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Abstract

The results of a continuing investigation on the effect of vortex generators, in the form of small tabs at the nozzle exit, on the evolution of a jet are reported in this paper. Primarily tabs of triangular shape are considered, and the effect is studied up to an equivalent jet Mach number of 1.8. By changing the orientation of the tab with respect to the nozzle exit plane, streamwise vortex pairs of opposite sign were generated. This resulted in either an outward ejection of jet core fluid into the ambient or an inward indentation of the mixing layer into the core of the jet. A triangular shaped tab with its apex leaning downstream, referred to as a delta-tab, was found to be the most effective in influencing the jet evolution. Two delta-tabs, spaced 180° apart, completely bifurcated the jet. Four delta-tabs increased jet mixing substantially, more than by various other methods tried previously; the mass flux at fourteen jet diameters downstream from the nozzle increased by about 50 percent over that for the no tab case. The tabs were found to be effective in jets with laminar or turbulent boundary layers as well as in jets with low or high core turbulence intensities.

Introduction

The effect of tabs, or small protrusions in the flow at the exit plane of a nozzle, is being studied experimentally with the aim of mixing enhancement and noise reduction in supersonic jets. Results of the effect of rectangular tabs projecting normally into the flow, referred hereafter as "simple tabs," have been reported previously in Refs. 1 and 2. The reader may consult these two references for a background and discussion of previous work on the topic. Here, we begin with a summary of the earlier results discussed in Refs. 1 and 2.

The simple tabs eliminated screech noise from supersonic jets while altering the shock/expansion structure drastically. They distorted the jet cross section while increasing the spread rate significantly. The basic mechanism of the effect was inferred to be independent of compressibility as the flow distortions produced were similar at subsonic and supersonic conditions. It was inferred from the experimental results that each tab produced a pair of streamwise vortices which were of the "trailing vortex" type rather than of the "necklace vortex" type.[2] Based on the evidence it was conjectured that a substantial pressure differential must exist between the upstream and downstream faces of the tab in order to produce the "trailing vortices" effectively. This explained why the tabs were less effective or ineffective in over-expanded flows, because an adverse pressure jump occurring near the nozzle exit in that condition diluted the pressure differential produced by the tab. It was further conjectured that a triangular shaped tab should act similarly, but if this were placed like a "delta wing" with the apex leaning upstream, vortices of opposite sign would be produced which would result in an ejection of core fluid from the jet.

In this paper, the primary consideration is the effect of triangular shaped tabs on the evolution of supersonic jets. The conjecture made above regarding the effect of a "delta wing" shaped tab turned out to be true, as will be shown later. However, a more

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pronounced distortion of the jet and enhancement of mixing could be achieved when the triangular shaped tab was tilted backwards, i.e., having its apex leaning downstream. This configuration, to be discussed further shortly, is referred to as the "delta-tab." For the same area blockage at the nozzle exit, the effect of the delta-tab is found to be much greater than that of a simple tab.

Further results with the simple tabs are also included in the paper to evaluate the influence of boundary layer thickness, and state, on the effect. Limited data are presented for subsonic jets with the delta-tabs to reaffirm that the effect is essentially the same in that condition and thus compressibility has little to do with the underlying mechanism. The likely vorticity distributions for different tab configurations are discussed based on the flow visualization data. The latter data also illustrate the enormous flow distortions produced by the delta-tabs. An example is shown at the end to demonstrate that the jet cross section can be distorted almost arbitrarily by using tabs of suitable shapes and sizes.

Experimental Facility and Method

The experiments were carried out in a small jet facility at the NASA Lewis Research Center. Compressed air with a maximum pressure of 560 kPa (80 psig) and approximately ambient temperature was supplied through one end of a 10-cm diameter plenum chamber. The flow exited through a 3.81-cm diameter "nipple" on the opposite end of the plenum, to which nozzles of different shapes could be attached.[2] For the data presented in the following a converging nozzle was used. This is shown schematically in Fig. 1. It was machined out of plexiglass and the inside was contoured, according to a fourth order polynomial, terminating in a short cylindrical section of diameter, $D = 1.27$ cm. Two extension pieces having lengths, $L = 1.27$ and 5.04 cm, could be attached to the nozzle to provide different exit boundary layer characteristics at a given Mach number. A trip ring could be placed at the inlet junction of the nozzle to ensure turbulent exit boundary layer. A turbulence generating grid could be placed in the plenum chamber to increase the jet core turbulence.

Tab Geometry

At the end of each extension piece (Fig. 1), a retainer disc could be attached to hold tabs of different shapes and sizes. Two simple tabs, with square ends, are shown in the end view on the right. For a simple tab the protrusion height into the flow will be denoted by "h" and the width by "w." Unless otherwise specified a simple tab will have the dimensions, $h/D = 0.17$ and $w/D = 0.08$. The triangular shaped tab is shown in the inset of Fig. 1. The apex angle is about 90°, and the orientation with respect to the nozzle exit plane is denoted by ϕ. Most data presented are for $\phi = 135°$, which is the specific configuration to be referred to in the following as the delta-tab. The blockage due to each delta-tab was about 2 percent (or less) of the nozzle exit area. The delta-tabs were hand sheared and bent and thus the angles and dimensions quoted are not precise. Furthermore, these were positioned under the retainer disc by eye estimation and thus some differences were likely to have occurred from set to set of the experiment. This should explain some minor non-repeatability in the data, as to be pointed out later.

Experimental Method

For the supersonic jets, the notation M_j is used to denote the "fully expanded Mach number," i.e., the Mach number had the jet expanded to ambient pressure for a given plenum pressure, p_{t0}. Standard total pressure measurements, with a 0.76 mm (o.d.) pitot tube, were conducted to obtain centerline variation of the stagnation pressure (p_{t2}). Cross-sectional profiles of Mach number were measured with the same pitot tube in the subsonic regions of the flow. For a given downstream station, several of the cross-sectional profiles were integrated to calculate the mass flux. A single hot-wire was used to measure the boundary layer characteristics at the nozzle exit for subsonic conditions. All probe traverses and data analysis were done with a Microvax computer.

Flow visualization pictures were obtained by laser sheet illumination. For the supersonic jets this was performed without any artificial seeding of the flow. The cold supersonic jet core caused natural moisture condensation in the mixing layer from the entrained ambient air. The condensed/frozen moisture particles, and therefore the mixing layer region, was illuminated by the laser sheet.[1] For the subsonic jets, cigar smoke was forced into the plenum chamber, so that the core of the jet in that case was illuminated by the laser sheet. A 4-W argon-ion laser was used as the light source. A gated double-intensified CCD camera was used to record successive images on a super-VHS video tape. The exposure time for each frame was long so that the pictures represent averages rather than instantaneous flow fields.

The Exit Boundary Layer

The jet exit boundary layer characteristics were measured at Mach numbers $M_j = 0.3$ and 0.5. For the short extension (L = 1.27 cm), the boundary layer was found to be nominally laminar, with the momentum thickness θ/D varying as $CRe_D^{-1/2}$, the constant C having a value of about unity. With the long extension (L = 5.04 cm) and the trip ring, a nominally turbulent boundary layer was measured at the nozzle exit. The boundary layer characteristics at $M_j = 0.5$ are listed in Table 1.

At $M_j = 0.5$, the turbulence intensity at the nozzle exit center was measured to be about 0.5 percent of the jet exit velocity. With the turbulence generating grid in the upstream plenum, the core turbulence increased to about 3 percent. The boundary layer characteristics and the turbulence intensity in the supersonic regime remain unknown, as presently it is extremely difficult to make such measurements in compressible flows with adequate spatial resolution and accuracy. However, the boundary layer state in the supersonic regime for the short extension case is also likely to be laminar as the contraction ratio was large. Whether the long extension with the trip resulted in a turbulent boundary layer in the supersonic condition remains unclear. However, the grid in the plenum is certainly likely to have increased the core turbulence. Limited data will be presented for the supersonic jets under these two flow configurations.

Results

Mixing Enhancement Data

Let us begin with data showing a significant increase in jet mixing under the influence of the delta-tabs. Figure 2 shows stagnation pressure variation along the centerline measured by a pitot probe, for $M_j = 1.63$. The measured pressure in the supersonic regime represents the stagnation pressure, p_{t2}, behind the standing bow shock produced by the probe itself. In the subsonic regions, of course, the measured pressure represents the local stagnation pressure.

The solid curve in Fig. 2, for the natural jet, is characterized by the oscillations due to the standing shock/expansion structure in the jet. Note that there is a rapid initial decrease and a subsequent recovery in p_{t2} with the superimposed oscillations. A similar trend for underexpanded jets has been reported by others, e.g., in Ref. 3. In a moderately underexpanded jet, the flow expands from the nozzle exit to a Mach disk causing increasing Mach number, approximately constant stagnation pressure, and a decreasing p_{t2} along the centerline. For such a jet, the centerline flow just downstream of the Mach disk becomes subsonic but then accelerates to supersonic conditions farther downstream. Downstream of the Mach disk there is a gradual decay of the stagnation pressure due to turbulent diffusion. These, together with the successive expansion and compression waves give rise to the observed trend in p_{t2}.

The tabs obviously alter and weaken the shock/expansion structure drastically. The jet centerline stagnation pressure (or velocity) decays much faster which is an indication of increased mixing and faster jet spread. The effect of two delta-tabs is the most pronounced. The effect of four delta-tabs is not as much and is even less than the effect of two simple tabs. However, the centerline data are not fully representative of the actual jet spread. Two delta-tabs completely bifurcate the jet, as will be shown shortly, and thus the effect in this context is overemphasized by the centerline data.

The centerline profiles of velocity or stagnation pressure are, however, reasonable measures of the comparative jet spread in most cases. In some previous work,[4,5] a single value of the centerline velocity measured at x/D = 9 has been used to compare the spreading of the axisymmetric jet under various conditions of acoustic excitation. This represents a simple measurement and can provide a reasonable comparison. The comparison, of course, is fair only when the jet cross-sectional velocity profiles are reasonably axisymmetric and similar in shape. A lower value of the centerline velocity would generally indicate a faster spreading of the jet. For a lack of available data on other parameters quantifying jet spread, this quantity, plotted as a function of M_j, is shown in Fig. 3 to illustrate the significant effect of the delta-tabs. The source references for the various data are indicated in the graph. The data without any reference numbers are from the present experiment. The data from the literature are by no means exhaustive, and only a selected few are shown in order to compare the effectiveness of the tabs.

The core length for the natural subsonic jet has been observed to increase with increasing M_j.[7] This is accompanied by the trend shown by the curve on the top of Fig. 3. The dashed part of the curve pertains to the M_j-range characterized by some scatter in the available data. The solid data points are from Ref. 9 for a supersonic hot jet, the diamond data point showing the effect of four simple tabs. The value for the natural jet in this case (solid circular data) appears low, which could be due to the shock/expansion structure influencing the measurement at $x/D = 9$.

The effect of acoustic excitation using single frequency, plane waves, on the jet evolution has been studied previously by many.[6] The "single frequency excitation" data in Fig. 3 shows the minimum value (or "saturation" value) of the normalized Mach number at $x/D = 9$, when using high amplitudes of excitation.[5] A further decrease is achieved using dual frequency excitation which induces subharmonic resonance. A corresponding best case value is shown in Fig. 3.[10] In comparison, four tabs are clearly more effective. The tabs used in the present experiment are the delta tabs. A faster spread of the jet is indicated under the influence of the tabs compared to that achieved by the excitation methods. (A limited number of diametral profiles of total pressure were measured at $x/D = 9$ for the four delta-tab case, at $M_j = 0.53$. The deviation of the profiles for different azimuthal angles was not significant. Thus, the inference on faster jet spread made from the data of Fig. 3 should be reasonably valid.) Figure 3 also shows that the effect of the tabs is similar at subsonic and supersonic conditions. The velocity ratio is reduced to less than 0.5 over the entire M_j-range.

The mass flux was measured in the present jet with and without four delta-tabs. Diametral profiles of Mach number were obtained for the $M_j = 1.63$ jet. A pitot tube was used and the measurements were confined to downstream regions where the flow was subsonic. With respect to the orientation of a tab, the profiles were measured for several azimuthal angles. Integration and averaging provided estimates of the flux which, normalized by the flux at the nozzle exit, is shown in Fig. 4. Also shown are the data for the four simple tab case from Ref. 1. The data for the no-tab case from the present nozzle agreed well with that from the C-D nozzle used in Ref. 1. Thus, the four simple tab data shown are also thought to be representative, and these measurements were not repeated with the present nozzle. Figure 3 shows that the delta-tabs are clearly more effective and increase the mixing significantly. At $x/D = 14$, the mass flux has increased by about 50 percent compared to that for the no-tab case.

Flow Visualization Data

Tabs producing core fluid ejection. As predicted in Ref. 2, a triangular shaped tab placed with the apex leaning upstream ($\phi < 90°$, see Fig. 1) was indeed found to produce an outward bulge in the jet cross section. This is shown in Fig. 5, as compared to the no-tab case. As expected, the mixing layer is circular in shape for the no-tab case in (a), indicated by the brightest region.[*] A large distortion is introduced by one tab as shown in (b), with a clear outward ejection of core fluid in the middle. Similar distortions are observed at diametrically opposite locations of the mixing layer for the two tab case in (c). The outward bulge in the middle of the distortion is due to a pair of streamwise vortices, originating from the tab under consideration, having a sense of rotation opposite to that observed for the simple tab case.[2]

For reasons remaining unclear, a somewhat similar distortion of the jet cross section was also observed when using a simple tab (rectangular, $\phi = 90°$) with

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[*] The core of the jet can be seen to be somewhat bright with a small dark region in the middle. This is believed to be due to variable moisture condensation in and outside of a shock cell. The size of the dark region varied with x, and also varied from day to day probably depending on the moisture content of the supply air.

large width. This is shown in Fig. 6. Note that besides the core fluid ejection, the pictures in Fig. 5, as in Fig. 6, also indicate an overall inward indentation. The likely vorticity distribution causing these complex deformations is discussed later in this section.

Effect of multiple delta-tabs. As stated before, the delta-tab ($\phi = 135°$) has been observed so far to pro duce the most pronounced effect. The jet cross section at different x/D are shown in Fig. 7 for the influence of two delta-tabs. The indentations produced are found to be more pronounced than those produced by two simple tabs. By $x/D = 6$ the jet core is seen to be completely split in Fig. 7, whereas with the simple tabs the two bifurcated parts were still close together at $x/D = 16$.[1,2] Figure 8 compares the jet cross section at $x/D = 10$ with and without the two delta-tabs. The two cores of the bifurcated jet are approximately 5D apart at this location. Thus the "angle of bifurcation" is almost 30°. This angle was found to be sensitive to the exact size, shape and placement of the delta-tabs. The observed bifurcation explains why the centerline velocity decay was so fast for the two delta-tab case (Fig. 2).

Attempts were made to visualize the streamwise vortices originating from a delta-tab. However, this was difficult because these vortices were embedded in the sheet of azimuthal vorticity of the mixing layer. The naturally condensed moisture, or smoke introduced upstream, marked both vorticity regions. Thus, the streamwise vortices were not clearly discernible from the background of the mixing layer, when, for example, the flow field was illuminated globally by a spherically expanded beam of light. However, the cross sections of the streamwise vortices could be observed quite clearly under certain circumstances. Figure 9 shows the laser sheet illuminated jet cross section, at $x/D = 2$. The view is from upstream at an angle, for the effect of one delta-tab at $M_j = 1.81$. The ambient is seeded with some smoke so that the entire background is bright. The mixing layer region is brighter because of the moisture condensation, and the arc-shaped indentation due to the delta-tab is quite clear. The brightest region on the lower left is due to reflection from the nozzle block. The core of the jet is dark as expected. In addition, two dark regions, as marked by the arrows,* can also be seen on the corners of the indentation. These two represent the cores of the pair of streamwise vortices originating from the delta-tab.

The vortex cores became clear and appeared dark in the bright background only at high M_j. It is not quite clear why the smoke particles do not mark the vortex cores at that condition. It is possible that at high M_j the vortices are sufficiently strong so that the smoke particles are centrifuged out from the core. It has been shown in a computational study that when the Stokes number, representing the ratio of the time scale of the flow and that of the particle response, becomes large then the particles fail to track the fluid motion in the core of the vortices.[11] In any case, the spiralling paths of the illuminated smoke particles converging on the two cores, observed during the experiment, made the presence of the two vortices amply clear. These vortices are schematically shown and discussed more in the following.

The effects of one, two, and four delta-tabs, at $x/D = 2$ for $M_j = 1.63$, are compared with the no-tab case in Fig. 10. These are similar laser-sheet illuminated flow fields as in Figs. 5 to 8. The distortions produced are enormous and, to the authors' knowledge, far more than that observed in any previous investigation in the relevant area. For the four delta-tab case, one vortex from a pair is presumably thrust against another from a neighboring pair, resulting in the pinching off of the jet core into the four fingers. The picture for two delta-tabs here appears somewhat different from the corresponding picture in Fig. 7 because these data were taken at an earlier time with a different set of tabs. The corresponding effects of three, five, and six delta-tabs are shown in Fig. 11. These data were taken in a later experiment when the effect on subsonic jets was also studied (discussed shortly). The three delta-tabs produced the three fingers, as expected. When five delta-tabs were used, however, a tendency for an interaction was apparent. Two adjacent fingers were clearly drawn closer to each other. Occasionally, the affinity would switch and a different pair would be drawn to each other. It was noted that although the flow deformations were

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*Unfortunately, the picture quality in Fig. 9 is not as good as desired. In the actual experiment, these two dark regions could be clearly observed by bare eyes. These appeared analogous to the "eyes" of two little hurricanes, which were moving around somewhat about their mean positions.

mostly steady there was some unsteadiness in all cases, which was more pronounced in the five delta-tab case. When six delta-tabs were used, the flow field settled back into the steadier three finger configuration, as can be seen in Fig. 11.

The likely vorticity distributions in the flow fields, as inferred from the flow visualization pictures, are shown in Fig. 12. The cross sections of the streamwise vortices are shown by the hatched regions, and a plus sign represents a counter-clockwise rotation when viewing from downstream. Figure 12(a) represents the delta-tab case ($\phi = 135°$), the corresponding vorticity distribution is rather clear from Fig. 9. From a similar visualization experiment as in Fig. 9, the vorticity distribution for the triangular tab with $\phi = 45°$ appears to be as shown in Fig. 12(b). Figure 12(c) is a conjecture for the four delta-tab case. As the number of delta-tabs is increased, two opposite sign vortices, between two adjacent fingers, are forced to exist closer together. Such a pair of vortices would repel each other rather than amalgamate. Thus, the interactions observed with five and six delta-tabs (Fig. 11) appear intriguing. For the six delta-tab case, it is possible that three alternate pairs are ingested, perhaps, eventually annihilated, by the other three pairs as shown in Fig. 12(d).

The effects of three, five, and six delta-tabs for a subsonic jet at $M_j = 0.3$ are shown in Fig. 13. These data were obtained in the same set of experiment providing the data of Fig. 11. Recalling that in the subsonic case the smoke-laden core of the jet is illuminated as opposed to the mixing layer region in the supersonic case, the similarity between corresponding pictures in Figs. 11 and 13 is unmistakable. Essentially the same vortex interaction is observed in the subsonic case as in the supersonic case. This proves further that compressibility has little to do with the effect of the tabs.[2]

Influence of boundary layer state and core turbulence. The effect of two simple tabs, with varying protrusion heights, is shown in Fig. 14 for the subsonic jet at $M_j = 0.5$. In Fig. 14(a), it is observed that a tab height as small as $h/D = 0.01$ already produces an indentation which is just visible. In this case the laminar boundary layer was thin (Table 1) and the tab height was roughly twice the displacement thickness (δ_1). For the thicker turbulent boundary layer case in (b), no clear effect is observable for the same tab height, $h/D = 0.01$. Here, the height h is about one half of δ_1. However, when the tab height is increased to roughly correspond to $2\delta_1$, a clear effect is observed even in the turbulent boundary case, as shown in Fig. 14(c). Thus the tabs are found to be just as effective in jets with turbulent exit boundary layers. It can also be inferred that a tab height comparable to or exceeding the boundary layer thickness, (say, defined as the distance of the 99 percent velocity point from the wall), is required to produce a significant distortion.

The flow visualization experiments for the supersonic jet, corresponding to Figs. 5 to 11, were repeated for the tripped boundary layer case as well as for the flow with the turbulence generating grid placed in the plenum. Without exception, the already described effects of the delta-tabs were reproduced for both these conditions. Two examples are shown in Fig. 15. The effect of four delta-tabs at $M_j = 1.63$ is shown in Fig. 15(a) for the tripped boundary layer case. Corresponding effect for the higher core turbulence case is shown in Fig. 15(b). No significant difference could be identified between these and the short nozzle case in Fig. 10. Thus, even though the boundary layer state and the core turbulence intensity remain undetermined in the supersonic jets (see Experimental Facility and Method), the delta-tabs may be expected to work just as well in a "dirtier" practical flow environment.

Effect of tabs with various geometry. Tabs of various other geometries were tried. The following is a list of observations made from the laser sheet visualization of supersonic jets.

(1) For a simple tab, the shape of the end of the tab made no noticeable difference in the distortion produced. This was checked by changing the shape of the end from triangular (as in Ref. 4) to rounded to square (as in Fig. 1), while maintaining approximately constant flow blockage.

(2) A simple tab placed slightly downstream from the nozzle end, i.e., leaving a small gap (of the order of the tab width), failed to produce any distortion. Such a tab configuration also failed to eliminate the screech noise; the far field noise spectrum essentially

remained unchanged. Of course, the screech noise was completely eliminated when the tab was placed against the nozzle.[1]

(3) For a simple tab and for constant flow blockage, the distortion produced was influenced more by the width rather than the height of the tab. For example, a tab with $w/D = 0.04$ and $h/D = 0.5$ (i.e., spanning the nozzle exit) produced less distortion than a tab with $w/D = 0.08$ and $h/D = 0.17$. Observations (1), (2), and (3) have been discussed in an article submitted for Journal publication.

(4) With $\phi = 90°$ (Fig. 1), tabs of rectangular, triangular or inverted triangular shapes, but having same flow blockage, produced essentially similar distortions of the jet.

(5) The orientation of the tab was more critical than its shape. For the triangular shape, limited experiments for varying ϕ showed most pronounced effect occurring around $\phi = 135°$ (the delta-tab). Of course, for values of $\phi < 90°$ the distortion was of a different nature as described in the preceding text.

(6) The jet cross section could be almost arbitrarily distorted using tabs of various combination. Figure 16 is included to demonstrate this. Here, the "T" is produced by three delta-tabs with uneven spacing, the "H" by two delta-tabs, the "E" by a wide simple tab and a triangular tab with $\phi = 45°$, the "N" by two simple tabs with some twists, and the "D" by a simple tab with large width.

Concluding Remarks

A simple vortex generator configuration, referred to as a delta-tab, has been found to be quite effective in influencing jet evolution and mixing. Recently, a lot of research has been directed towards developing jet nozzles that will produce faster mixing and less noise. Various concepts have been considered so far which involve basically variations in the nozzle geometry. Here, it is demonstrated that the exit flow from a nozzle of complex geometry, e.g., the "lobed mixer nozzle," may be reasonably reproduced with the judicious use of a few tabs fitted to a simple primary nozzle. A significant conceptual attractiveness of the method is that the tabs (or delta-tabs) could be used in an "active" sense; they could be inserted in the flow when needed but withdrawn when not desired. This way, one might be able to avoid the disadvantages of a complex nozzle, e.g., possible thrust loss during level flight or during other regimes of operation as appropriate. Conceivably, the tabs could also be used in a variety of other applications where increased mixing is desired, e.g., in combustors. However, it is quite reasonable to say at this time that more exploration will be required to unravel the full potential of this simple device. Further studies will be required, for example, to evaluate thrust losses, and especially to shed light on the underlying fluid dynamics and the vorticity generation mechanisms so that the method could be understood clearly and applied intelligently in practice.

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TABLE 1.—EXIT BOUNDARY LAYER
CHARACTERISTICS
AT M_j = 0.5

Extension	θ/D	H_{12}	B.L. state
Short	0.0026	2.52	Laminar
Long + trip	0.0124	1.80	Turbulent

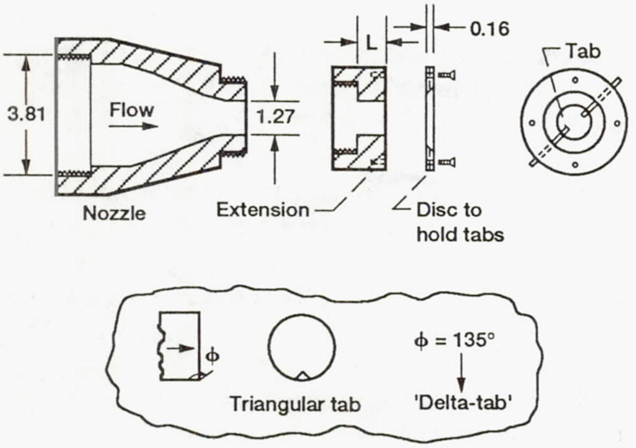


Figure 1.—Schematic of nozzle with shape and orientation of delta-tab shown in the inset. Dimensions are in cm.

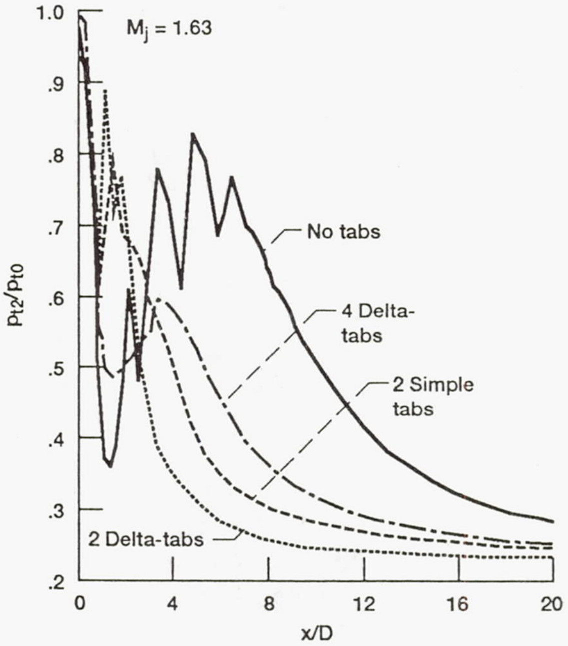


Figure 2.—Centerline variation of stagnation pressure, normalized by plenum pressure, for different tab cases.

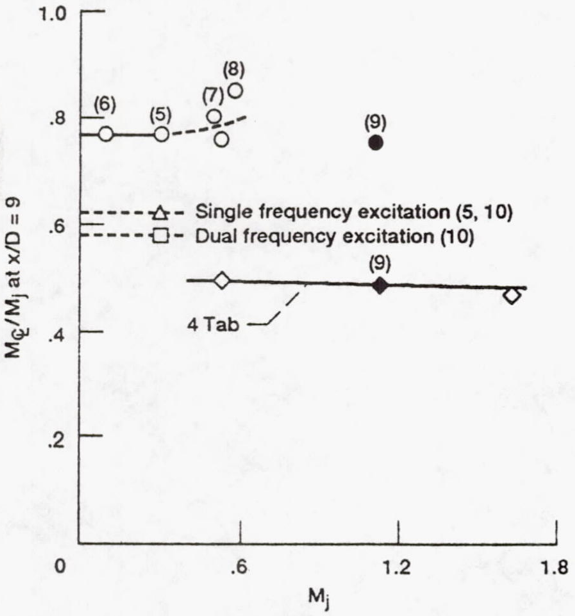


Figure 3.—Centerline velocity at x/D = 9, normalized by jet velocity, at different jet Mach number.

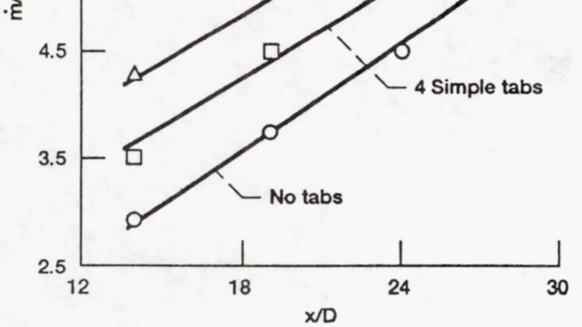
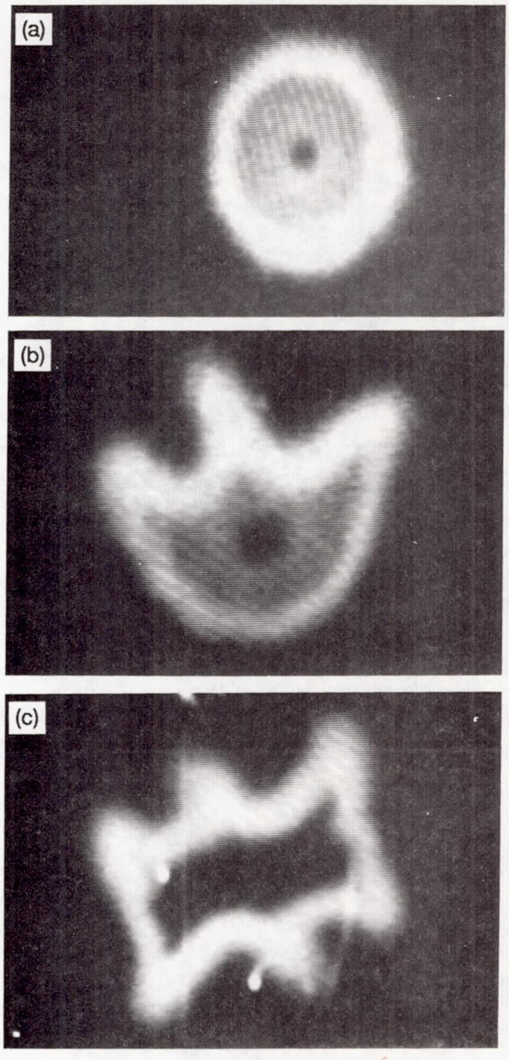


Figure 4.—Mass flux, normalized by initial mass flux, versus x/D, for indicated tab cases.



(a) None.
(b) One.
(c) Two.

Figure 5.—Jet cross section at x/D = 2. Triangular tabs having ϕ = 45°; M_j = 1.63.

Figure 6.—Jet cross section at x/D = 2 for two large simple tabs with width w/D = 0.2 and height h/D = 0.17; M_j = 1.81.

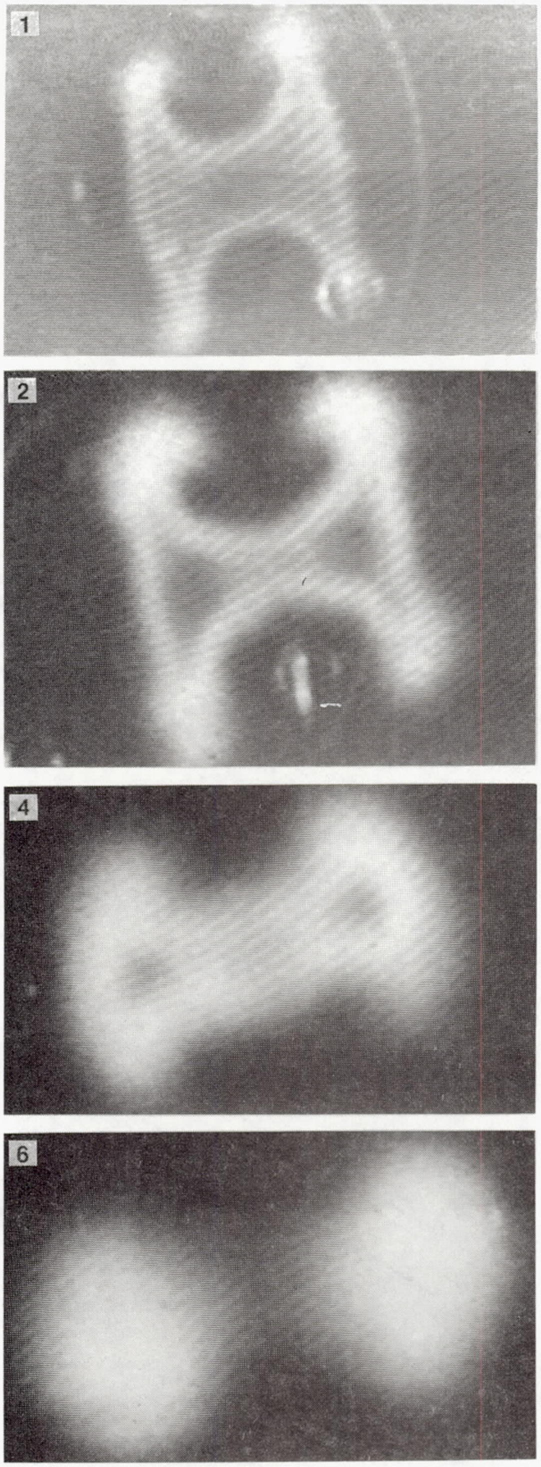


Figure 7.—Jet cross section at indicated x/D for two delta-tabs (ϕ = 135°); M_j = 1.63.

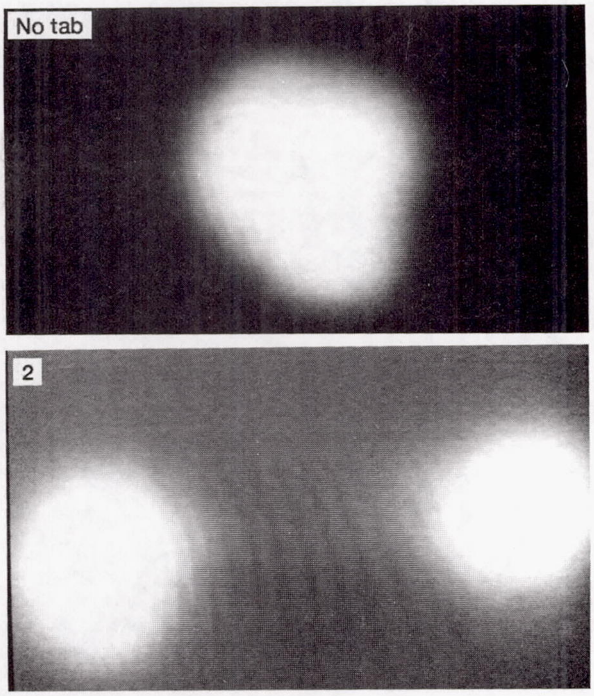


Figure 8.—Jet cross section at x/D =10 with and without two delta-tabs for the same flow as in Figure 7.

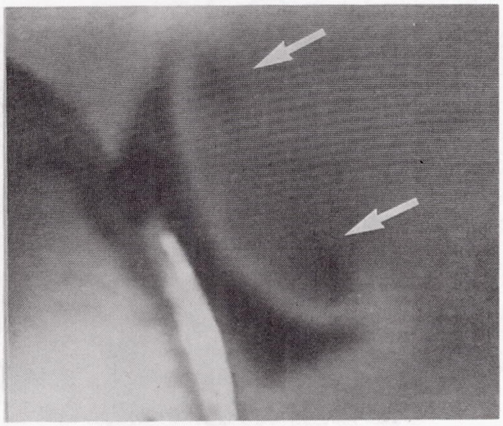


Figure 9.—Jet cross section at x/D = 2 for one delta-tab; M_j = 1.81. View is from upstream and ambient is seeded with smoke.

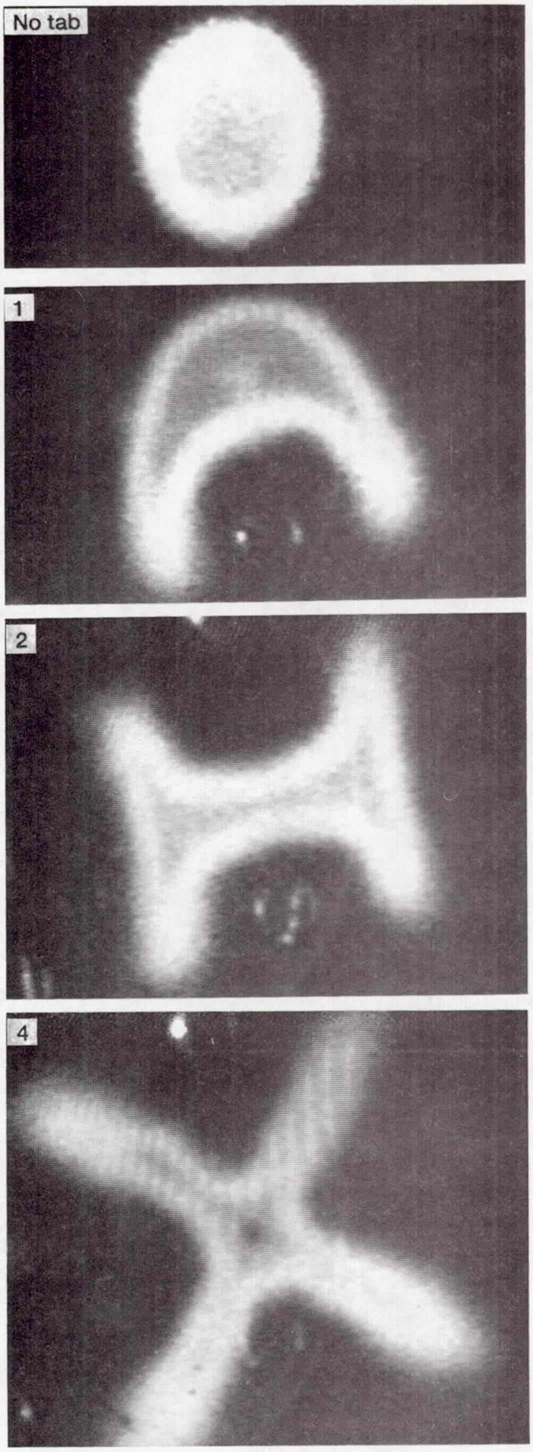


Figure 10.—Jet cross section at x/D = 2 for indicated number of delta-tabs; M_j = 1.63.

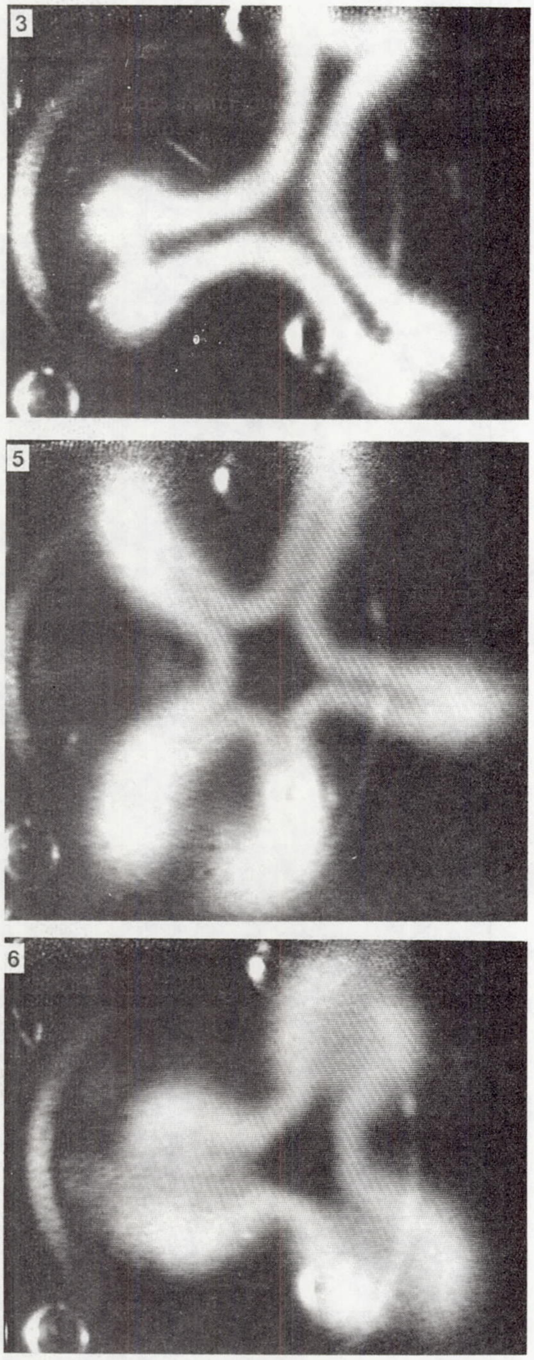
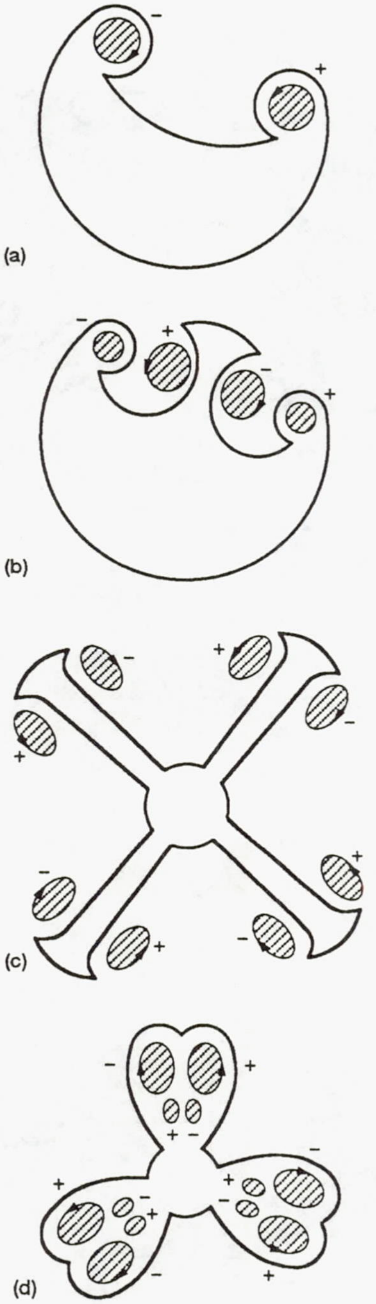


Figure 11.—Data as in Figure 10 for indicated number of delta-tabs.



(a) 1 Delta-tab.
(b) 1 Triangular tab; ϕ = 45°.
(c) 4 Delta-tabs.
(d) 6 Delta-tabs.

Figure 12.—Likely vorticity distribution on the jet cross section for indicated tab cases.

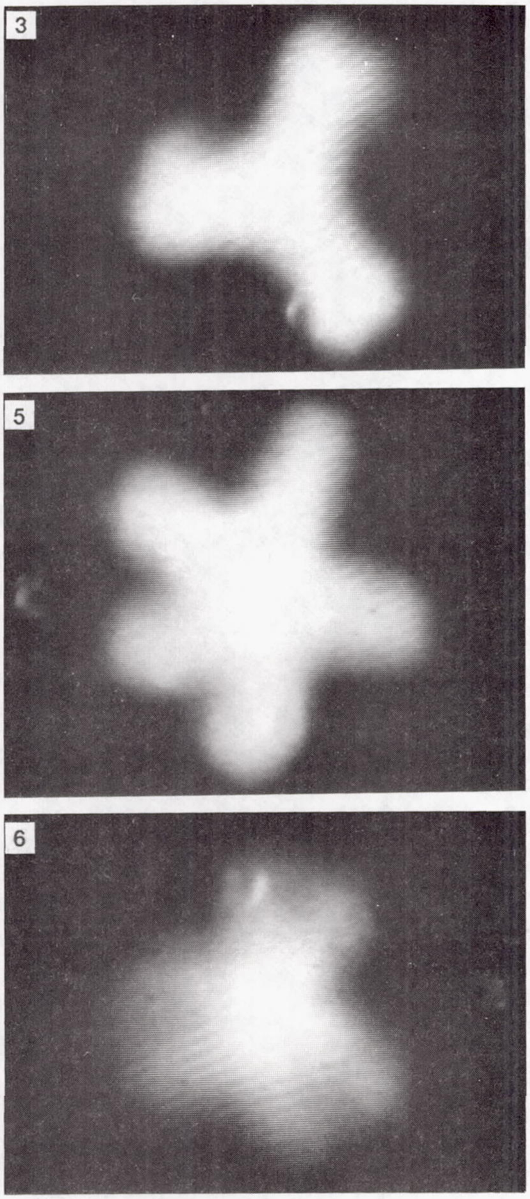
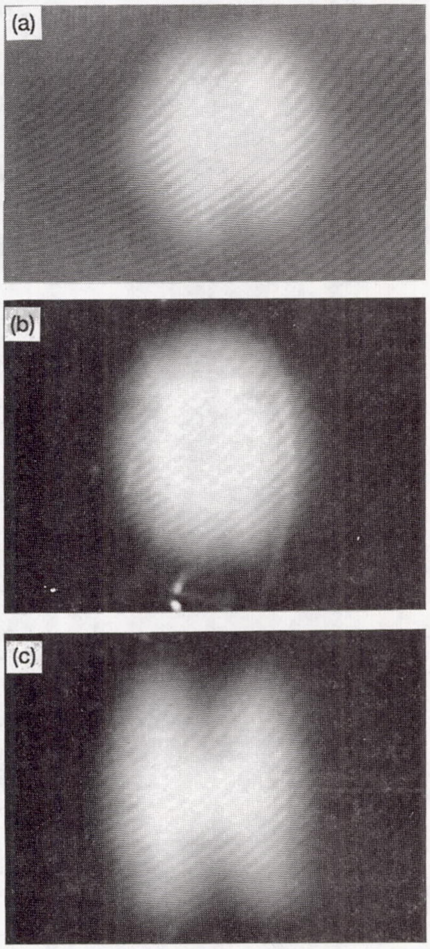
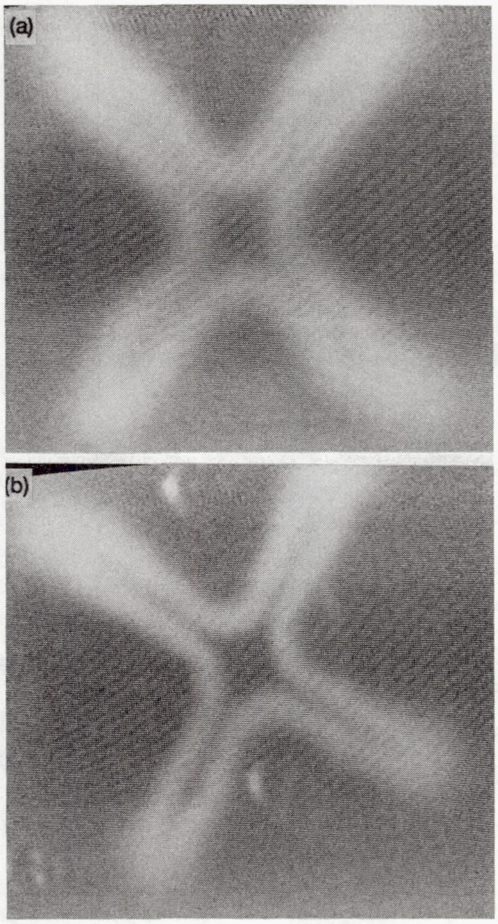


Figure 13.—Cross section of subsonic jet, seeded with smoke, for corresponding delta-tab cases of Figure 11; x/D = 2, M_j = 0.3.



(a) 0.01, laminar.
(b) 0.01, turbulent.
(c) 0.05, turbulent.

Figure 14.—Cross section of jet seeded with smoke for 2 simple tabs; x/D = 2, M_j = 0.5. Tab width w/D = 0.08. Tab height h/D and exit boundary layer state are indicated.



(a) Tripped boundary layer.
(b) With turbulence generating grid in plenum.

Figure 15.—Jet cross section at x/D = 2 for 4 delta-tabs; M_j = 1.63.

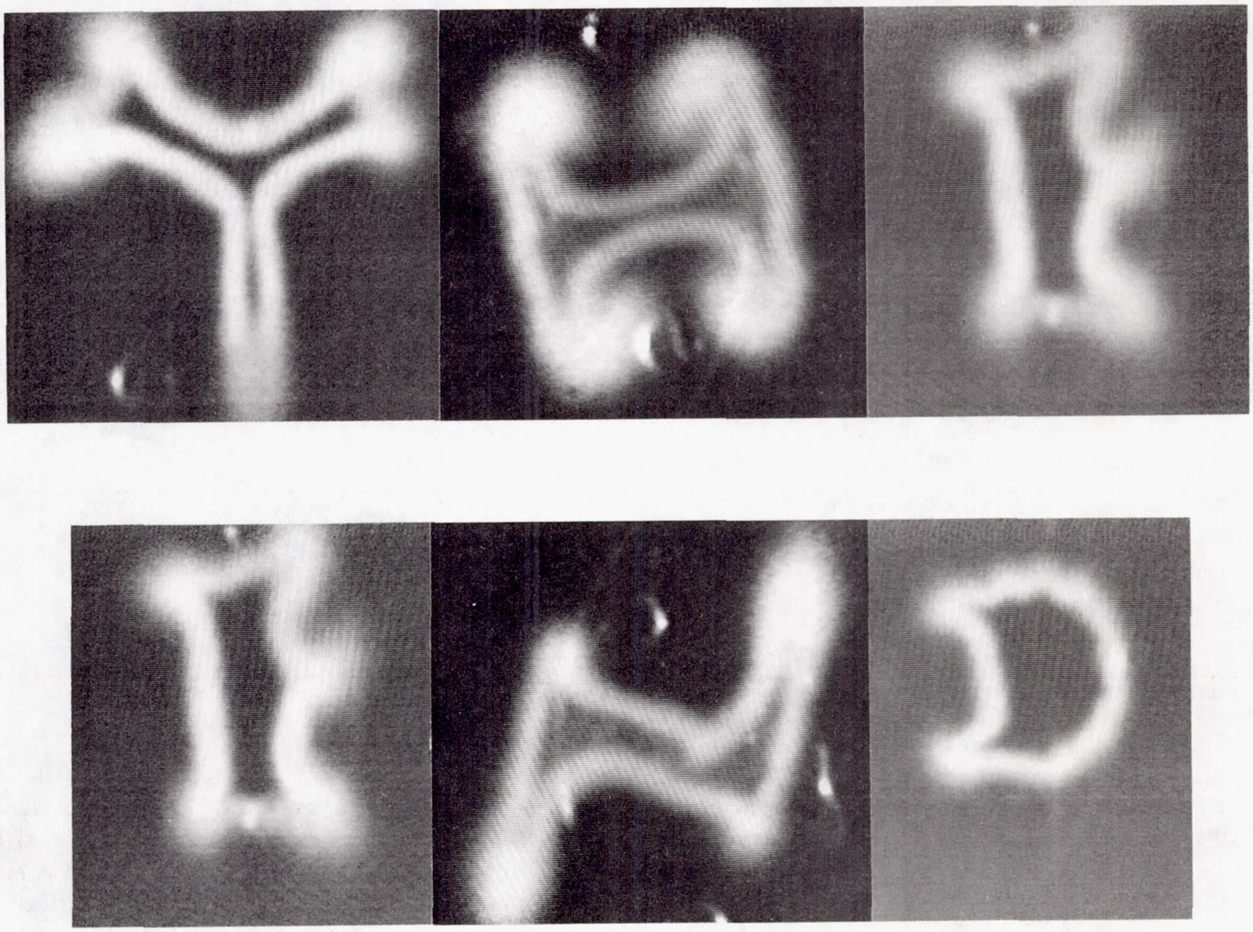


Figure 16.—Jet cross section at $x/D = 2$ for different combination of tabs; $M_j = 1.63$.

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13. ABSTRACT ***(Maximum 200 words)***

The results of a continuing investigation on the effect of vortex generators, in the form of small tabs at the nozzle exit, on the evolution of a jet are reported in this paper. Primarily tabs of triangular shape are considered, and the effect is studied up to a equivalent jet Mach number of 1.8. By changing the orientation of the tab with respect to the nozzle exit plane, streamwise vortex pairs of opposite sign were generated. This resulted in either an outward ejection of jet core fluid into the ambient or an inward indentation of the mixing layer into the core of the jet. A triangular shaped tab with its apex leaning downstream, referred to as a delta-tab, was found to be the most effective in influencing the jet evolution. Two delta-tabs, spaced 180° apart, completely bifurcated the jet. Four delta-tabs increased jet mixing substantially, more than by various other methods tried previously; the mass flux at fourteen jet diameters downstream from the nozzle increased by about 50 percent over that for the no tab case. The tabs were found to be effective in jets with laminar or turbulent boundary layers as well as in jets with low or high core turbulence intensities.

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