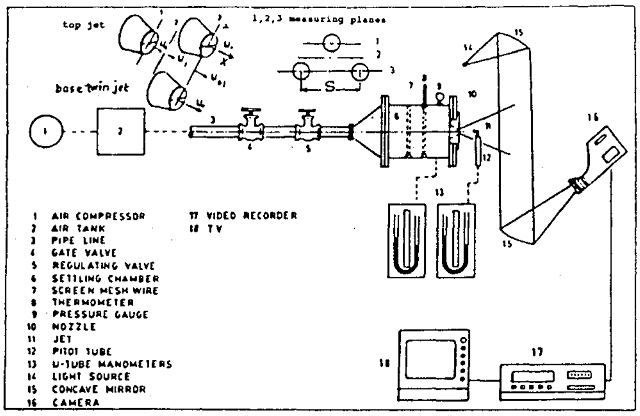

Fig. 1 Experimental apparatus.

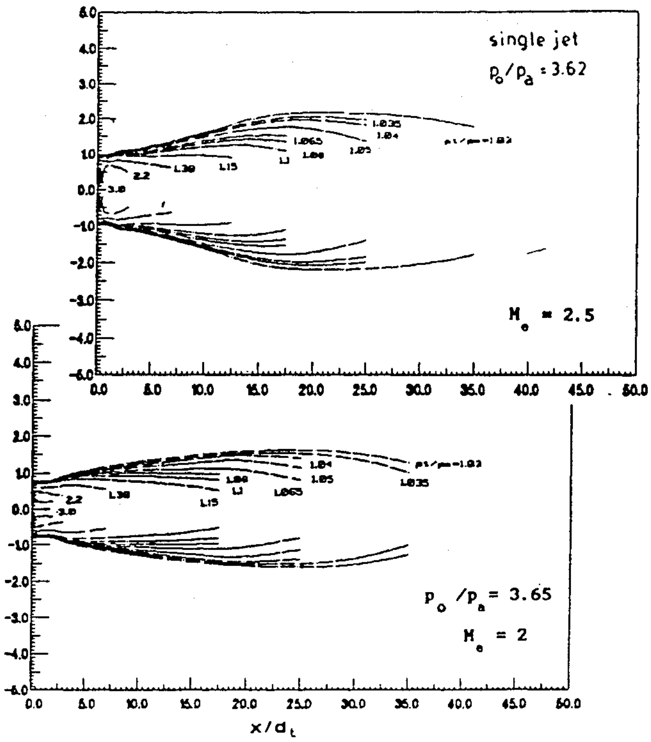

Fig. 2 Total pressure contours of the single jet.

Results and Discussion

The total pressure contours of the single jet are shown in Fig. 2 for $M_e = 2$ and 2.5. It is important to note that all of the jets are overexpanded. From this figure it can be seen that immediately after the nozzle exit the jet spreads sidewise and the jet width increases with axial distance as the jet moves downstream. The shock cell patterns (shown as oscillation patterns in the contours) appear in the core region for each jet. The main features of the pressure contours are almost similar for different exit Mach numbers. However, it is apparent from the figure that, at the same value of p_0/p_a, the jet width changes with the exit Mach number. This is because at a constant value of stagnation pressure the degree of overexpansion varies with the exit Mach number. In turn, the initial jet divergent angle changes and, therefore, the jet width alters. This is also because the screech tones associated with supersonic jets change with the exit Mach number. The screech tones, in fact, under certain conditions, help to induce large-scale vortical motions in the jet.[18] The interaction between these vortical motions and the shear layer as well as the shock waves leads to an alteration of the jet growth rate. These results are in accord with those obtained by Gutmark et al.,[8] who measured the jet width of underexpanded sonic jets through schlieren photographs.

Figure 3 shows the total pressure contours of the top jet for $M_e = 2$. In the near field, the contours depict similar structure of shock cell patterns which are also observed within the single jet. In Fig. 3a, the contours of the top jet with different nozzle spacings for $M_e = 2$ show considerably different behaviors from those of the single jet. Comparing the results in this figure with those in Fig. 2, the following observations can be made. Reflecting the effect of jet interaction on the flowfield (the effect of the base twin jet on the top jet), the top jet spreads to greater downstream distance. This behavior of the top jet is related to the increase of the subatmospheric region between the jets which generates a large amount of entrainment. This, in fact, enhances the far-field mixing. It is also seen that the behavior of the top jet depends considerably on the nozzle spacing. For $S = 2.8$, the top jet spreads smoothly, and the jet width is maximum around $x/d_t = 45$. For increasing S ($S = 3.6$), the effect of the base jet is stronger, as is clearly seen in the figure. The jet width increases with distance, and its boundaries assume a curved shape. At a distance of about $x/d_t = 20$, the jet width shows a steep increase, indicating greater interaction between the top and base twin jets. For $S = 4.4$, another structure of the top jet is shown. A sharp variation of the pressure contours is observed in many places, especially in the merging region ($8 < x/d_t < 20$). The jet width is maximum around $x/d_t = 35$. For $S = 6$, once again the top jet changes its structure and exhibits behavior similar to that of $S = 2.8$. However, the jet boundary grows up to $x/d_t = 20$ and then propagates parallel to the abscissa. This also shows that for higher values of S, the top jet behavior comes close to that of the single jet, but due to combination with the base twin jet it spreads for a longer distance. The same observation can be made for other Mach numbers. It is clear from the results that the structure as well as the jet spreading rate for the multijet vary considerably for different combinations of exit Mach number and nozzle spacing.

In Fig. 4, the pressure contours of the base twin jet for $M_e = 1.5$ are given for different nozzle spacings. Similar to the top jet, the pressure contours show considerably different behaviors for different S. The general features are almost similar; for instance, the two jets attract each other, mix and combine, and then the combined jet spreads as a single jet. There is a good similarity between the behavior of the pressure contours of the base twin jet and that of the top jet corresponding to every S. For $S = 2.8$, the contours of the base jet moves smoothly. The width of the combined base jet is larger compared to that of the top jet which results in a larger spreading rate in the base side relative to that in the top side. This difference in the spreading rates is necessary in many industrial applications for promoting mixing. For $S = 3.6$, a different structure is evident. At $x/d_t = 20$, the jet boundaries move in a straight line parallel to the x axis. The waviness associated with the jet boundary in the near field may be caused by the jet expansion due to entrainment and the compression by the ambient atmosphere. It might also be related to the jet stability.[8] For $S = 4.4$, the mean behavior of the contours is similar to that of $S = 3.6$, with larger width. The sudden jump in the jet width is also seen as in the top jet but at different locations. At $S = 6$, the base jet spreads smoothly, and there is a good correspondence between the top and base jet behaviors.

Figure 5 illustrates the total pressure profiles of the single jet as a function of exit Mach number. For supersonic flows, the pressure profiles are more meaningful than the calculated velocity profiles. This is because the results from a pitot tube cannot be converted directly into velocity or Mach number because of the unknown entropy increase that occurred in the core region. This is due to the shock waves associated with supersonic flows. In this figure, close to the nozzle exit, the total pressure profiles indicate the presence of a potential core region surrounded by an axisymmetric shear layer. The centerline total pressure deficit in this region is related to the upstream shock wave (Mach disk). Although this behavior appears for every Mach number, the distribution of the average total pressure tends to be flat, like that of a low-speed jet. For $x/d_t > 10$, the shock waves disappear, and the fully developed behavior of the jet flow dominates. The distributions at $x/d_t = 20$ and 30 appear

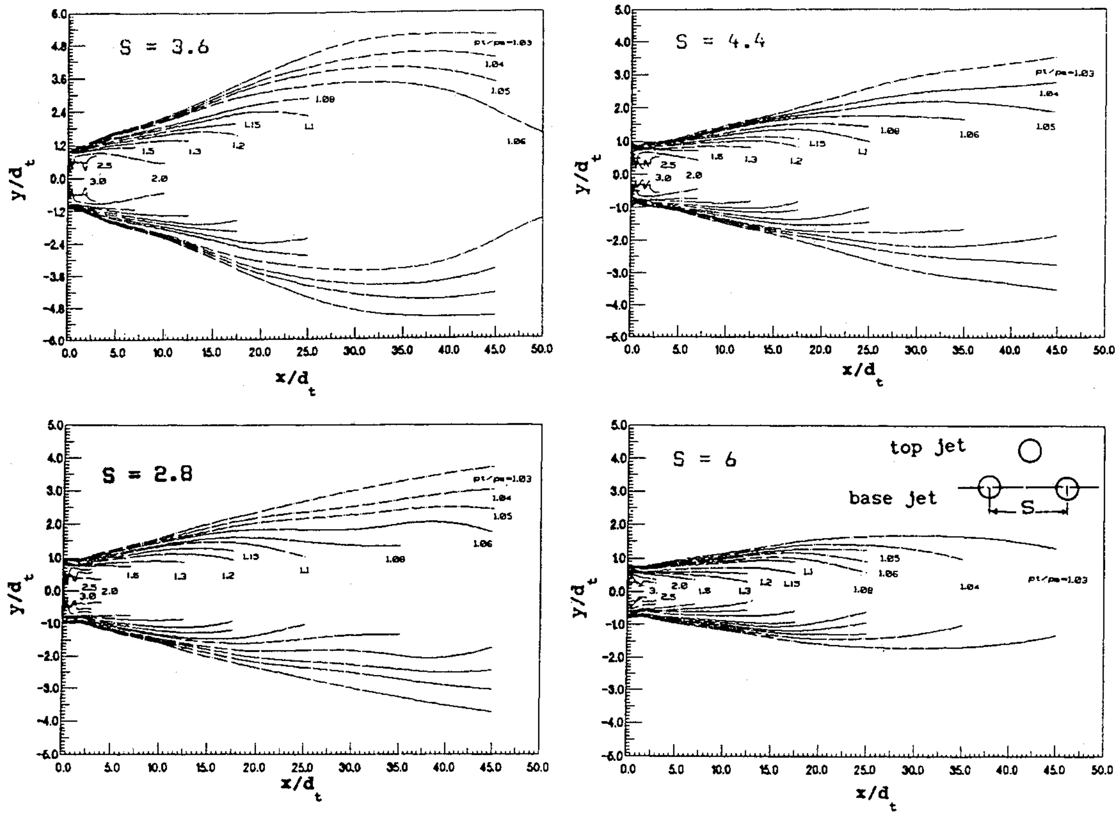

Fig. 3 Total pressure contours of the top jet, $M_e = 2.0$ and $p_0/p_a = 3.65$.

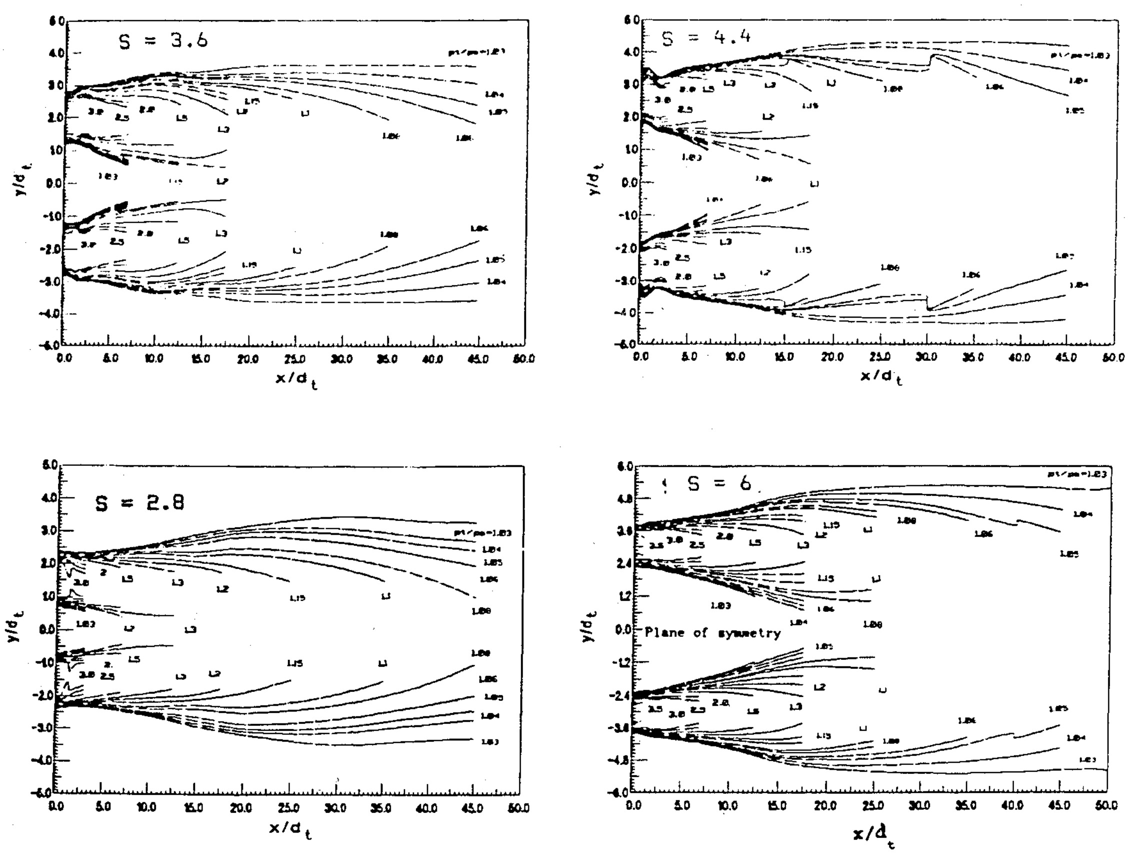

Fig. 4 Total pressure contours of the base jet, $M_e = 1.5$ and $p_0/p_a = 3.65$.

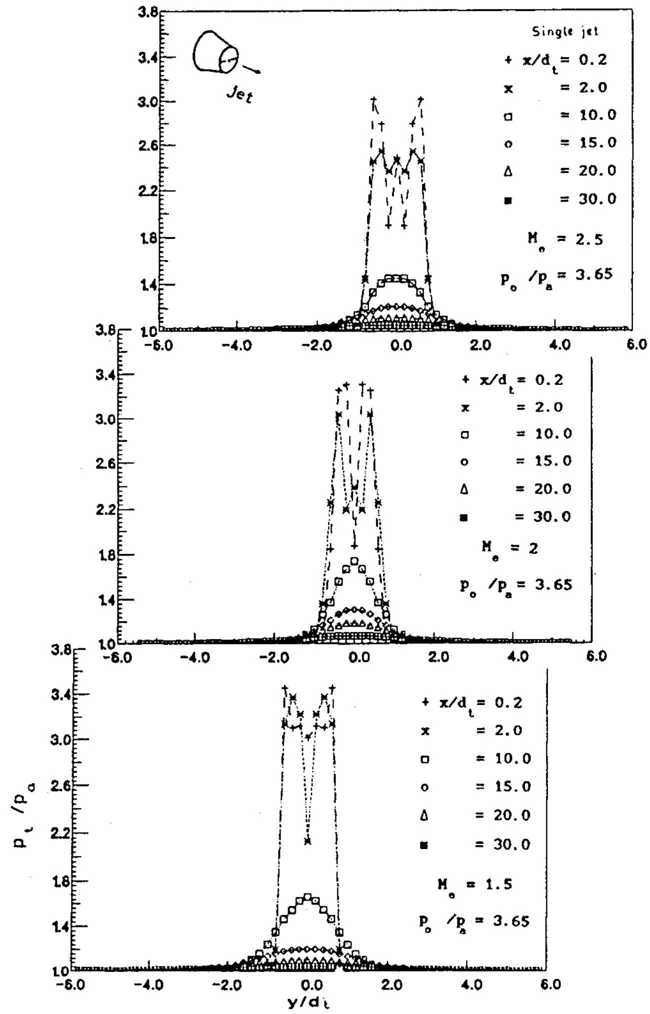

Fig. 5 Total pressure profiles of the single jet.

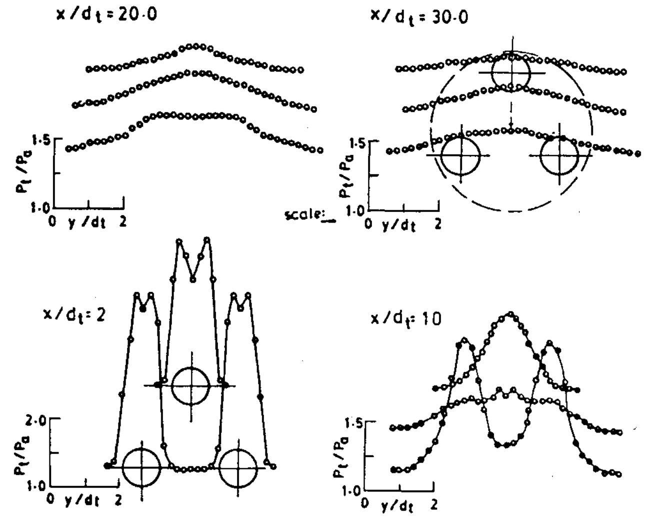

Fig. 6 Triple jet behavior, $M_e = 1.5$, $p_0/p_a = 3.62$, and $S = 2.8$.

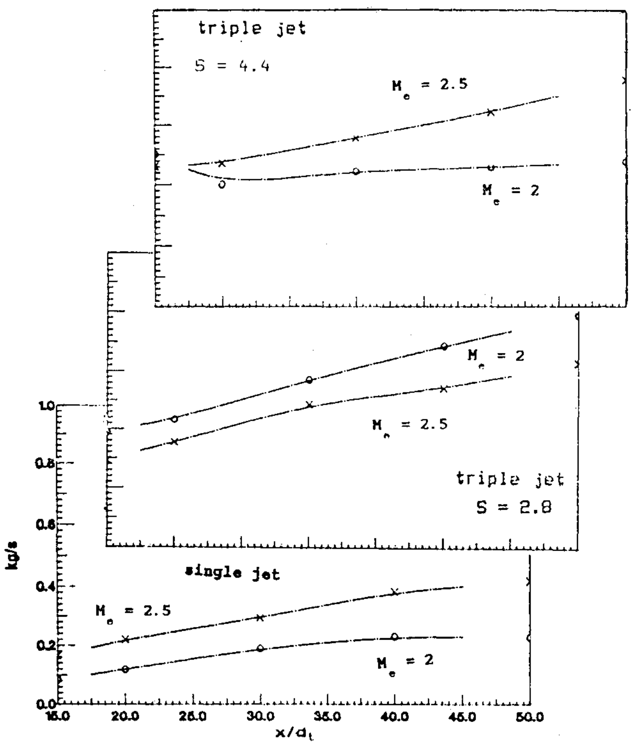

Fig. 7 Entrainment of the ambient fluid.

to be almost similar. It is also seen that the general features are similar for various Mach numbers. However, it is clear that in the near field there are many differences between the flow structures, especially in the shock wave strength and position.

Figure 6 shows the triple jet behavior at four downstream stations indicating the different stages of development of the flowfield. The figure shows the total pressure reading taken along the three measuring planes [at the top jet, the middle section between the top and base jets, and at the base twin jet (Fig. 1)]. In fact, for multijet configurations, the flowfield of high-speed jets is found to consist of three distinct regions, namely the converging, merging, and combining regions. The results show that in the near region ($x/d_t = 2$), the pressure profiles are seen at planes 1 and 3 whereas at the second plane, the pressure profile does not yet appear. This means that at this location, the top jet and the base twin jet are still in the converging regime. Between the two base jets, there exists a region where the pressure is below the ambient pressure; but across the jet, the pressure rises suddenly about the ambient pressure. Beyond the jet core region ($x/d_t > 10$), the profiles are seen without any oscillation patterns (shock waves). The profile at the second plane has also appeared indicating that the jets are now in the merging region. It is clear that the two base jets also merge whereas the top jet exhibits almost a fully developed behavior, and its width is greater than that at $x/d_t = 2$. Also, the peak of the total pressure is lower than that at $x/d_t = 2$, and the peaks of the top jet and base jet profiles are higher compared to that at the second measuring plane. The observed trend of the pressure profile at the second plane is due to the interaction between the top and base jets. The jet width at the base side is clearly larger than that at the top side. At $x/d_t = 20$, the profiles are seen just before the combining point. The total pressure of the second plane at this location is higher than those at the top and base planes. This indicates that both the top and base jet axes have shifted to a location lying between the jets. Farther downstream ($x/d_t = 30$), the profiles on all three planes have the same trend and the same width. This means that the three jets have combined to form a single jet. If one draws a contour plot through the triple jet (say, for $p_t/p_a = 1.075$), it can be observed that the $p_t/p_a = 1.075$ contour has a circular shape with its origin lying approximately at a distance of $h/3$ from the base side (shown by a cross in Fig. 6). It means that the combined jet has an axisymmetric profile. The streamwise variation of the pressure field, as the triple jet develops downstream, is noteworthy. In fact, such a pressure field variation leads to enhancement of the far-field mixing.

The mass flux has been calculated via integrating the area under the curve (for the total pressure profiles) assuming that axisymmetric profiles exist in the merging and combing regions. The results are shown in Fig. 7. For the single jet, the mass flux increases with Mach number. With regard to the base twin jet, the mass flux

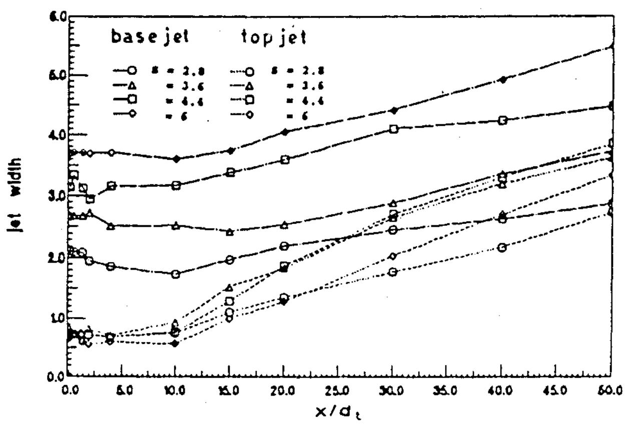

Fig. 8 Width of the triple jet, M_e = 1.5 and p_0/p_a = 3.65.

is governed by the nozzle spacing as well. For S = 4.4, the result agrees with that of the single jet with respect to the influence of Mach number. However, the opposite behavior is observed for S = 2.8. In general, the triple jet configuration implies higher mass flux than the single jet. This result supports the earlier observation.

Flowfield measurements show that the overexpanded triple jet in a triangular configuration also undergoes a transformation in its shape and axis orientation downstream, as seen in Fig. 6. The unequal spreading rate between the top and base sides produces a crossover point. The jet width in Fig. 8 is defined as the distance from the jet centerline (the plane of symmetry in the case of the base twin jet) to the location in the Y direction where the total pressure p_t drops to 50% of its centerline value. In Fig. 8, the crossover point associated with the triple jet can be seen clearly as corresponding to the location where the curves of the jet width of the top jet and those of the base twin jet crossover. Downstream of this point, the combined jet has almost a circular shape. The distance from the exit plane to the crossover point depends on the nozzle spacing. The unequal spreading rate was obtained by many investigators using asymmetric single jets.[5,8]

Conclusions

The main objective in many industrial applications is to get better mixing between the fuel and oxidizer streams. The present study provides a lot of new data on the interaction and mixing of supersonic jets which have not been observed in the previous investigations. Some of the important results obtained by this study are given as follows.

1) The exit Mach number, stagnation pressure ratio, nozzle spacing, and nozzle configuration have strong influences on the interaction process and the bending phenomena.

2) In the far field, the jets attract each other, mix, and finally combine to form a single jet. The combined jet has an axisymmetric shape, and it spreads to a longer distance than that of a single jet. The interaction process in the far field is also affected by the nozzle configuration. The nozzle configuration considered in the present study enhances the mixing process. The enhanced mixing is attributed to the large amount of entrainment and the flow disturbance generated by the bending of the jet axes. The entrainment increases the mixing between the jet flow and the ambient fluid, whereas the flow disturbance enhances the mixing between the individual jets.

3) Finally, the bending of the jet axes and its effect on the shock cell structure might help to reduce the noise level associated with supersonic jets.

References

[1]Sforza, P. M., Streuger, M., and Trentacoste, N., "Studies on Three Dimensional Viscous Jets," *AIAA Journal*, Vol. 4, No. 5, 1966, pp. 800–806.

[2]Tanaka, E., and Nakata, S., "The Interference of Two-Dimensional Parallel Jets," The Region Near the Nozzles in Triple Jets, Third Rept., *Bulletin of the Japan Society of Mechanical Engineers*, Vol. 18, No. 124, 1975, pp. 1134–1141.

[3]Krothapalli, A., Baganoff, D., and Karamcheti, K., "Development and Structure of a Rectangular Jet in a Multiple Jet Configuration," *AIAA Journal*, Vol. 18, No. 8, 1980, pp. 945–950.

[4]Quinn, W. R., "On Mixing in an Elliptic Turbulent Free Jet," *Physics of Fluids*, Vol. A1, No. 10, 1989, pp. 1716–1722.

[5]Quinn, W. R., "Mean Flow and Turbulence Measurements in a Triangular Turbulent Free Jet," *International Journal of Heat and Fluid Flow*, Vol. 11, Sept. 1990, pp. 220–224.

[6]Krothapalli, A., Hsia, Y., Baganoff, D., and Karamcheti, K., "On the Structure of an Underexpanded Rectangular Jet," Stanford Univ., AIAA-TR-47, Stanford, CA, July 1982.

[7]Schadow, K. C., Gutmark, E., Koshigoe, S., and Wilson, K. J., "Combustion Related Shear Flow Dynamics in Elliptic Supersonic Jets," *AIAA Journal*, Vol. 27, No. 10, 1989, pp. 1347–1353.

[8]Gutmark, E., Schadow, K. C., and Bicker, C. J., "Mode Switching in Supersonic Circular Jets," *Physics of Fluids*, Vol. A1, No. 5, 1989, pp. 868–873.

[9]Gutmark, E., Schadow, K. C., and Bicker, C. J., "Near Acoustic Field and Shock Structure of Rectangular Supersonic Jets," *AIAA Journal*, Vol. 28, No. 7, 1990, pp. 1163–1170.

[10]Raghunathan, S., and Reid, I. M., "A Study of Multiple Jets," *AIAA Journal*, Vol. 19, No. 1, 1981, pp. 124–127.

[11]Krothapalli, A., Karamcheti, K., Hsia, Y., and Baganoff, D., "Edge Tones in High Speed Flows and Their Application to Multiple Jet Mixing," *AIAA Journal*, Vol. 21, No. 7, 1983, pp. 937, 938.

[12]Glass, D. R., "Effects of Acoustic Feedback on the Spread and Decay of Supersonic Jets," *AIAA Journal*, Vol. 6, No. 10, 1968, pp. 1890–1897.

[13]Krothapalli, A., McDaniel, J., and Baganoff, D., "Effect of Slotting on the Noise of an Axisymmetric Supersonic Jet," *AIAA Journal*, Vol. 28, No. 12, 1990, pp. 2136–2138.

[14]Gutmark, E., Bowman, N. L., and Schadow, K. C., "Flow and Acoustic Features of a Supersonic Tapered Nozzle," *Experiments in Fluids*, Vol. 13, 1992, pp. 49–55.

[15]Wlezien, R. W., "Nozzle Geometry Effects on Supersonic Jet Interaction," *AIAA Journal*, Vol. 27, No. 10, 1989, pp. 1361–1367.

[16]Gamal, H. M., "Experimental and Numerical Investigations of Subsonic, Sonic and Supersonic Multiple Free Jets," Ph.D. Thesis, Dept. of Mechanical Engineering, Indian Inst. of Technology, Kanpur, India, Aug. 1992.

[17]Barata, J. M., Durao, D. F., and Heitor, M. V., "Velocity Characteristics of Multiple Impinging Jets Through a Cross Flow," *Journal of Fluids Engineering*, Vol. 114, June 1992, pp. 231–239.

[18]Powell, A., "The Noise Emanating From a Two Dimensional Jet Above the Critical Pressure," *Aeronautical Quarterly*, Vol. 4, Feb. 1953, pp. 103–122.