AIAA JOURNAL
Vol. 33, No. 5, May 1995

Interaction of Axisymmetric Supersonic Twin Jets

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

Measurements are reported of the pressure fields within overexpanded supersonic twin jets. The flowfield was produced by two identical parallel axisymmetric Laval nozzles set in a common end wall and issuing into the ambient atmosphere. A mainstream flow in the jet is presented, with the design Mach number of 1.5, 2, and 2.5 throughout the experiments. The stagnation pressure was varied from 2.9 to 4 atm. The nozzle spacing was chosen as 14, 18, 22, and 30 mm. The twin jets are compared to circular supersonic single jets operating at the same initial flow conditions. The studies show that structure of supersonic twin jets is identical to that of low-speed twin jets. The two jets attract each other, mix and then combine to form a single jet. The flowfield, therefore, contains three distinct regions, namely, converging, merging, and combining regions. The merging between the jets occurs in the distance close to the nozzle exit for smaller nozzle spacings and higher Mach numbers. The shock cell structure as well as the mixing process vary with the exit Mach number and nozzle spacing. The spreading rate shows an irregular variation with the exit Mach number. There is a transition region between the near and far field at which the overexpanded jet starts to spread linearly with downstream distance as that of a low-speed jet.

Introduction

SUPERSONIC jets have been used in many engineering applications: The propulsion systems of many high-performance aircraft such as F-15 and B-1B use twin nozzle configurations. Thus, multiple supersonic jets, axisymmetric and asymmetric in an array in parallel or opposite directions have been a subject of recent investigations.[1,2]. The objective of these studies was to achieve better mixing, to control noise, and to develop thrust. Hence, most of the earlier investigations on multijets have been concerned on the structure and turbulence characteristics of the flowfield for incompressible jet flows and the screech phenomenon for high-speed jet flows. The mean velocity and velocity fluctuation for a low-speed rectangular jet in a multiple jet configuration were measured by Krothapalli et al.[3] Lin and Sheu[9] studied the unventilated low-speed twin jet. The flow and noise characteristics of jets placed around a central jet operating at 520 m/s were studied by Raghunathan and Reid.[5] Reduction in the noise level was achieved when multijets were used. Krothapalli et al.[6] 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. Seiner et al.[7] defined and studied the mechanism of the twin plume resonance. The coupled interaction of supersonic twin jets as a function of nozzle spacing was investigated by Wlezien.[1] Gamal[8] carried out experimental and numerical studies on over- and underexpanded multiple free jets. On the other hand, the main behavior of high-speed single jets has also been reported by many investigators. Krothapalli et al.[9] studied the flowfield of two-dimensional underexpanded jets. They found that the spread rate and the minor axis side grew even further, relative to a subsonic flow. Schadow et al.[10] showed that an underexpanded elliptic jet of $M_e = 1.26$ had a larger growth rate relative to a subsonic elliptic jet. A possible explanation for the high-spreading rate of underexpanded jets could be related to the interaction between the expansion/compression waves and the jet shear layer.[11] Measurements made by Gutmark et al.[12] with underexpanded sonic jets showed irregular change of the jet spreading rate with the Mach number. This behavior was attributed to a change in the jet acoustic mode with the Mach number. The flow and acoustic features of over- and underexpanded jets issuing from tapered nozzles were studied by Gutmark et al.[13] No similar data is available in literature for axisymmetric overexpanded multijets.

The objective of the present investigation is to describe the overexpanded twin jet structure and dependence of the spreading rate of such jets on the nozzle exit Mach number. The study also includes the effects of stagnation pressure and nozzle spacing on the flowfield behavior. Comparison with single jets at the same flow conditions is provided.

Experimental Apparatus and Procedure

The airflow was generated by a blowdown facility shown in Fig. 1. Stored high-pressure dry air was ducted through control valves into a settling chamber. A control gate valve at the exit of the storage tank and a pressure regulating valve were used to adjust the stagnation pressure p_0 at the desired value in the settling chamber. The air was passed through three mesh wire screens, set 3 cm apart in the cylindrical settling chamber to reduce the air turbulence at the nozzle inlet. Axisymmetric Laval nozzles with design Mach numbers M_e of 1.5, 2, and 2.5 were used. The throat diameter of the nozzles (d_t) was 5 mm and the exit diameter was varied according to the design Mach number. The nozzle profiles are given in Fig. 2. The spacing between the nozzles S was chosen as 14, 18, 22, and 30 mm. The nozzles were held horizontal and were aligned parallel to the X axis of a traversing system. The traversing system with a uniform pitch of 0.5 mm in the X, Y, and Z directions was used. Measurements of the total pressure were made with a pitot tube (Fig. 2). The flow pattern was filmed using a spark light schlieren system, in conjunction with two 250-mm-diam concave mirrors. The flow pattern was first photographed by a video camera and recorded onto a video cassette. Pictures were later taken from the video cassette. The room temperature was almost constant with an error of ±0.5°C during the experimental program. The nearest wall from the apparatus was as far as 3.5 m so that wall effects could be neglected. The stagnation pressure was varied from 2.9 to 4 atm and was maintained with an accuracy of ±1.7%, whereas the reading total pressure p_t across the jet was uniform within ± 0.6%. The uncertainty in the nozzle dimensions was ± 1.2%, and in the normalized spacings x/d_t and y/d_t was ± 0.006.

Results and Discussion

Figure 3 shows the distribution of the total pressure along the Y axis at $x/d_t = 0.2$, 2, 10, 20, and 40. In the near field, each jet behaves as the single jet in which the oscillation patterns (shock patterns) are clearly seen. There is a negative pressure region between the jets whose exist can be explained as follows. From the central portion of the twin jet, fluid is entrained into the shear layers adjacent to the jets. However, the fluid entrained has to be replaced by surrounding atmospheric air. Because the flow of the outside air is unable to replace the entrainment in the central region of the jets

Received March 1, 1993; revision received Sept. 25, 1994; accepted for publication Oct. 18, 1994.

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

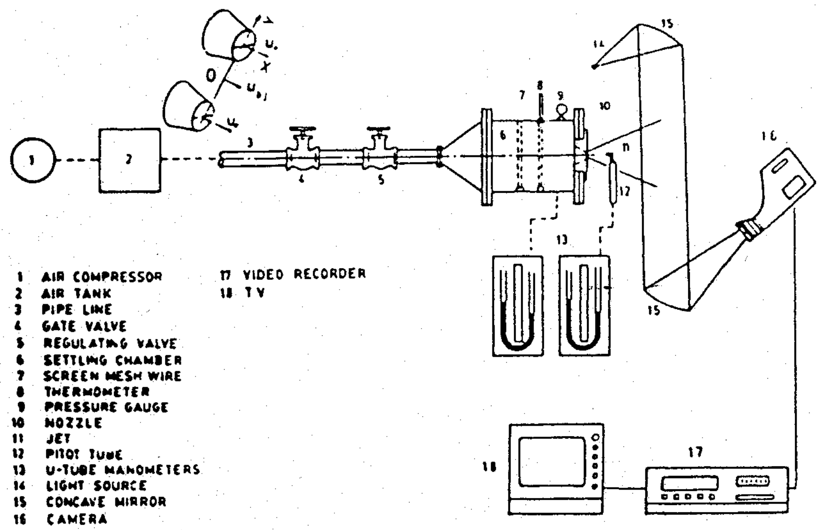

Fig. 1 Experimental apparatus.

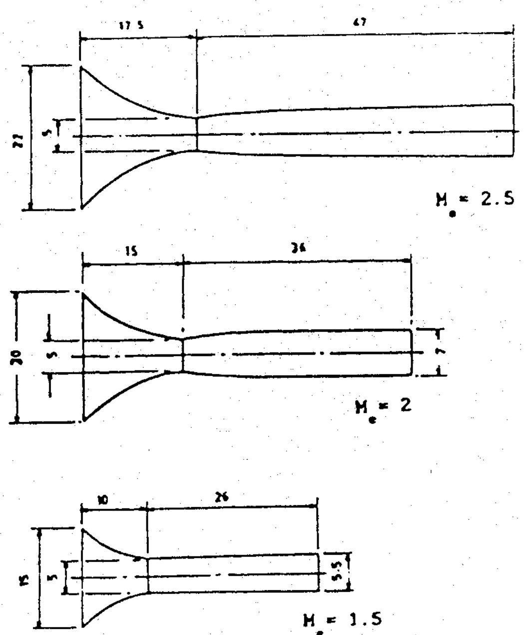

Fig. 2a Supersonic nozzle profiles.

Dimensions in mm

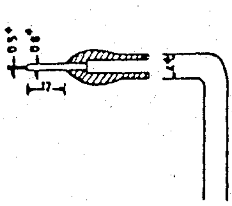

Fig. 2b Pressure probes.

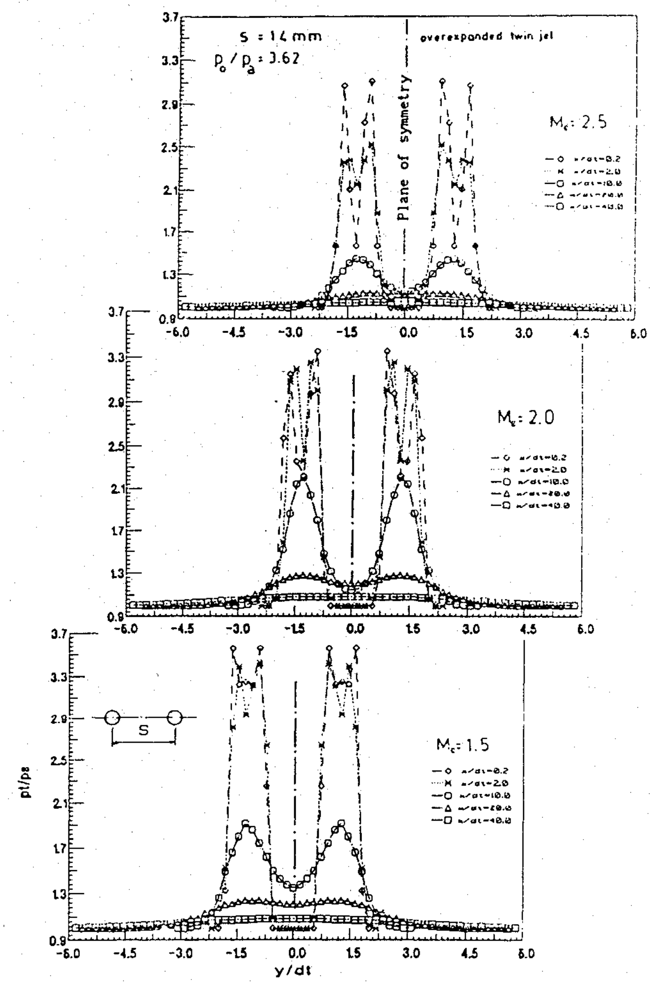

Fig. 3 Total pressure profiles of the twin jet.

(due to the front wall between the jets as well as the shock waves in the near region of the jet), the pressure in that zone becomes subatmospheric. Therefore, the two jets attract each other. The maximum total pressure and its location from the X axis decrease with the distance from the nozzle. Then, the two jets approach the plane of symmetry and this region is termed the converging region. The merging region follows the converging region where the two jets intermix. The total pressure in the plane of symmetry increases gradually from zero at the merging point until it reaches a maximum just upstream of the point where the two jets combine to form a single jet. The combined jet behaves as the single jet, and the fully developed behavior appears. This behavior is quite similar for all of the tested Mach numbers and nozzle spacings. However, the merging point is found to be proportional with the nozzle spacing. The two jets merge over the distance range, $5 \leq x/d_t \leq 20$, whereas the combining between jets occurs with the range of x/d_t from 20 to 30. The maximum value of the total pressure changes with Mach number as well as nozzle spacing. The influence of nozzle spacing on the maximum total pressure can be attributed to the attraction between the jets which leads to bending of the jet axes toward the axis of symmetry. The axes bending affects the shock cell structures which leads to alteration of the shock strength and, in turn, the maximum total pressure.

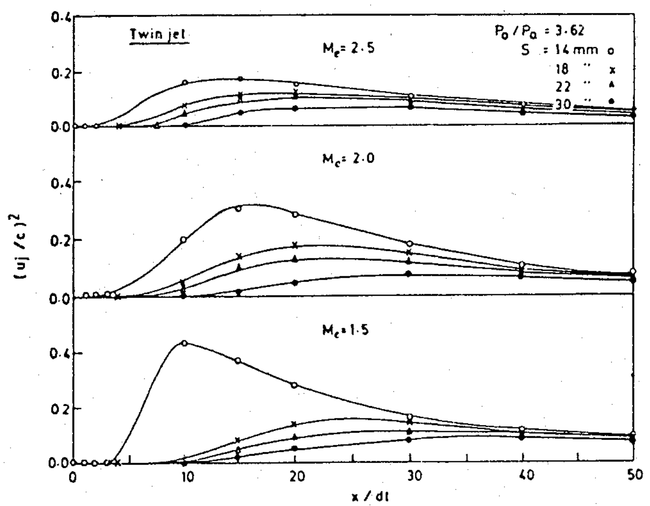

Fig. 4 Variation of the jet velocity of the twin jet.

The beginning of the merging region depends on the nozzle spacing and initial flow conditions. This can be seen in Fig. 4, which indicates the variation of the jet velocity u_j in the plane of symmetry with downstream distance for different exit Mach numbers. The effect of nozzle spacing on the jet velocity as well as the onset of the merging process are also depicted in the figure. The jet velocity is normalized by the acoustic velocity c calculated based on the room temperature. The jet velocity increases gradually from zero at the merging point to become maximum at a point just upstream of the combined point and again decreases as the jet decays far downstream. The peak velocity u_{max} decreases with increasing nozzle spacing, which indicates that for smaller nozzle spacings, u_j shifts more rapidly toward the plane of symmetry. As a result, the processes of merging and combining between jets are faster. Far downstream, there is no difference between the jet velocity for all nozzle spacings. This implies that the combined jet flow behavior is quite similar for different S and that it is essentially an incompressible jet flow. The effect of the exit Mach number on u_j is significant. The jet velocity decreases with an increase of the exit Mach number for all tested nozzle spacings. This is due to the fact that with an increasing exit Mach number, the jet velocity increases and the density ratio decreases. As a consequence, with an increasing Mach number, the jet decays rapidly and the peak value becomes lower.

The total pressure contours of the twin jets are shown in Fig. 5. The overexpanded twin jet exhibits several features similar to a low-speed twin jet.[4] Indeed, the three regions defined in the previous section are clearly seen. The two jets attract each other, mix, and finally spread as a single jet. The nozzle spacing plays a vital role in

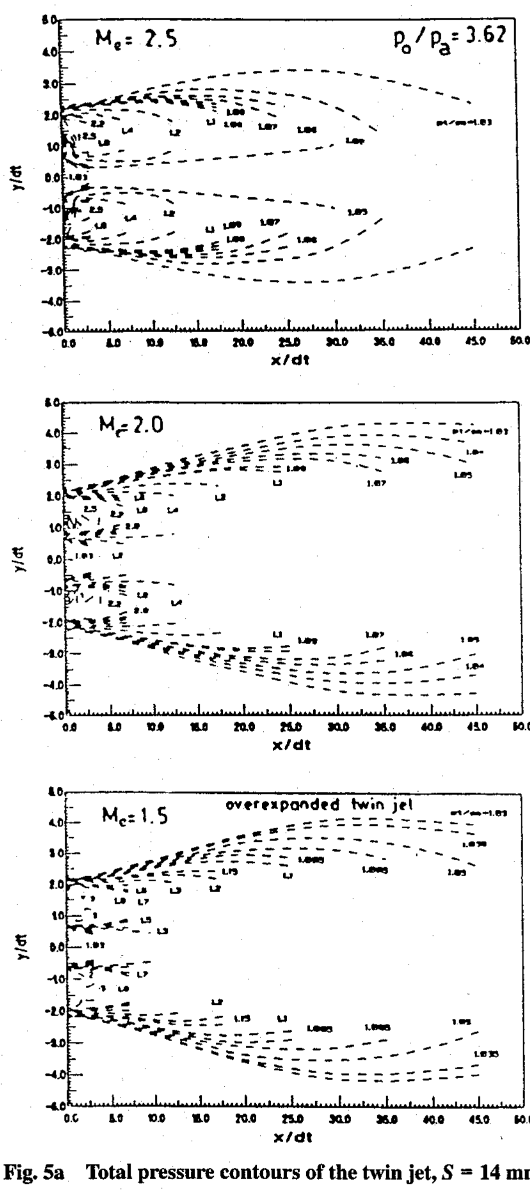

Fig. 5a Total pressure contours of the twin jet, S = 14 mm.

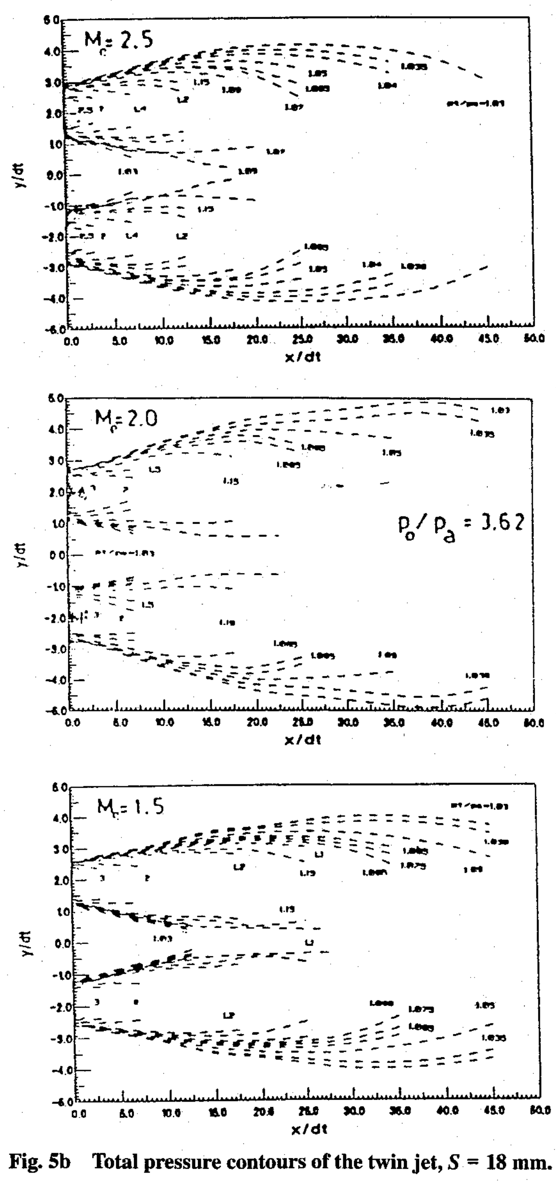

Fig. 5b Total pressure contours of the twin jet, S = 18 mm.

the interaction process as well as the spreading rate. Since each jet becomes a sound source for the feedback loop, especially for smaller values of S. The interaction between the sound waves generated from each jet and also between them and the initial portion of the jet is capable of altering the acoustic disturbances as well as the mixing process. The axes bending is also strongly affected by the nozzle spacing. It increases as the nozzle spacing is increased. Also, the pressure contours and the jet width change with the exit Mach number. The shock pattern is observed in the near field for each jet of the twin jet configuration. The interaction between the jets significantly affects the structure of the shock cells. This in turn, affects the twin jet structure, decay, and spreading rates.

Figure 6 shows the effect of nozzle spacing on the decay rate of the twin jet at $M_e = 1.5$ and 2. Close to the nozzle exit, due to the complex nature of the shock patterns, it is not possible to explain exactly what happens with a change in the nozzle spacing. For $5 \leq x/d_t \leq 30$, the nozzle spacing shows a significant influence on the jet decay rate. A comparison of the twin jet decay rate with that of the single jet shows that the twin jet decay rate is lower, in general, for all nozzle spacings. For an overexpanded single jet, the effect of the surrounding atmosphere is to compress it from all sides. As a result of such strong compression, the strength of these shocks is high (the jet velocity is maximum and the density ratio is minimum) and, therefore, the single jet decays more rapidly. On the other hand, for a twin jet, the region enclosed between the two jets experiences subatmospheric pressure levels. Therefore, compression due to the ambient atmosphere occurs from one side only on each of the jets. Thus, the shocks that arise due to compression waves are less severe for the twin jet configuration so that the density ratio is greater compared to that of the single jet and, therefore, the decay rate is lower.

Several definitions have been used to calculate the spreading rate of the jet. The most important of them are as follows. The jet half-width $y_{0.5}$ is the distance from the jet axis (the axis of symmetry-in the case of the twin jet) to the location in the Y direction where the total pressure becomes half of the total pressure along the jet axis. The approximate full jet width $y_{0.05}$ is where the total pressure is 0.05 of the total pressure along the jet axis at the same value of downstream location.

Figure 7 shows the growth of the single and twin jets at various downstream locations. The effect of nozzle spacing on the jet growth is plotted in Fig. 8. It is seen that the jet changes its spreading rate as a function of the axial distance. There is an initial transition in the near-field region, where the spreading rate is different from that of the far-field or the fully developed region. The boundary between the two regions changes with the initial flow condition and nozzle spacing. In the first 10 nozzle throat diameters from the nozzle exit, the spreading rate of the jet is affected by the existence of compression/expansion waves. Beyond this region, the half-width spreads linearly with the distance from the nozzle exit as a low-speed incompressible jet.[14] The full jet width exhibits a curved shape. This behavior of the full width is attributed to the viscous dissipation effects.

Comparison between the growth of the single and twin jets shows that, in the near field, the jet half-width of the twin jet is greater than that of the single jet. For $x/d_t \geq 10$, both the single and twin jets grow linearly with downstream distance. However, the slope of the half-width of the twin jet is slightly smaller than that of the single jet. The lower spread rate for the twin jet is attributed to the streaming effect of the entrainment fluid as well as the axes bending. The cross-over point between the half-widths of the single and twin jets depends on the nozzle spacing. For $S = 14$ mm, the cross-over point is located at $x/d_t = 35$ and for $S = 18$ mm, at $x/d_t = 45$. For higher values of S ($S = 22$ and 30 mm), it is located beyond $x/d_t = 50$.

Figure 9 shows schlieren photographs of the flow pattern for the twin jet at different pressure ratios. The photographs seen in this figure cover a distance of $0 < x/d_t < 10$ from the nozzle exit plane. In fact, they clearly show several interesting features of the jet flow structure in the near field but are not useful for studying the far field where the jets intermix. Therefore, a sample is given in the present report. These pictures show that the near field is influenced by the stagnation pressure. The shock patterns and the jet shear layer are clearly observed in these pictures. The jets increase their sizes and come closer to each other as they spread downstream.

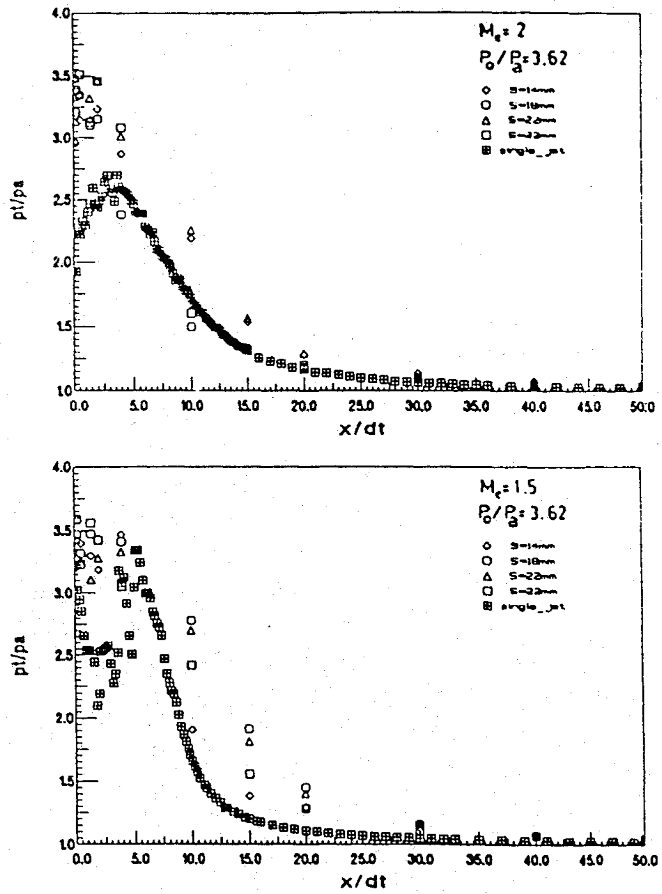

Fig. 6 Effect of nozzle spacing on the jet decay.

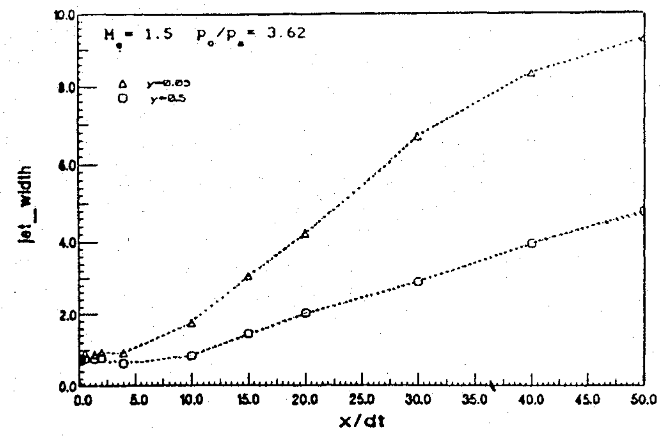

Fig. 7a Spreading ratio of the single jet.

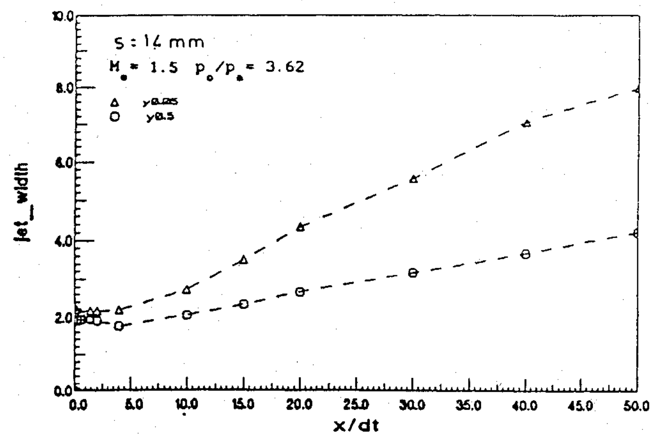

Fig. 7b Spreading ratio of the twin jet.

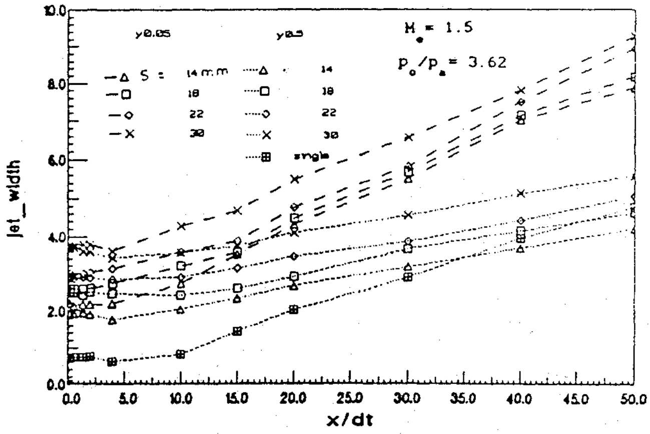

Fig. 8 Spreading ratio of various nozzle spacing.

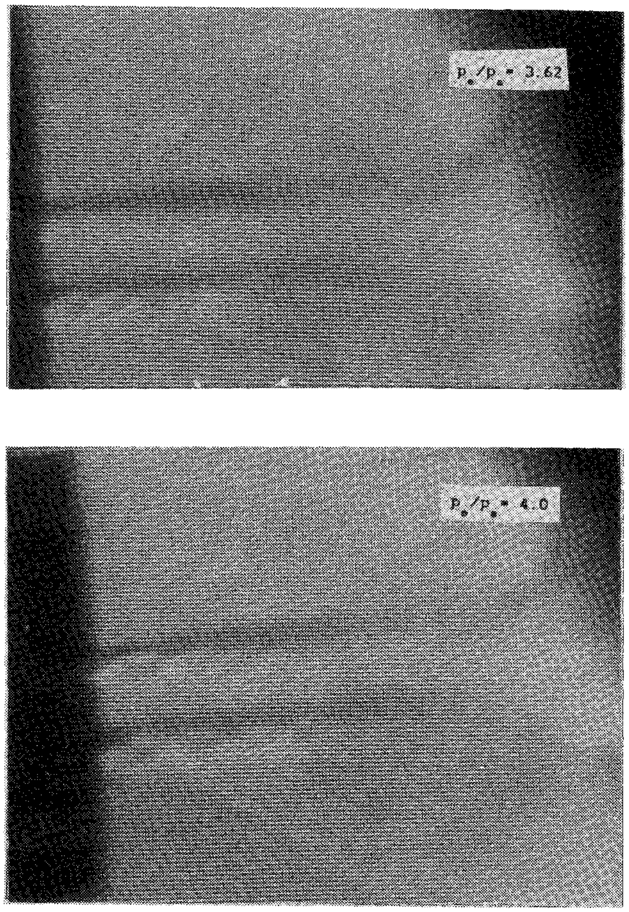

Fig. 9 Schlieren photographs of the twin jet, $M = 2.5$, $S = 18$ mm.

The photographs suggest that the shock cell size increases as the pressure ratio is increased.

Conclusions

It is obvious from the results which have been presented here that the overexpanded jets exhibit similarities with underexpanded jets with respect of the behavior of total pressure profiles, decay, and spreading rates.

Measurements of the pressure field of the overexpanded single and twin jets at the range of Mach number of 1.5–2.5 show that the total pressure distribution along the Y direction, in the near field, suffers complicated changes due to the effects of shock/expansion waves and viscosity diffusion. These changes result in corresponding variations of the jet decay and spreading rates. The variation in the jet spreading rate with the degree of overexpansion is irregular. The total pressure contours provide good and clear information about the effect of the exit Mach number and nozzle spacing on the jet structure as well as the jet decay and spreading rates. The flowfield of overexpanded twin jets is characterized by three distinct regions similar to those of low-speed incompressible jets. The converging, merging, and combining regions exist in a similar fashion. The two jets attract each other, mix, and finally combine to form a single jet. The nozzle spacing and Mach number have strong influences on the shock cell pattern and mixing process. The Mach number directly affects the strength and position of shock cells, whereas the nozzle spacing affects the bending of the jet axes. As a result of these effects the structure of the shock cell pattern and mixing process are altered. The merging between the jets occurs nearer to the nozzle exit plane for smaller nozzle spacings and higher Mach numbers. The half-width of the combined jet spreads linearly with downstream distance as a low-speed incompressible jet. the growth of the twin jet in the far field is slightly lower compared to that of the single jet.

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