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ON THE SELF-PRESERVATION OF A SQUARE JET

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ABSTRACT

This paper presents the velocity measurements of an unheated jet issuing from a square nozzle into stagnant ambient air. Measurements were accomplished by means of hot-wire anemometer. Experimental results concluded that the jet initial boundary layer was laminar. Based on the local maximum velocity and half-width, the interaction region was determined to be $8De$. Decay and spreading rates of the jet were also studied and compared with those of other researchers. Lastly, plots of velocity half-width profiles predicted that there may be no axis-switching in the present square jet although more measurement evidence is required.

INTRODUCTION

The jet is the most common flow configuration, its applications ranging from heat and momentum transfer, to entrainment and mixing of ambient fluid with the jet fluid (Dahm and Dimotakis, 1987), and control of chemical reaction rate (Komoris and Ueda, 1984). It is especially significant in aerodynamics and aircraft propulsion where intense jet mixing is of primary importance for efficient combustion, by-pass flow mixing, as well as jet/wake interaction in compressors and turbines.

One of the most intriguing aspects of the square jet is the phenomenon of axis-switching, which is of interest from a fundamental scientific viewpoint and for its potential applications in areas such as reduced jet noise and attaining increased mixing of the jet plume with the surroundings. Occurrence of axis-switching is due to the dynamics of rolled-up azimuthal vortex structures (aptly called ω_θ-dynamics) which induce jet cross-section expansion in one axis and simultaneous contraction in the other (Hussain and Husain, 1989). The yz-axis of the jet would then be perceived to continuously rotate 45° at various downstream locations. While this mechanism always tends to cause axis-switching, the second mechanism (ω_x-dynamics) which is due to induced velocities of streamwise vortex pairs acts to resist axis-switching (Liepmann and Gharib, 1992). These two dynamics are dependent on each other and together, they act to promote or delay axis-switching. Several conditions affect axis-switching, two of the more important ones are jet speed and initial condition, an example of which suitable placement of tabs was discovered to inhibit or augment the occurrence (Zaman, 1996). In order to study the axis-switching phenomenon, mean velocity profiles across the diagonal (defined as the w-axis) were also measured and presented.

EXPERIMENTAL METHOD

Measurements were taken on the air supplied by a centrifugal blower through a 25mm square nozzle (of equivalent diameter $De = 28.2$mm) fabricated from fibre-glass with an area contraction ratio of 100:1. Installed between the blower and nozzle were a divergence section, settling chamber of size 250mm X 250mm X 250mm, screens and honeycomb section to convey the flow and reduce turbulence. A variable speed a.c. (alternating current) three-phase induction motor was selected to drive the blower and motor speed regulation was achieved through a frequency control system using pulse width modulation inverter. The jet exit velocity U_j was set at 31±0.5m/s which corresponds to a Reynolds number Re of 57500 ($Re = U_j De/\nu$, where ν is the kinematic viscosity). A definition sketch of the jet nozzle and velocity profile is shown in Figure 1.

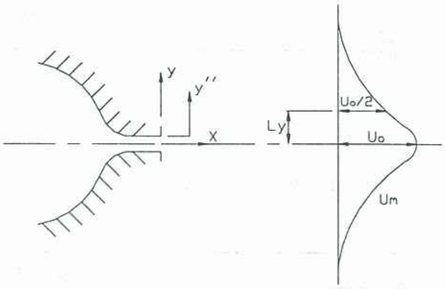

Figure 1: Definition sketch

Instantaneous velocities of the jet were acquired through a single hot-wire probe (ϕ5μm Wollaston Pt 10%-Rh, length ≈ 1.2mm) connected to a constant temperature anemometer (CTA) module operating at an overheat ratio of 1.5. The probe was mounted onto a dial height gauge fixed to a traversing mechanism capable of travelling in three perpendicular directions (x, y and z axes). An attachment on the height gauge enabled data in the w-axis (which is the axis parallel to the square nozzle diagonal, i.e. inclined at 45° to z-axis) to be captured for purpose of axis-switching investigation. The hot wire was calibrated prior to each measurement set in the potential core with reference to a pitot-static tube connected to a pressure transducer. A sample of 999 voltages each from the CTA and pressure transducer were digitized by a 12-bit analog-to-digital converter before input into a computer for processing. After calibration constants were computed using least squares method, they were then fed into the second part of the computer program which converts hot-wire voltages into velocities. In the measurement segment, mean velocities were obtained from 999 samples.

RESULTS AND DISCUSSION

The mean axial velocity across the immediate exit of the square nozzle was top-hat in shape and symmetrical about the jet centreline. At the nozzle exit plane centreline, the turbulent intensity u'/U_j (single prime denoting rms values) was measured to be approximately 1.5%. Estimates of the random component of uncertainty for mean and rms velocities were ±1.1% and ±3.9% respectively. Using the method of propagation of errors, the experimental uncertainty in u'/U_o was estimated to be ±4.1% from uncertainties in the mean and rms velocities (Kline and McClintock, 1953). Figure 2 illustrates good agreement of the jet boundary layer with Blasius' solution for a flat plate. The normalizing scale is the boundary layer momentum thickness δ_m which was evaluated to be 0.115mm and 0.413mm for y and w axes respectively.

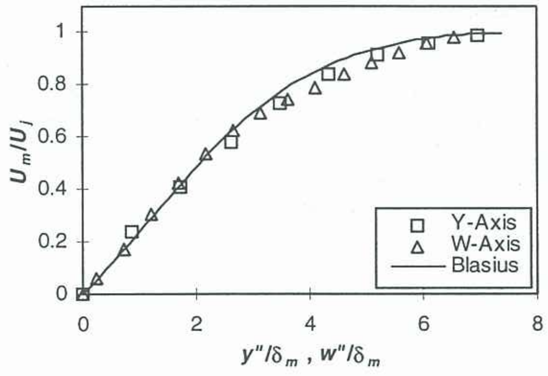

Figure 2: Boundary layer velocity profile at nozzle exit

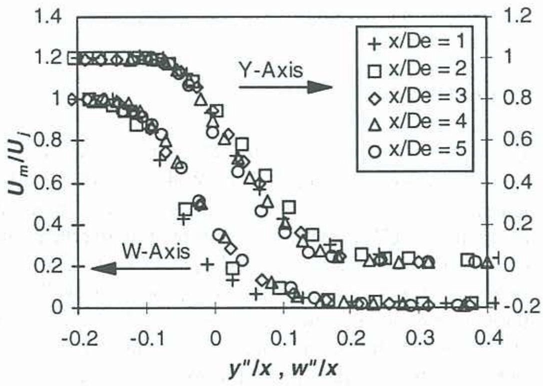

Figure 3: Mean velocity profiles in jet mixing layer

Mean velocity profiles of the quasi-two dimensional mixing layer near the nozzle exit are presented in Figure 3. Note that y'' and w'' were measured outwards from the nozzle wall (see Figure 1). Although the dimensionless quantities y''/x and w''/x relate to the mixing layer, their use in the interaction region can indicate degree of departure from the self-preserving mixing layer. It can be observed that the mixing layer became self-similar at $x/De = 3$ for both y and w axes.

On the other hand, mean velocity profiles in the interaction and self-preservation regions in the range $5 \leq x/De \leq 45$ are displayed in Figure 4. Here, the local centreline mean velocity U_o and half-width L_y or L_w (which is the lateral distance y or w where U_m is reduced to $U_o/2$) are the normalizing co-ordinates. As evident in the figure, the mean velocity distributions collapse into a single curve indicating that U_m reached self-preservation at the end of potential core, that is $x = 5De$.

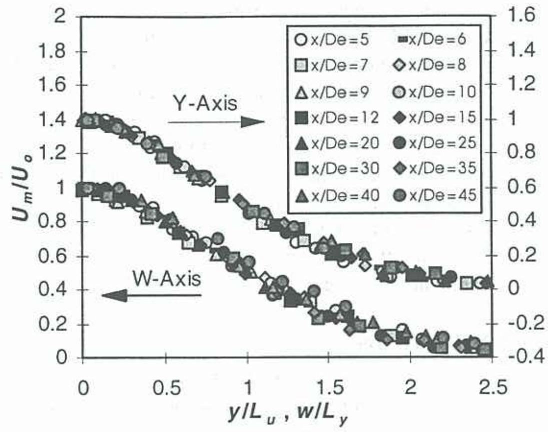

Figure 4: Mean velocity profiles from $x = 5De$ to $x = 45De$

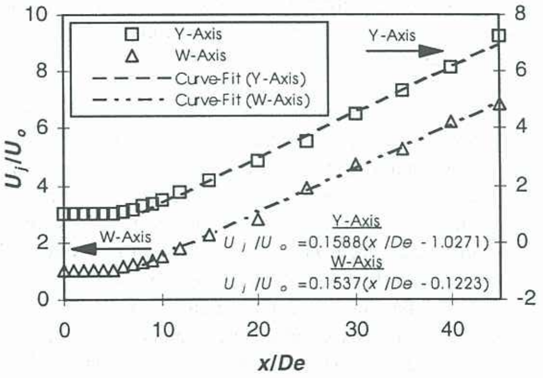

Figure 5: Streamwise variation of U_o

Figure 5 plots the variation of centreline mean velocity U_o in the y and w directions against x/De. Data in the range $8 \leq x/De \leq 45$ collapse reasonably well into a straight line which can be expressed as

$$\frac{U_j}{U_o} = A_l\left(\frac{x}{De} + B_l\right) \qquad (1)$$

where A_1 is the decay rate and B_1 the kinematic virtual origin of the jet. The decay rate of a jet depends on the amount of fluid available for entrainment, the process of which increases the internal energy of the fluid at the expense of its kinetic energy (Kundu, 1990). Other contributing factors are initial conditions of the jet such as its geometry and turbulence level (Hussain and Clark, 1977). In the experiment, decay rates for U_o should be the same for both axes, the slight discrepancy (of 3%) attributed to experimental uncertainty. In addition, self-preservation of U_o at ≈ 8*De* indicates that the interaction region of the present square jet is rather short.

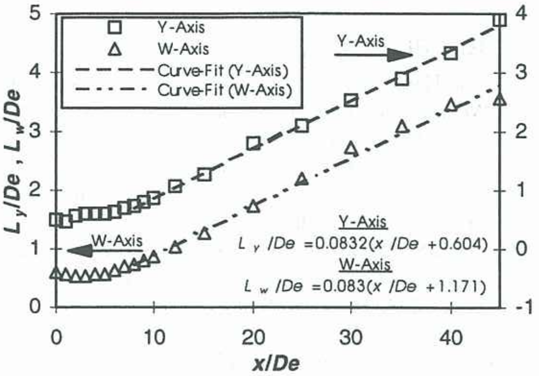

Figure 6: Streamwise variation of half-width

Investigator(s)	Initial Condition	*Re*	A_1	B_1	A_2	B_2	Range
Pani, 1972	Turbulent	---	---	---	0.0970	0.000	5≤x/De≤100
Quinn & Militzer, 1988	Turbulent	184000	0.1850	-0.150	---	---	8.4≤x/De≤62
	Turbulent	184000	---	---	0.0870	0.650	9.8≤x/De≤22.4
Yevedjerich, 1988	Turbulent	---	0.1430	0.000	---	---	20≤x/De≤200
Present Work:							
Y-Axis	Laminar	57500	0.1588	-1.0271	0.0832	0.604	8≤x/De≤45
W-Axis	Laminar	57500	0.1537	-0.1223	0.0830	1.171	8≤x/De≤45

Table 1: Comparison of present results with those of other researchers

With reference to Figure 6 which contains the graph of half-width variation along the downstream direction, the linear relationship is now given by

$$\frac{L}{De} = A_2\left(\frac{x}{De} + B_2\right) \qquad (2)$$

where A_2 and B_2 in the equation are the jet spreading rate and geometric origin. The figure shows that self-preservation was achieved at streamwise location of *x*/*De* = 8.

Table 1 presents the current results along with those of other investigators, Comparing the entries, differences between the decay and spreading rates for the current square jet and those of other researchers are seen to be relatively small, and the present square jet had a slightly lower spreading rate. These may be due to the difference in jet initial condition.

One means to study the axis-switching characteristics of a square jet is to plot the variations of L_y/De and L_w/De against *x*/*De* from which intersections of the two graphs imply locations of axis-switching. With reference to Figures 7(a) and (b), axis-switching was suspected to occur at locations 1*De* to 2*De*, 20*De* to 25*De*, as well as 40*De* to 45*De*.

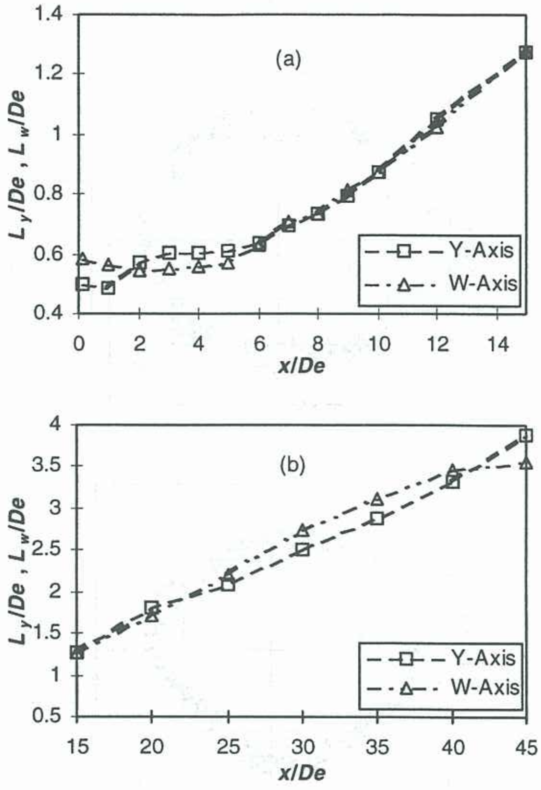

Figure 7: Comparison of half-widths in *y* and *w* directions for (a) 0.1 ≤ x/De ≤ 15 (b) 15 ≤ x/De ≤ 45

To perform a more detailed analysis of jet axis-switching, cross-sections of the jet were cut at various streamwise distances and exhibited in Figures 8(a), (b) and (c) for clarity of presentation. Figure 8(a) displays the cross-sectional profiles at the immediate exit of the jet from 0.1*De* through 3*De*. The 0.1*De* contour resembles the square shape of the nozzle and at 1*De*, the jet spread slightly at the sides. At *x*/*De* = 2 and 3, it can be observed that the profiles had changed to a polygon (vague hexagon) instead of a square rotated 45°, except in the 4th quadrant. As the boundary layer is much thicker in the *w*-axis than in the *y*-axis, the jet might have undergone an axis-switching due to the ω_θ-dynamics. However, it seems that ω_x-dynamics is more dominant and consequently suppressed the switching. More measurements, especially in the streamwise vorticity, are nevertheless required to support the above statement.

The half-width profiles in Figure 8(b) could be generalized as an elliptical-eye shape with spreading rate in the right half not as rapid as that on the opposite side. This can be deduced from the closer conformance of points to the nozzle on the former side in which the rotated square shape was preserved. In the left half, data indicate jet expansion such that the previously vague corner was smoothened and the readings resemble a semi-circle, which may explain the short interaction region of the present jet. Thereafter, the jet continued to expand downstream and the formed corner on the right side in Figures 8(a) and (b) was consequently rounded so that Figure 8(c) consists of concentric circles, except at $x/De = 30$, eliminating the possibility of axis-switching.

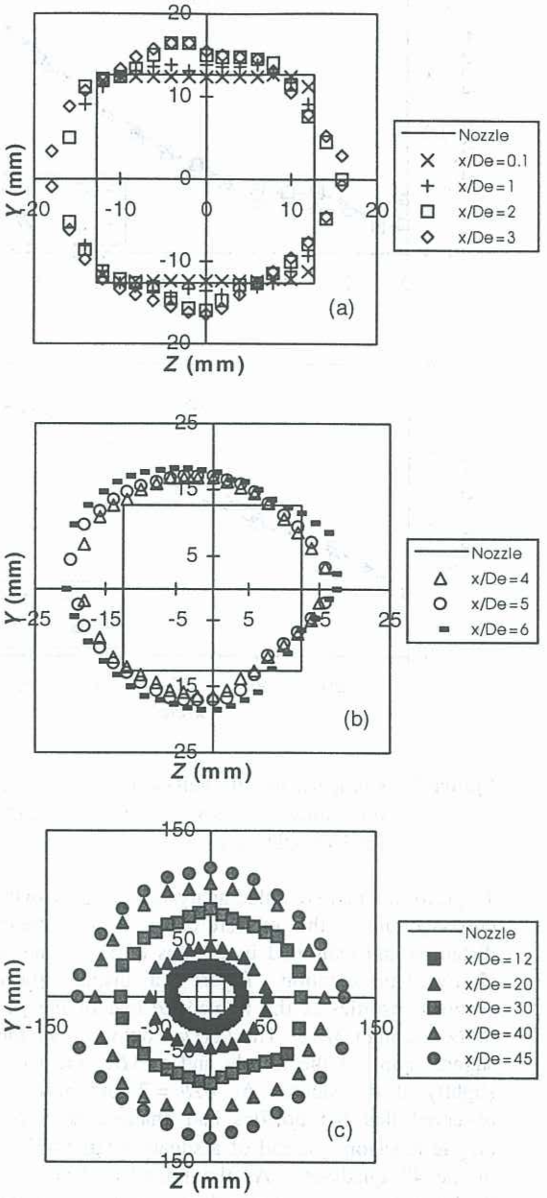

Figure 8: Half-width profiles in (a) immediate nozzle exit (b) near field (c) far field

The discrepancies between results in Figures 7 and 8 on axis-switching arise due to the half-widths in Figures 7(a) and (b) being derived from mean values in the corresponding axes and streamwise distances. As the jet is of high turbulent intensity flow, it is difficult to obtain accurate measurements at high x/De locations. The closeness between half-widths values in y and w-axes also explains the misleading presentation of axis-switching in Figures 7(a) and (b).

CONCLUSIONS

The initial flow condition of the square jet under investigation was found to be laminar. The potential core was detected to end at $\approx 5De$ into the exit jet. As for self-preservation, it was achieved at $3De$ for mixing layer and $8De$ for both local maximum mean velocity and velocity half-width. The interaction region, if existent, was very short. To provide a better comprehension of axis-switching, further measurement on the streamwise vorticity is required.

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