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Effect of Tabs on Rectangular Jet Plume Development

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The near-field mixing performance of a rectangular jet with and without solid tabs introduced at the nozzle lip was studied under supersonic (underexpanded) operating conditions. The effects of tab shape, tab location, and tab number were investigated. Flow visualization of the jet plume was accomplished via Schlieren imaging, and the velocity and turbulence fields quantified via laser Doppler anemometry measurements. Laser Doppler anemometry data were gathered along the jet centerline and on cruciform transverse and spanwise traverse lines downstream of the nozzle exit. Tab shape has only a minor effect, however tab location and number are sensitive parameters for jet plume development. Tabs located on the nozzle wide edge can lead to jet bifurcation, whereas tabs located on the narrow edge cause increased mixing primarily in the major axis direction. A nozzle with four tabs located on its wide edges was the most effective for overall enhancement of jet mixing.

Nomenclature

D_h = nozzle hydraulic diameter
U = mean axial velocity
u = rms axial fluctuating velocity
x = axial direction
y = spanwise (horizontal) direction
z = transverse (vertical) direction

I. Introduction

EXTENSIVE research on jet mixing enhancement has been carried out over the last 50 years. Many techniques such as the use of solid tabs, acoustic excitation, and serrated nozzles have been employed, and studies up until 2001 have been usefully summarized by Seiner et al. [1]. A solid tab is a small protrusion placed at the jet nozzle exit as shown in Fig. 1. Each tab produces a counterrotating streamwise vortex pair as schematically shown in Fig. 2, with a sense of rotation such that, between the two vortices, ambient fluid is ingested into the core of the jet as highlighted in Fig. 2 (view orthogonal to plane A–A). Clearly, if beneficial, one or more tabs can be attached at the nozzle exit to enhance the mixing process (e.g., to effect plume infrared signature reduction), although this may also increase the associated drag (thrust loss) penalty. Tabs appear to be a practical method for jet plume mixing enhancement in the near field, that is, between two and ten diameters from the jet exit. Tabs have also been shown to eliminate or reduce screech noise substantially and, as demonstrated by Tam and Zaman [2], tabs impact the noise field primarily by shifting the spectral peak to a higher frequency. Tabs also alter the shock structure drastically in the case of jet nozzles operating at underexpanded nozzle pressure ratios (NPR).

Bradbury and Khadem [3] are usually credited with the first demonstration of the flowfield modifications due to tabs and correctly surmised that this modification to the jet near-field development would reduce the generation of broadband jet noise. Tabs have been shown by Bohl and Foss [4] to enhance the local convective transport and mixing of ambient and jet-core fluid. The works of Samimy et al. [5], Zaman et al. [6], and Reeder and Samimy [7] have provided much detailed data on the effects of tabs on axisymmetric jet flow. Two sources for the generation of streamwise vorticity behind the tab have been identified. The dominant source comes from the pressure "hill" formed upstream of the tab (Bohl and Foss [4]). The flow deceleration upstream of the tab creates an increased pressure that, together with the strain rate associated with the boundary layer on the nozzle wall, produces a pair of counterrotating vortices. The second source (again linked to the pressure gradients on the tab surface) is the vorticity shed on flow separation from the sides of the tab. The combined vortex system becomes fully formed as the flow goes past the tab edge. As it convects downstream, it is reoriented by the velocity gradients in the tab shear layers to become a streamwise vortex. If the approaching boundary layer upstream of the tab has appreciable thickness, an additional vortex pair rotating in the opposite sense to the main pair is developed, which is consistent with a horseshoe vortex system. Reeder and Zaman [8] have investigated the effect of the streamwise location of the tab, and Behrouzi and McGuirk [9] have studied the effect of tab geometry on mixing rate. In particular, in order to reduce the drag (thrust loss) penalty of the tabs, Behrouzi and McGuirk [9] examined various 3-D shapes for the tab while maintaining the same projected area. The mixing improvement for all 3-D-shaped tabs was found to be substantially reduced compared with the simple 2-D (i.e., thin flat plate) tab for the same projected area. All attempts to reduce the drag and performance loss penalty of the tabs were accompanied by significant reductions in tab mixing effectiveness. Foss and Zaman [10] have presented a detailed study of the effects of tab orientation and spacing, showing that the optimal pitch angle of a delta tab (as shown in Fig. 1) is 45 deg and the optimal spacing of an array of tabs is 1.5 tab base widths, because this configuration produced large-scale motions with peak streamwise vorticity, and maximized the strength of small-scale turbulent mixing. Behrouzi and McGuirk [11] have carried out extensive research on the effects of velocity ratio (nozzle exit mean axial velocity/coflow mean axial velocity), tab shape, tab number, and tab orientation angle on round jet plume development. The experimental results revealed that the decay of the jet-core velocity was only weakly dependent on velocity ratio, tab orientation angle, and tab shape. The mixing of the jet was, however, a strong function of the tab projected area, tab width, and tab number.

All the preceding work has focused primarily on axisymmetric nozzles. Jets from 3-D rectangular nozzles are known to spread and mix faster than their axisymmetric counterparts. A primary mechanism responsible for this faster spreading is thought to be self-induction of the velocity field linked to the asymmetric vortex rings created in 3-D nozzle flows, specifically associated with secondary flows at the corners of the nozzle. The self-induction process causes the vortex ring to deform towards an axisymetric shape through a sequence of near elliptical shapes in which major and minor axes

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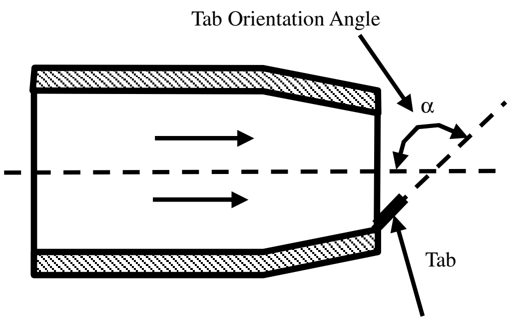

Fig. 1 Tab mounting orientation.

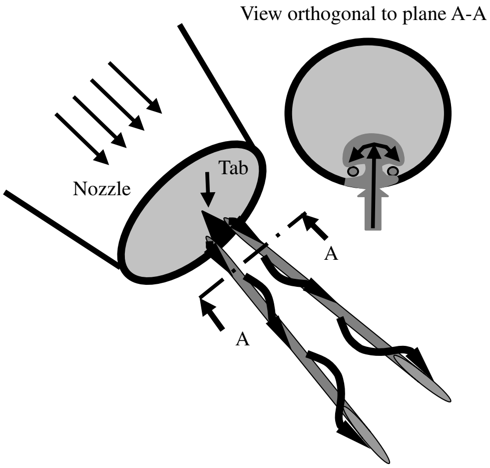

Fig. 2 Formation of pair of counterrotating streamwise vortices from each tab.

exchange directions; it is argued that the higher mixing rate with the surrounding fluid is driven by this axis-switching phenomenon. Several works have already reported on rectangular nozzle jet flow characteristics, for example Quinn [12] and Krothapalli et al. [13], both of which indicated impressive enhanced entrainment characteristics. The possible impact of faster jet spreading on noise reduction has been addressed by Seiner and Krejsa [14] and Krothapalli et al. [15], who have also investigated features of the discrete tones that are generated by rectangular nozzles. McGuirk and Rodi [16] provided an early example of a computational fluid dynamics calculation of the flowfield from a rectangular nozzle using the k-ε turbulence model. They were able to demonstrate the observed axis-switching feature by including in the nozzle exit conditions secondary flows generated within the 3-D nozzle. They noted, however, that the strongly 3-D turbulent shear stress field in the rectangular jet flow also plays an important role in the downstream development. With a rectangular nozzle tab effects are more complex than for an axisymmetric nozzle. This is because the rectangular jet already contains a complex vorticity field, into which the tab-induced vorticity is injected. As pointed out by Zaman [17], by considering the sense and strength of the complex nozzle exit conditions and the vortices produced by the tabs, the resulting interaction can vary. Depending on the location, size, and orientation of the tabs, the vortex interactions can be either beneficial, increasing spreading, or detrimental, actually reducing spreading.

As noted previously, the axis-switching phenomenon has been noted by many researchers including Abramovich [18] and Zaman [19] and is a well-known flow characteristic of rectangular nozzle flow. As noted by Zaman [19], by suitable placement of the tabs, axis switching may be avoided or augmented. Brown and Ahuja [20] have studied the effects of tab height and width on jet mixing enhancement for a rectangular nozzle. They observed that a six-tab rectangular nozzle configuration provided a lower peak velocity than either a two-tab or four-tab configuration. Zaman et al. [21] noted that with a suitable choice of the tabs, a large increase in jet spreading could be achieved with rectangular nozzles. They pointed out, however, that more measurements were needed to address fundamental issues, for example: vorticity dynamics, mixedness, and small-scale mixing, as affected by the tabs.

As previously described by Behrouzi and McGuirk [11], experimental facilities at Loughborough University for the study of the near field of nozzle flows under static test conditions have been under development and in use to produce datasets since 1994. Because there is currently growing interest in use of 3-D nozzles in both civil and military applications, especially in rectangular nozzles for military aircraft propulsion systems, the present research is aimed at improving the current understanding of the effect of various tab system design parameters on flow control and jet mixing enhancement of a rectangular jet under supersonic (underexpanded) operating conditions.

II. Experimental Setup and Instrumentation

The experiments were carried out in a specially designed and constructed high-pressure nozzle test facility (HPNTF). The HPNTF consists of a compressor, air reservoir tanks, delivery pipelines to a test cell containing the nozzle rig, control valves, a combustion unit (for possible jet heating), a rig control panel, and rig instrumentation. The compressor draws 0.86 m^3/s of ambient air (approximately 1 kg/s) at inlet and supplies high-pressure air with a maximum downstream pressure of 1.5 MPa (absolute). The eight storage tanks have a volume of 110 m^3 and act as a buffer to damp pressure fluctuations as well as providing an air supply for the test facility to be run in blowdown mode. A desiccant-type compressed air drier is used for drying the high-pressure air to a dew point of −40°C. A computer-controlled valve is employed to hold the jet mass flow rate and NPR constant (to an accuracy and repeatability of $\pm 1.0\%$). The facility can be used in continuous or blowdown mode. In blowdown mode the tanks are first filled to a substantially higher pressure than the desired NPR for the selected test operating point. The automatic control valve allows the rig to run with decreasing pressure upstream of the valve but fixed NPR until the supply system pressure approaches the operating set point. Typical blowdown run times are between 15 and 30 min depending on the nozzle size and NPR. Figure 3 presents an exit plane view of the rectangular nozzle considered in the present work with twin tabs installed, fitted to the test facility delivery pipe and also showing the two-component LDA (laser Doppler anemometry) system in operation.

For the experiments reported here, a convergent rectangular nozzle was selected and tested at cold supersonic operating conditions. Figure 4 presents the internal dimensions of the nozzle. The nozzle exit minor and major axis dimensions are 12.76 and 93.8 mm, respectively (aspect ratio of 7.35). A special collar section as shown in Fig. 3 was fabricated and fitted over the nozzle lip outer area in order to attach the tabs.

Figure 1 shows a schematic of the tab mounting. The tabs were small pieces of metal (of different shapes, see later) and were attached at the nozzle exit plane. Where more than one tab was used, tabs were positioned symmetrically around the nozzle axes. Five different

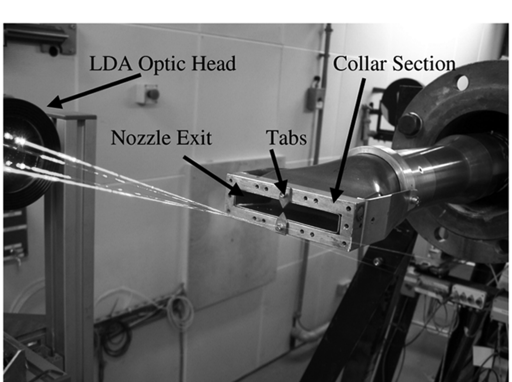

Fig. 3 Rectangular nozzle mounted in the test facility.

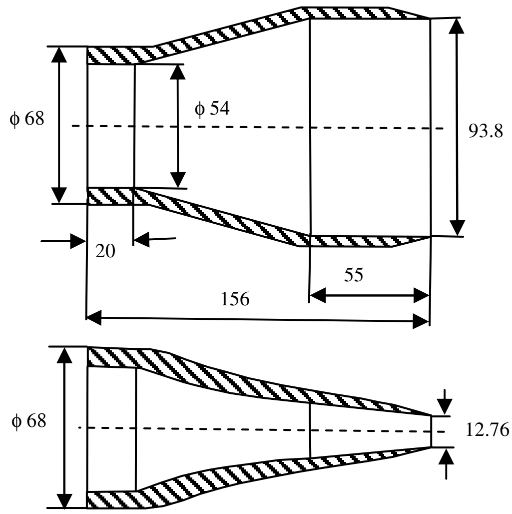

Fig. 4 Schematic design of rectangular nozzle (all dimensions in mm).

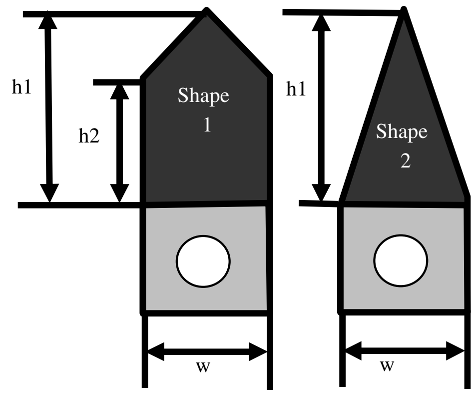

Fig. 5 Schematic design of tab shapes 1 & 2.

types of tab geometry were employed in the present study; the dimensions and description of each tab geometry are presented in Table 1 and Fig. 5. Tabs were manufactured from a 0.2 mm brass sheet and screwed to the nozzle lip collar section in 7 separate tab configurations as indicated in Table 2. All tabs were mounted at a 90 deg orientation angle as defined in Fig. 1. Figures 6 and 3 present photos of the clean (no tabs) nozzle and the nozzle mounted with twin tabs of shape-2, respectively.

The Schlieren technique is a convenient method of establishing the position and shape of shock waves. The Schlieren method depends on the deflection of a ray of light from its undisturbed path when it passes through a fluid medium in which there is a gradient of the refractive index normal to the ray. The Schlieren system used for the present study was of a Z-type design and consisted of a Halogen lamp, two concave mirrors of 10-in. diameter, two plane mirrors of 12-in. diameter, a rainbow color filter, and a Sony XCD-SX910CR digital camera. Fire-I 3.X software was employed to capture Schlieren images. Schlieren pictures were taken from both top and side views of the jet plume, that is, orthogonal to the x-y and x-z planes, respectively, just downstream of the nozzle exit.

A two-component DANTEC LDA system was used in backscatter mode for nonintrusive measurement of the mean velocity and turbulence fields. A SCITEK-10F01 model solid particle seeder employing AP-D Al2O3 powder (deagglomerated alumina powder of 0.3 microns) was used to seed the air supply to the nozzle.

III. Experimental Procedure

In the coordinate system used below to report measurements, the origin is located at the nozzle center in its exit plane (see Fig. 6); the longitudinal (x) coordinate is oriented along the jet axis (positive downstream), the transverse (z) coordinate is positive vertically upward, and the spanwise (y) coordinate has its positive direction such that a right-handed orthogonal set is formed.

The effects of tab shape, number, and location on jet plume development were investigated under underexpanded supersonic flow conditions in the test facility. To fulfill the objective of this study, eight test cases were defined as listed in Table 2. These test cases were defined to satisfy the following objectives: 1) C01: clean (no tab) nozzle as datum case, 2) C11 and C21: nozzles with installation of a pair of tabs, for tab shape effect study, 3) C21 and C22; and C31, C32, and C33: nozzles with installation of two or four tabs, for tab location effect study, and 4) C21, C31, and C41: nozzles with installation of two, four, and six tabs, for tab number effect study.

It is important to note that the total area blockage for all tabbed cases was the same and fixed at 3% as highlighted in Table 1. This blockage magnitude is more representative of the blockage level

Table 2 Description of nozzle test cases

Case	Tab location	Description
C01		No tab (clean nozzle)
C11		Two type-1 tabs
C21		Two type-2 tabs
C22		Two type-2 tabs
C31		Four type-3 tabs
C32		Four type-3 tabs
C33		Four type-4 tabs
C41		Six type-5 tabs

Table 1 Description of tab types

Tab type	Description	h2	h1	w	Area, mm^2	Blockage ratio, %	Tab number	Total blockage ratio, %
		(see Fig. 5)						
1	Baseline tab shape 1 (Fig. 5-left) as reported by Ahuja and Brown [22]	4.00	5.00	4.00	18.00	1.50	2	3.00
2	Delta tab shape 2 (Fig. 5-right), same area as tab type 1, as used by Reeder and Samimy [7]	—	5.00	7.20	18.00	1.50	2	3.00
3	Shape 2 but 1/2 area of tab type 2 to maintain blockage	—	3.54	5.09	9.00	0.75	4	3.00
4	Shape 2, same blockage as tab type 3 but modified geometry for attachment in nozzle corners	—	5.00	5.63	9.00	0.75	4	3.00
5	Shape 2 and 1/3 area of tab type 2 to maintain blockage as used with larger tab number	—	2.89	4.16	6.00	0.50	6	3.00

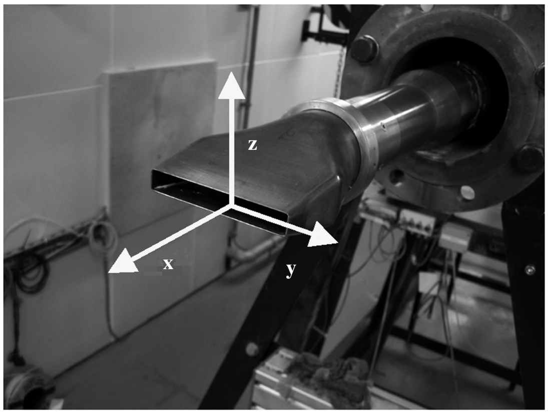

Fig. 6 Photo of the clean (no tabs) rectangular nozzle and measurement coordinate system.

likely to be acceptable in practical applications to minimize the thrust loss penalty than the 12% blockage employed by Zaman [17].

LDA measurements were carried out for all test cases listed previously under unheated nozzle operating conditions at NPR= 2.45, with a jet exit Reynolds number of 8.14×10^5. Transverse and spanwise cruciform profiles along y and z directions at $x/D_h = 5.0$ were measured for all test cases and at $x/D_h = 10.0$ for some cases (note D_h is the hydraulic diameter of the nozzle exit area). A total of 85 points covering the $15D_h$ axial distance were used for jet centerline measurements. Schlieren images were taken at nozzle operating conditions of NPR = 1.9, 2.45, 3.0, 3.5, and 4.0.

The accuracy and repeatability of LDA results depend on the sampling time, especially in the regions where the flow was highly turbulent (such as the fully merged jet zone). More accurate data may be obtained by using a higher sampling rate and collecting a larger number of samples to form the time-averaged statistics, but this clearly increases the measurement time per point. The effect of number of samples and sampling time on the repeatability of the LDA measurements were both studied in order to minimize the statistical (random) error. As a result, the number of individual velocity samples used in the experiments to form time averages was set at the large value of 20,000 and the sampling time limit was fixed at 30 s (whichever was fulfilled first). Every effort was taken to reduce and to eliminate experimental errors and uncertainties. A summary of estimated important experimental uncertainty magnitudes is listed below:

1) The maximum uncertainty of mean and rms velocity measurements is ±2.0 and ±5.0%, respectively.

2) The maximum uncertainty in locating the LDA probe measurement volume was ±0.1 mm.

3) The maximum NPR deviation from a set value was ±0.5%.

IV. Results and Discussion

A. Clean Rectangular Nozzle Jet Flow Characteristics

Figures 7a and 7c present measured mean and rms axial velocity along the jet centerline for the clean nozzle and operating conditions of NPR = 1.9, 2.45, and 3. These clean nozzle data form a datum or benchmark for near-field plume development for comparison with tabbed nozzle data. At a just critical condition (NPR = 1.9), the core region is free of shock structure and the potential core length is $\sim 4D_h$. At higher nozzle pressure ratios, the initial region is dominated by shock cell structures. The strength and size of the shock cells, especially the first cell, increases with higher NPR; in addition, a slight increase in potential core length at higher NPR is noticeable (e.g., $\sim 4.5D_h$ at NPR = 3). This is evidence of a compressibility effect (higher convective Mach number of the jet) causing a reduction in jet shear layer spreading and extending the potential core length. The jet turbulence intensity within the central core region is strongly influenced by nozzle operating conditions. At higher values of NPR, a more rapid rise in axial turbulence level was measured (Fig. 7c) although the peak value was changed a little.

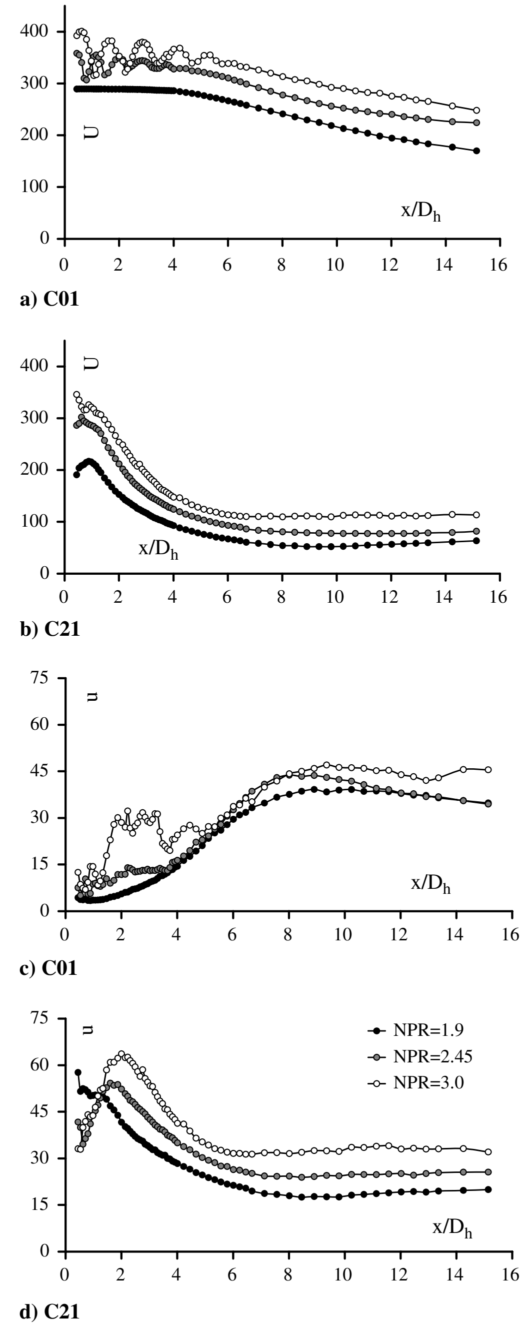

Fig. 7 Measured mean and rms axial velocity profiles (in m/s) along jet centerline for clean nozzle (C01) and twin-tabbed nozzle (C21).

There is some evidence of shock unsteadiness appearing as measured "turbulence" particularly at NPR ~ 3. To complete the characterization of the clean nozzle, profiles were also measured in the y and z directions. The measured mean and rms axial velocity along the nozzle minor/major axes at $x/D_h = 5$ and for three pressure ratios of 1.9, 2.45, and 3.0 are shown in Figs. 8a and 8c, again for the clean nozzle. Note that in this and following Figures the open and closed symbols represent LDA measurements along minor (z direction) and major (y direction) axes, respectively. At this axial location, the jet shear layers have not spread sufficiently to reach each other in the major axis direction but have merged in the minor axis direction (Fig. 8a). The peaks measured in the rms profile represent the high turbulence production zone in the center of the major axis jet shear layer. Although at $x/D_h = 5$ the jet aspect ratio is still large, spreading has reduced this to approximately half of the nozzle exit value of seven. The continued mixing is such that the jet cross section has deformed to a nearly circular shape at $x/D_h = 10$ distance, as shown in Fig. 9 (C01) below. As pointed out by Behrouzi and

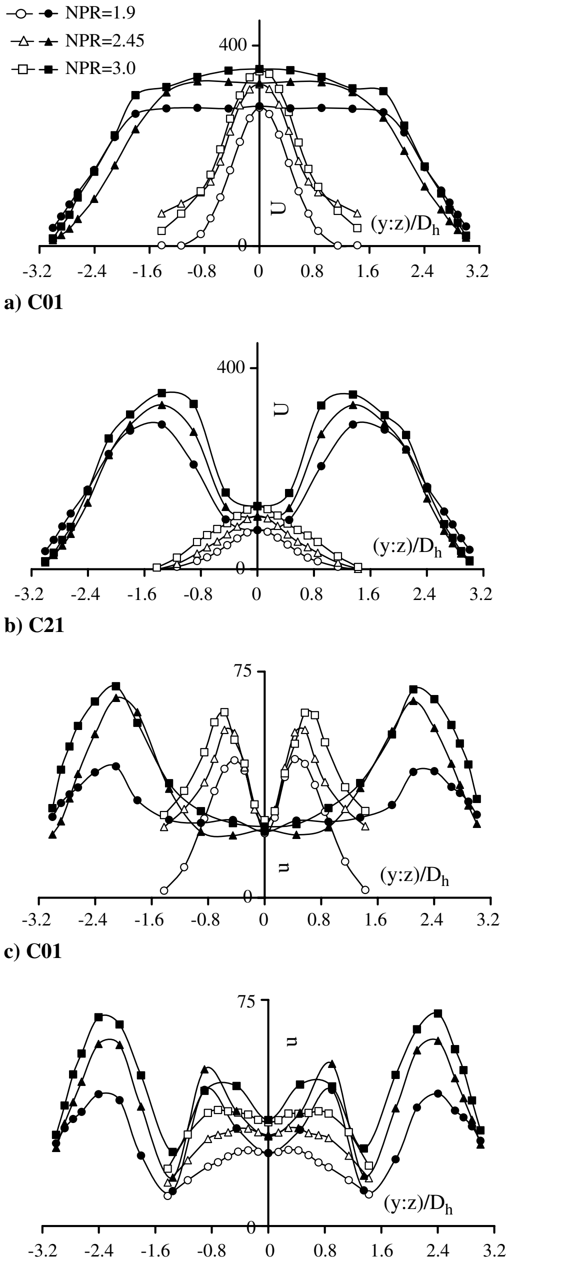

Fig. 8 Measured mean and rms axial velocity profiles (in m/s) along minor (open symbols) and major (closed symbols) axes for clean nozzle (C01) and twin-tabbed nozzle (C21) at $x/D_h = 5$.

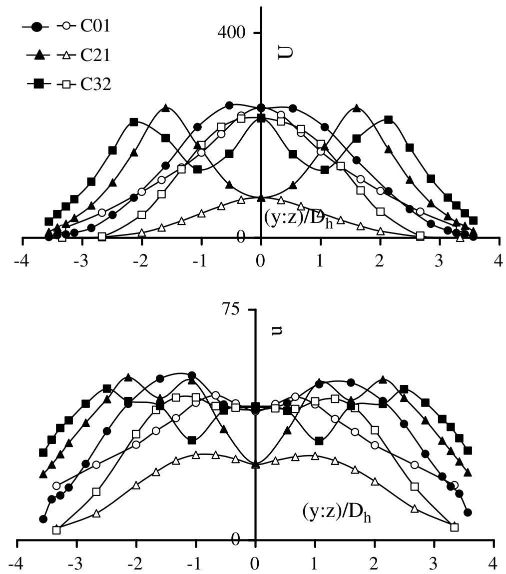

Fig. 9 Effect of tab number on measured mean and rms axial velocity profiles (in m/s) along minor (open symbols) and major (closed symbols) axes at $x/D_h = 10$.

McGuirk [23], due to the existence of fairly weak streamwise vortices caused by the 3-D nozzle geometry, a mild axis-switching phenomenon was noticed further downstream at around $x/D_h = 15$ with the longer axis direction now associated with the vertical (z) axis. Finally, Figs. 10 and 11 (left column) present Schlieren photos of side (perpendicular to minor axis) and top (perpendicular to major axis) views of the clean rectangular nozzle jet plume. The Schlieren images were taken at the three nozzle operating conditions, NPR= 2.45, 3.0, and 4.0. The expansion of the jet plume in the minor and major axis directions and the spread of the z-direction jet shear layer toward the axis are clearly visible via the curved shock shapes in the shear layer regions, particularly at the highest nozzle operating pressure; the strength and size of the shock cells are seen to be greater at higher NPR.

It can be concluded from inspection of the preceding Figures that, although NPR clearly affects absolute levels of, for example, turbulence in the near-field region of interest ($x/D_h < 10$), development trends are not strongly dependent on NPR. As noted by Zaman [17], a comparison of the effectiveness of using enhancement devices on jet spreading is best conducted at similar jet Mach numbers and preferably based on measurement of the whole flowfield. It was therefore decided, after this preliminary survey of the effect of NPR on the clean nozzle plume did not reveal any strong NPR influence, to concentrate further measurements at a nozzle operating condition of NPR $= 2.45$. This is in the NPR range of interest in military jet plume applications and, as a further advantage, the rig can be operated continuously at this NPR with the nozzle size selected, requiring no blown-down time and providing longer run times for LDA measurements.

B. Effect of Twin Tabs on Jet Development

As noted in the Introduction, a single tab produces a pair of counterrotating streamwise vortices that move the ambient fluid into the core along the tab axis (referred to here as inflow and shown in Fig. 2) and convects core jet fluid toward the ambient in the direction perpendicular to the tab axis (outflow). A twin-tabbed nozzle produces two pairs of vortices, each of which creates its own inflows and outflows. These inflows and outflows combine with the effects of turbulent mixing to determine the precise location of the jet/ambient boundary around the jet periphery at any downstream station. The strength of this boundary interface movement depends primarily on flow/mixing induced by tab and nozzle geometry and only secondarily on the nozzle operating condition. As suggested by Behrouzi and McGuirk [11], the optimum tab number for a round nozzle was two, because the two vortex pairs are then as far from each other as possible and can develop without any mutual interference for a long downstream distance. For a round nozzle with four or higher number of tabs, merging of adjacent vortex pairs takes place, which then reduces the tab-induced jet spreading rate compared with the twin-tabbed nozzle. As a result of this observation, it was decided to investigate first the twin-tabbed jet flowfield in detail for a rectangular nozzle to contrast the behavior to the round nozzle case.

The twin-tabbed rectangular nozzle case (C21) is shown in Figs. 7b and 7d in terms of measured jet centerline mean and rms axial velocity data, again for nozzle operating conditions of NPR $= 1.9$, 2.45, and 3.0. Comparing to the clean nozzle results (C01), the effect of twin tabs on enhancement of the decay of the jet centerline velocity and the initial rise of turbulence intensity is very clear. The potential core length (as deduced from centerline data) was reduced to less than $1D_h$, and the shock cell pattern has also been affected dramatically. The peak turbulence location has been changed from $\sim 9D_h$ to $\sim 2D_h$. The flat regions in both mean and rms plots for $x/D_h > 6$ indicate a readjustment from the very rapid development in the first few diameters dominated by the tab vortices to the more gradual development further downstream ($x/D_h > 20$) controlled by conventional turbulent mixing. Drastic shortening of the central core region is also noticeable from the rms values and at all nozzle operating conditions. Figures 8b and 8d present measured axial mean and rms velocity profiles along the minor/major axes at $x/D_h = 5$ for the twin-tabbed case (C21) and at nozzle operating conditions of NPR = 1.9, 2.45, and 3.0. Significant jet cross section distortion created by the streamwise vorticity introduced by the tabs is evident in both mean and rms results, with a strong bifurcation of the maximum mean velocity location occurring to either side of the jet major axis, leading to the double-peaked spanwise profile structure in the mean velocity, and a four-peak structure for the rms. The effect of the tabs is to cause the jet core to split into two parts, which therefore increases the interfacial area of the mixing region between jet and ambient fluid. This speeds up the mixing process because turbulence develops along the entire interfacial boundary and shortens the jet potential core length. Figure 9 (C21 profiles) shows the measured axial mean and rms profiles at $x/D_h = 10$ for NPR = 2.45. A single peak appears either side of the centerline for the clean (C01) nozzle in the rms profiles along the minor axis and is also visible for the twin-tab (C21) case. However, a double-peaked rms profile appears in the major axis direction in the tabbed jet case.

Further evidence of the bifurcation phenomenon is seen in the Schlieren results (Fig. 11). This phenomenon introduces a second jet/ambient shear layer and, hence, an additional high gradient region in the mean flow profile, causing a second zone of high turbulence generation. The magnitude of the twin-tabbed jet centerline velocity has been reduced to 1/3 of the clean jet value by $x/D_h = 10$ (Figs. 7 and 9). However, at this axial station, the maximum (off-axis) velocity magnitude in the major axis profile is almost unchanged from the clean jet centerline value although the overall area of flow possessing this maximum velocity level has decreased. This shows that the bifurcation process does lead to some extra mixing enhancement compared with the clean jet case. Figures 10 and 11 (C21 case, in middle column) present side and top Schlieren images of the twin-tabbed rectangular nozzle jet plume at NPR = 2.45, 3.0, and 4. The spread of the jet in the minor axis direction has been drastically reduced, as seen by comparing C01 and C21 results in Fig. 10, which shows extended shock cell structures. This effect is caused by the tab-induced inflows. The Schlieren photos confirm the LDA measurements and show that the supersonic, shock-containing regions of the jet have split into two zones in the major axis direction (Fig. 11), separated by a region of turbulent subsonic flow. The ambient fluid has been forced into the jet center by the streamwise vorticity. The shock pattern in the C21 views is notably different than the C01 pattern.

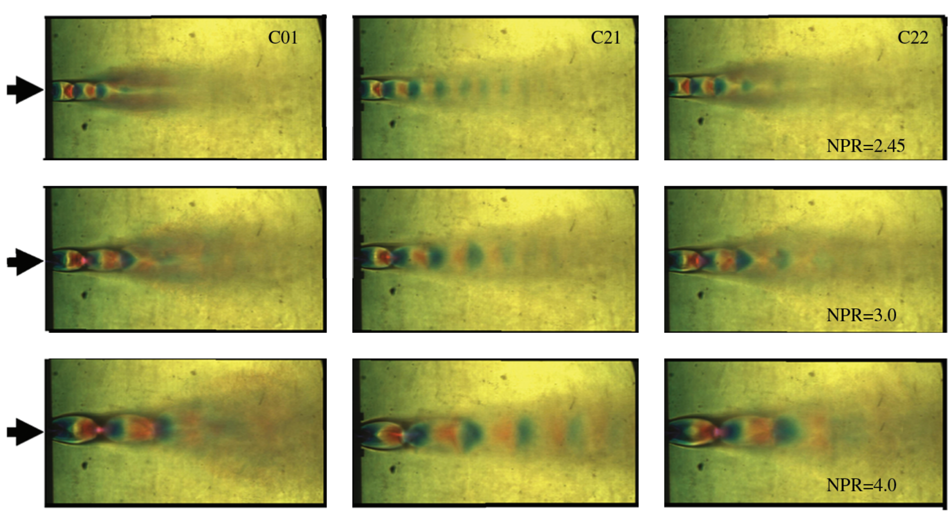

Fig. 10 Schlieren images of jet plume side views for test cases C01, C21, and C22 at three nozzle operating conditions.

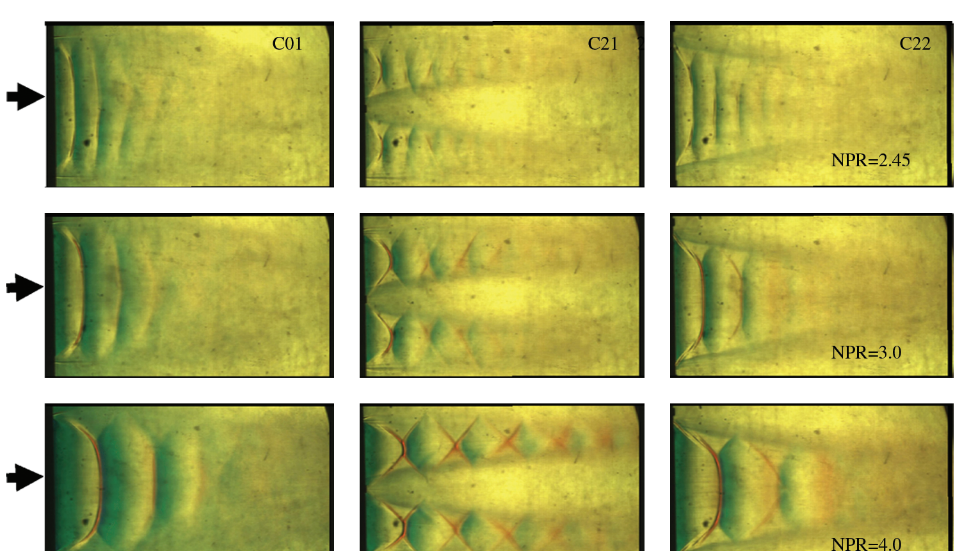

Fig. 11 Schlieren images of jet plume top views for test cases C01, C21, and C22 at three nozzle operating conditions.

C. Effect of Tab Shape

Figures 12 and 13 present the effect of tab shape on measured mean and rms jet centerline axial velocity and on the transverse and spanwise profiles at $x/D_h = 5$. Data are provided for the clean nozzle (C01), a nozzle with twin shape 1 tabs (C11), and twin shape 2 tabs (C21). The measurements were carried out at NPR = 2.45. Figure 12 shows that the trend of decay of mean velocity and initial rise of the rms velocity on the jet centerline is very similar for both tab shapes, except in the first diameter where the rectangular (shape 1) tab seems to have introduced a stronger streamwise vortex than the delta (shape 2) tab. Downstream of $x/D_h = 4$, flow development is almost identical. The cruciform profile measurement results for both tab shapes at $x/D_h = 5$ are also very similar (Fig. 13). Therefore, the precise shape of the tab (in particular at its upper end) does not seem to have a significant influence on the mixing process for high aspect ratio rectangular nozzle plumes. Research by Bradbury and Khadem [3] and the flow visualization results of Samimy et al. [5], Zaman et al. [6], and Behrouzi and McGuirk [11] showed that for a round nozzle, the delta tab (shape 2) was slightly more effective on jet spreading than a rectangular tab (shape 1), but the differences here seem to be smaller for rectangular jet flows. Hence, it was decided to retain only the delta tab for the further studies reported here.

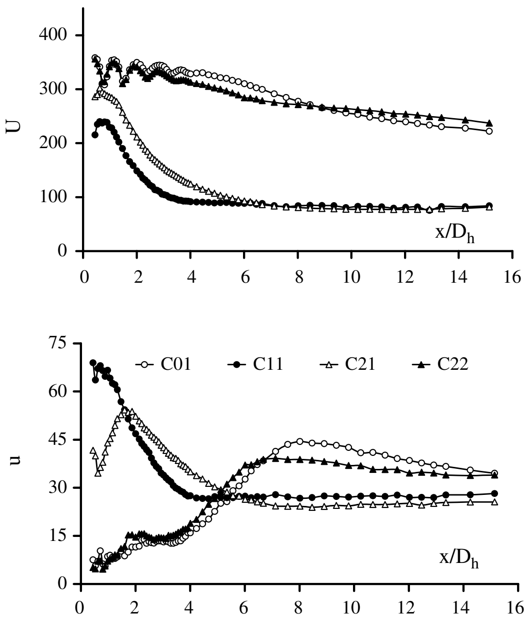

Fig. 12 Effect of tab shape (C11 and C21) and location (C21 and C22) on measured mean and rms axial velocity profiles (in m/s) along the jet centerline.

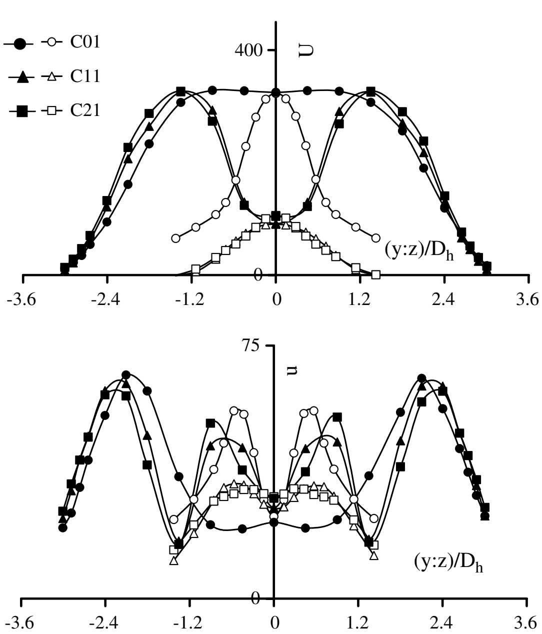

Fig. 13 Effect of tab shape on measured mean and rms axial velocity profiles (in m/s) along minor (open symbols) and major (closed symbols) axes at $x/D_h = 5$.

D. Effect of Tab Location

For a twin-tabbed rectangular nozzle, the tabs can be installed at various locations: either at the center of the wide edge (see Table 2, C21) or symmetrically on the narrow edge (C22). Jet plume spreading is observed to be certainly sensitive to the tab location. For example, for installation of the tabs on the narrow edges, strong inflow is produced perpendicular to the narrow edges. This overwhelms the naturally occurring vortices created at the corners of the rectangular nozzle and dominates the flow. The induced inflows move toward the jet axis and speed up the axis-switching process. Figure 12 presents the effects of twin-tab location on LDA measured axial mean and rms velocity along the jet centerline (NPR = 2.45). Tabs located on the nozzle narrow edges (C22) caused only a minor effect on the jet centerline velocity decay and turbulence level development (see C01 and C22 data). This is because the strong streamwise vortex effects mentioned previously are now local to the narrow nozzle edges, which are far from the jet centerline. Further downstream (x/D_h between 4 and 6), the vortex effects do spread to the centerline, and the decay rate is increased and turbulence level increased. Downstream of $x/D_h = 6$ these effects are reversed. However, as highlighted in the last section, tabs located on the nozzle wide edge have a much more dramatic effect, splitting the jet into two supersonic and one subsonic region. As suggested by Zaman [17], tabs positioned at these locations delay or even prevent jet axis switching. Figures 10 and 11 show side and top Schlieren images views of the jet plume for both tab mounting locations (C21 and C22) at NPR = 2.45, 3.0, and 4.0. When the tabs are located on the narrow nozzle edges (C22), the spread of the jet in the minor axis direction is reduced slightly in comparison to the clean nozzle (C01) particularly for NPR = 4. The inward spread of the jet shear layer in the major axis direction is, however, enhanced relative to the clean nozzle (C01) in the C02 picture due to the mixing effect of the tab-induced vorticity, which reinforces the vortices created in the nozzle corners; this speeds up the axis-switching process as noted previously.

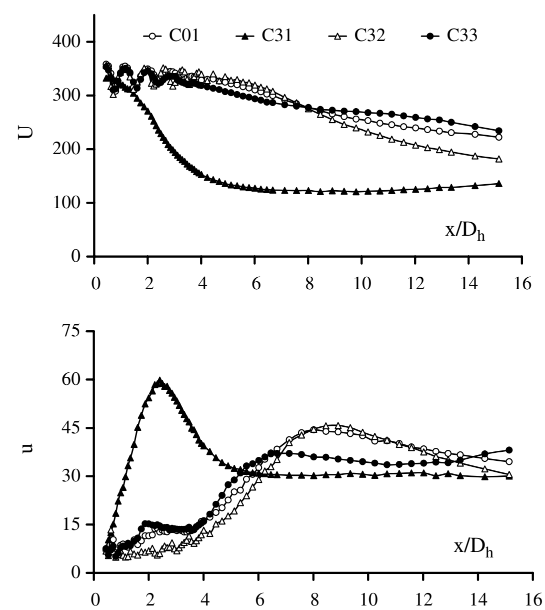

Fig. 14 Effect of tab location on measured mean and rms axial velocity profiles (in m/s) along the jet centerline.

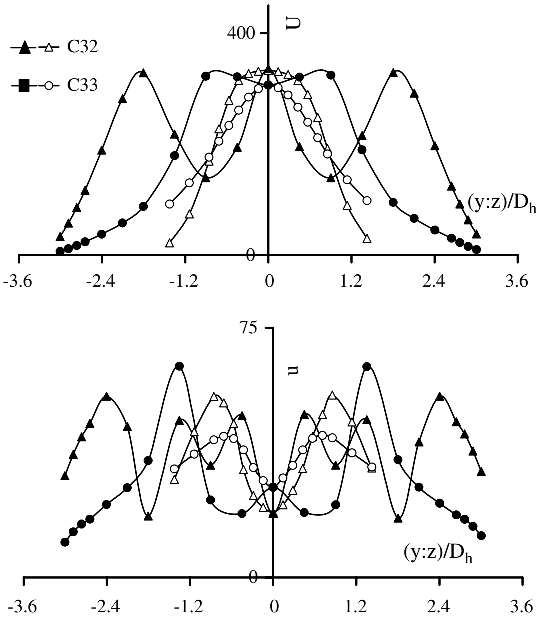

Fig. 15 Effect of tab location on measured mean and rms axial velocity profiles (in m/s) along minor (open symbols) and major (closed symbols) axes at $x/D_h = 5$.

There are three possible tab configurations for a nozzle with four tabs. One tab can be located on each edge (Table 2, C31), tabs can be located only on the wide edges (C32), or tabs can be positioned at each corner (C33). In all these cases the tab total blockage area was kept constant at 3%. Figure 14 presents mean and rms velocity data along the jet centerline for clean (C01) and four-tabbed nozzles for all configurations (C31, C32, and C33). Case C31 appears in this figure to be the most effective at manipulating the jet centerline values; it sharply increases the observed decay rate of the centerline velocity and the rise of the turbulence level. Cases C32 and C33 display only minor centerline changes compared with the clean nozzle results. However, centerline behavior alone is not a precise indication of the overall effects introduced by the tabs on the jet flow. For maximum manipulation of the entire jet-core flow, case C32 can be considered as the most effective tab configuration. For the C32 case the centerline velocity decay at $x/D_h = 15$ has been reduced by 20% compared with the clean nozzle, and Fig. 15 shows from measured data at $x/D_h = 5$ that the mean and rms axial velocity profiles for the C33 configuration are similar to those for C01 (C01 data are given in Fig. 8). However, for case C32, three velocity peaks and six rms peaks along the major axis are created. These are caused by the multiple vortex system induced by two tabs along each wide edge. These produce two inflow zones per nozzle edge and, hence, three supersonic flow regions separated by two subsonic flow regions. This is visualized most clearly in the Schlieren images for the C31, C32, and C33 cases in Figs. 16 and 17. In general, all tab configurations have reduced the expansion of the jet plume in the minor axis direction compared with the no-tab case, but the jet plume is divided into two and three supersonic subregions for the C31 and C32 cases, respectively. The strength and shock cell structure are similar in all subregions. Tabs located at the nozzle corners (C33) do not split the core flow but move the jet boundaries marginally inward along the major axis direction as observed when the tabs were located only on the narrow nozzle edges.

E. Effect of Tab Number

It is clear that the impact of tabs on the flow is primarily due to the induced dynamics of the tab-created streamwise vortex pairs. For a

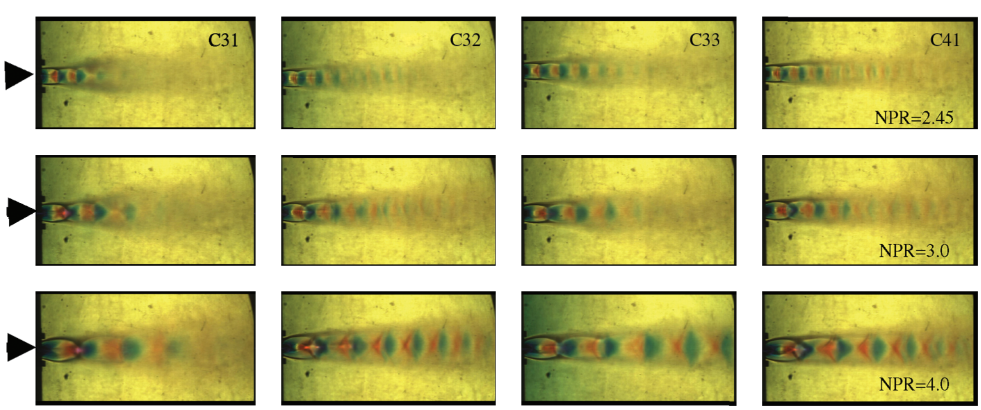

Fig. 16 Schlieren images of jet plume side views for test cases C31, C32, C33, and C41 at three nozzle operating conditions.

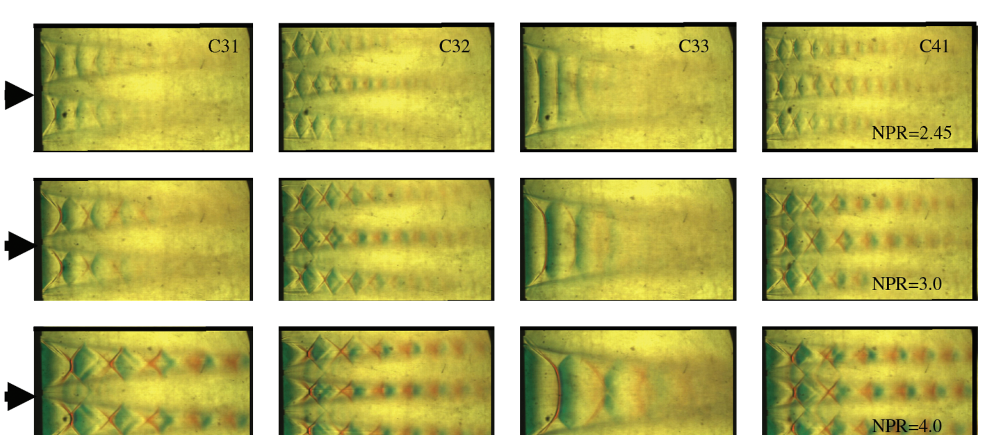

Fig. 17 Schlieren images of jet plume top views for test cases C31, C32, C33, and C41 at three nozzle operating conditions.

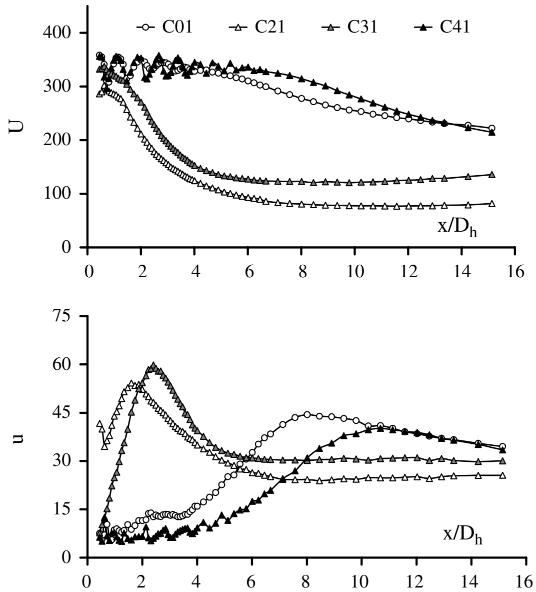

Fig. 18 Effect of tab numbers on measured mean and rms axial velocity profiles (in m/s) along the jet centerline.

high aspect ratio rectangular jet, the tab-induced flow also affects the axis-switching phenomenon. It is of interest to investigate the optimum number of tabs to achieve enhanced jet spreading. Three cases with two, four, and six tabs were therefore investigated. Table 2 indicates the tab locations. Figure 18 presents the jet centerline behavior, showing the effect of tab number for two (C21), four (C31), and six (C41) tabs. Once again it is important to remember that the total blockage area of all tabbed nozzles used in these tests was maintained the same in order to compare cases with (approximately) the same effective thrust loss. The two-tab (C21) results and four-tab (C31) data are close together, however, four tabs create more turbulence. The results for the six tab (C41) version show a centerline behavior remarkably similar to the clean nozzle case, with even lower turbulence levels. Once again, it is essential to note that the jet centerline behavior may in fact be misleading and is insufficient to capture the true impact of tab number on the jet spreading rate. This is easiest to deduce from profile information, as given in Fig. 19 for $x/D_h = 5$. Figures 10, 11, 16, and 17 present Schlieren images side

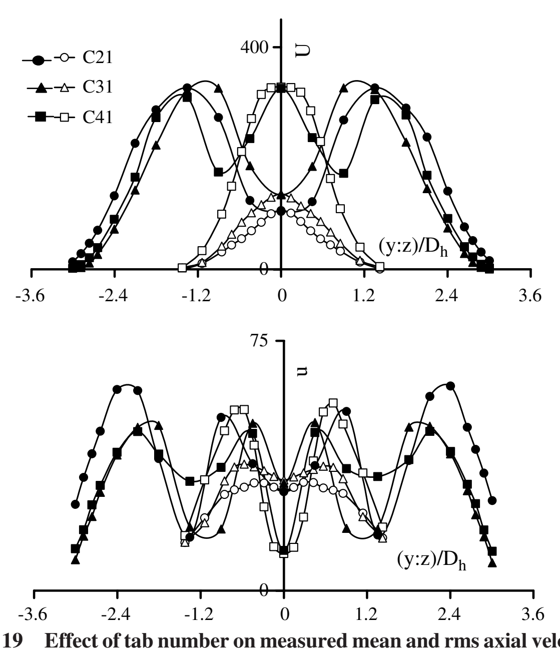

Fig. 19 Effect of tab number on measured mean and rms axial velocity profiles (in m/s) along minor (open symbols) and major (closed symbols) axes at $x/D_h = 5$.

and top views for a clean nozzle (C01), two tabs (C21), four tabs (C31), and six tabs (C41). The conclusion that may be drawn from the velocity data in Fig. 19 is that a four-tab configuration is more effective than either two or six tabs in terms of bifurcation of the jet in the major axis direction. Figure 19 also shows that the maximum axial velocity and rms values along the major axes are nearly the same for all three cases. However, the jet shape and jet plume characteristics are quite different with the smallest zones of peak velocity being for the four-tab case. This can be seen in the Schlieren images. All three cases have created complex shock cell patterns compared with the no-tab case. The dominant effect of the tab-induced vorticity and inflows and outflows is to cause ambient subsonic flow zones to penetrate the supersonic jet core. For two tabs (C21) a single subsonic zone is created, which gradually dissipates the shock reflections with downstream distance. For four tabs (C31), the picture is similar in the center of the nozzle major axis, but the tabs on the narrow edges create enhanced mixing that spreads inward from the major axis edges and causes further weakening of the shock cell structure. For six tabs (C41), although two embedded subsonic zones are created, because the individual tab area has decreased as the tab number has increased, the size and strength of the subsonic zones is less and a distinct shock cell structure is therefore able to persist further downstream. It seems from this evidence that, for the 3% blockage constraint used here, for maximum disruption and reduction of the supersonic jet core, four tabs is the most effective number.

V. Conclusions

As part of a program of experimental work aimed at identifying and improving understanding of rectangular nozzle flows and near-field exhaust plume mixing, specific tests have been performed to investigate the effects of shape, number, and configuration of tab vortex generators for a representative high aspect ratio ($\sim$7) rectangular nozzle. The near-field mixing performance of the rectangular jet with and without solid tabs introduced on the nozzle lips has been studied under supersonic (underexpanded) operating conditions. It was found that modification to tab shape (rectangular or triangular) introduced only minor changes in the spreading rate and shock cell structure. However, tab location and tab number are much more sensitive parameters for jet plume development. In the present work, a constraint (3%) on maximum tab blockage area was imposed, to enable comparative results between tabbed nozzles to be assessed at (approximately) equivalent levels of thrust loss penalty. Hence, as tab number increased, the blockage area per tab (and thus the strength/scale of the associated streamwise vortex introduced) decreased. It was observed that tabs located on the nozzle wide edges split the jet, whereas on the narrow edges they caused only localized increase in jet shear layer spreading rate. Tabs did influence the axis-switching phenomenon known to occur in rectangular jets, with tabs on the wide nozzle edge delaying axis switching and on the narrow edge accelerating this. In general, tabs on the narrow edges, or introduced in the nozzle corners, were much less effective at breaking up and eroding the supersonic jet core. Given the total blockage area constraint, the most efficient tab number (two, four, and six were investigated) was four, located symmetrically on the two nozzle wide edges. For even higher aspect ratio nozzles than the value of seven studied here, it is likely that larger tab numbers would be needed. The design principle would, however, still be the same, that is, to introduce sufficient tab numbers on the nozzle wide edges to allow a number of streamwise vortices to be created that are strong enough to cause jet bifurcation but that are far enough apart not to interfere with each others' tab-induced streamwise vorticity field within the jet near field (10 nozzle hydraulic diameter) where tab-induced enhanced mixing is effective.

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