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Axis-Switching of a Square Jet

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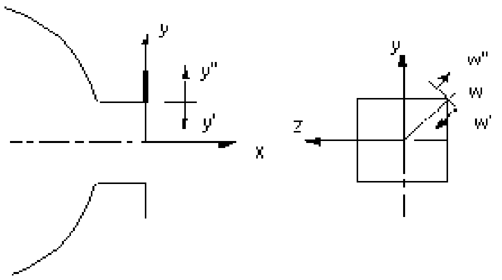
Abstract

The paper presents the velocity measurements of jet issuing from a square nozzle into stagnant ambient air. Comparison of velocity half-width along the *y*- and *w*-axes (parallel to the diagonal of the square) showed that there is axis-switching in the present jet. It was found that the large De/δ_{my} ratio and low turbulent intensity have overcome the adverse effect of the large ratio of jet momentum thickness at the diagonal and the flat side resulted that the jet has its first axis-switching at 1.75*De*. Note that *De* is jet equivalent diameter and δ_{my} is the momentum thickness along the flat side. Further measurements of mean velocity contours at various streamwise locations have indicated that there were axis-switching in the present square jet although more measurement evidence is required.

Introduction

The understanding of the mechanism of jet flow plays an important role in a number of engineering applications that deal with mass and heat transfer. Axis-switching is of interest from a fundamental scientific viewpoint and for its applications in enhancing entrainment, mixing and turbulence production. A considerable amount of work has been done on the axis switching using various jet configurations such as rectangular [4, 5], elliptic [2], triangular [3] and square [1, 4]. Besides, there were not much measurements done on the square jet, it was also observed that nearly all the measurements were done on the square orifice plate instead of a contour square nozzle.



Side view of the nozzle   Front view of the nozzle

Figure 1. Definition sketch of nozzle

The objective of the paper is to present a preliminary study on the axis-switching phenomenon of the contour nozzle square jet as compared to orifice square jet. For this purpose mean velocity profiles across the diagonal (defined as the *w*-axis as shown in Figure 1) of the jet are measured and the corresponding half-width *Lw* (*Lw* is velocity half-width in *w*-direction) is determined and compared with *Ly* (*Ly* is velocity half-width in *y*-direction). The effect of the jet initial condition such as the turbulence intensity at the jet exit, the ratios of De/δ_{my} and δ_{mw}/δ_{my} on the axis-switching have been investigated in detailed and compared with [1]. It was found that although the high δ_{mw}/δ_{my} (where δ_{mw} is momentum thickness along *w* axis) ratio has the adverse effect to initiate an early axis-switching, the high De/δ_{my} ratio and low turbulence intensity of the present jet have caused the first axis-switching at about 1.75*De* and subsequently at 5*De*. The mean velocity contours at a few streamwise locations are also presented in order to search for the evidence of the axis-switching. The mean velocity contour however is found to be not a sensitive indicator of axis-switching as well as the half-width which is based on the mean velocity profiles. More careful and extensive measurements on the velocity spectrum and streamwise vorticity are required to carry out for a conclusive finding on the axis-switching and its mechanism.

Experimental method

Measurements were taken on the air jet supplied by a centrifugal blower through a 25mm square nozzle (of equivalent diameter *De* = 28.2mm) fabricated from fibre-glass with an area contraction ratio of 100:1. The jet exit velocity U_j was set at 31±0.5m/s and the corresponding Reynolds number was 57500.

Instantaneous velocities of the jet were acquired through single hot wire probe (ϕ5μm Wollaston Pt 10%-Rh, length ≈ 1.0mm) connected to a constant temperature anemometer (CTA) module operating at an overheat ratio of 1.5. An attachment on the height gauge enabled data in the *w*-axis to be captured for the purpose of axis-switching investigation.

Voltages 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 the least squares method, they were then fed into the second part of the computer programs, which converted hot wire voltages into velocities. The sampling frequency (3200Hz) is double the cut off frequency (1600Hz) and the recording time is 5 seconds.

Results and discussion

In order to study the axis-switching characteristics of a square jet, the variations of L_y/De and L_w/De against x/De are compared in a graph and the intersections of the two curves indicate the locations of axis-switching. Figures 2 (a), (b) and (c) show the distributions of L_y/De and L_w/De along the streamwise directions. It can be observed in Figure 2(a) that L_w decreases from the jet exit to 1*De* and then follows with a gentle increase till 5*De* with an obvious hump at 1.5*De*. On the contrary, L_y has a slight decreased from the jet exit, follows by increasing from 0.5*De* to 2*De*, and then maintains at about the same level till 3*De*. A slight dip can be found at 3.5*De* before increasing more steeply to 4.5*De*. Following a small dip at 5*De*, L_y is then increase sharply thereafter. The profiles of L_y/De and L_w/De have thus the first and second crossovers at about 1.75*De* and 5.0*De* respectively. The third crossover is at 17.5*De* as shown Figure 2(b) and the variations of L_y/De and L_w/De are about parallel to each other without any crossover as demonstrated in Figure 2(c).

It is obvious from Figure 2(a) that the first crossover is happened with the shrinking of L_w and the faster growth rate of L_y. It should be noted however that the faster growth of L_y does not happen immediately after the jet axis but at a later streamwise location of 0.5De. Grinstein et al [1] have studied the effects of the initial conditions e.g. the turbulence intensity at the jet exit and the ratios of De/δ_{my} and δ_{mw}/δ_{my}, on the axis-switching of the square jet.

Table 1 compares the initial conditions of the three experimental results of unforced square jets of [1] with the present jet. According to the linear stability analysis of Koshigoe et al [3], the high δ_{mw}/δ_{my} ratio for the present jet is not favor of the axis-switching. Since the azimuthal nonuniformities of the initial shear layer are quite high, which may result in the amplification rates of the corresponding unstable eigenmodes become not comparable and thus the growth rates of the velocity fluctuations associated with the different modes are not comparable too. However, as can be seen from the table, the initial conditions of Re and *u'/Uo* (*u'* is root mean square of axial velocity fluctuation, *Uo* is axial centerline local mean velocity) of the present jet are similar to the OU1 (orifice jet). Furthermore the value of De/δ_{my} is even much higher than that of OU1. The large De/δ_{my} and low *u'/Uo* should have caused the faster growth rate of L_y and resulted in the first axis-switching as reported by [1] for their OU1 orifice low turbulent square jet.

Figure 3 shows the variations of maximum turbulent intensities of both y- and w-axes in the mixing layer which indicate the initial amplification of turbulence along the shear layers. It can be observed in Figure 3 that the difference between the amplification rate at the side (*y*-axis) and diagonal (*w*-axis) directions are not obvious. This is different from that of the orifice jet [1]. However, the maximum shear stress is consistently higher for y-axis than those of the w-axis till 1De and after that the shear stress for w-axis is higher than the y-axis but maintain about the same level after 2*De*.

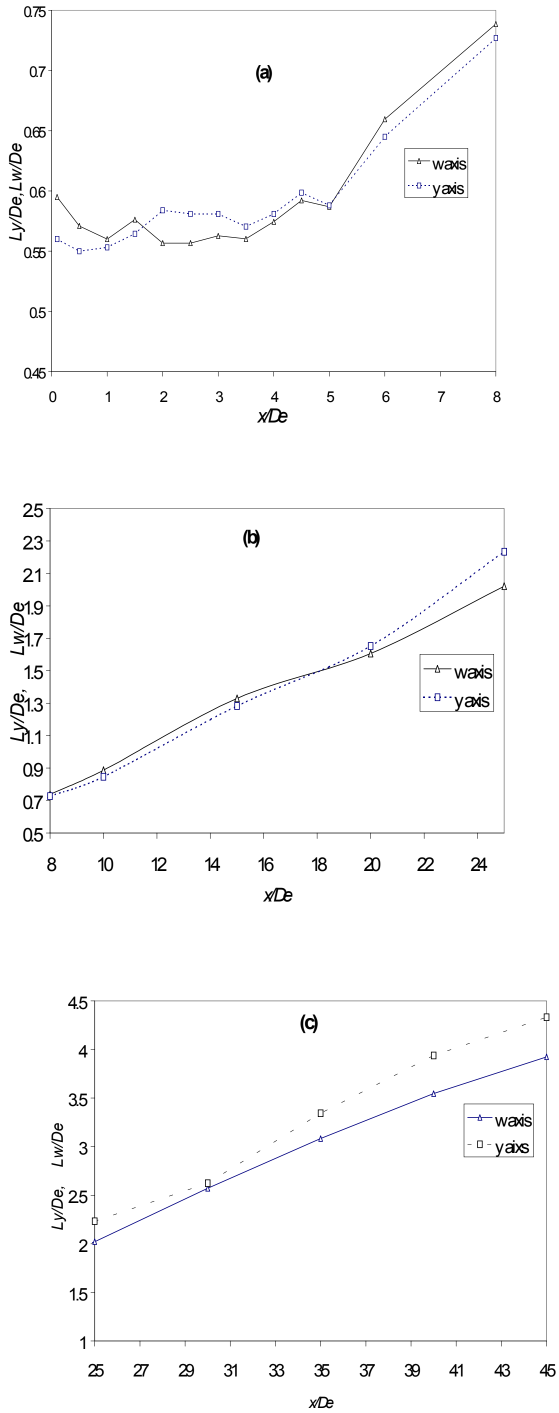


Figure 2. Comparison of half-widths in y- and w-directions for (a) $0.1 \leq x/De \leq 8$
(b) $8 \leq x/De \leq 25$ and (c) $25 \leq x/De \leq 45$

Figure 4 shows the variations of the centerline mean velocity and turbulent intensity. The centerline mean velocity has just slight variation around the *Uj* (jet exit velocity) within the potential core as expected, the centerline normal shear stress has increased continuously along the streamwise direction. The localize changes in the amplification rate are attributed to the axis switching dynamics and the shear layer amplification [1]. All these should have overcome the adverse effect of the high δ_{mw}/δ_{my} ratio and contributed positively the axis-switching of the present contour nozzle square jet.

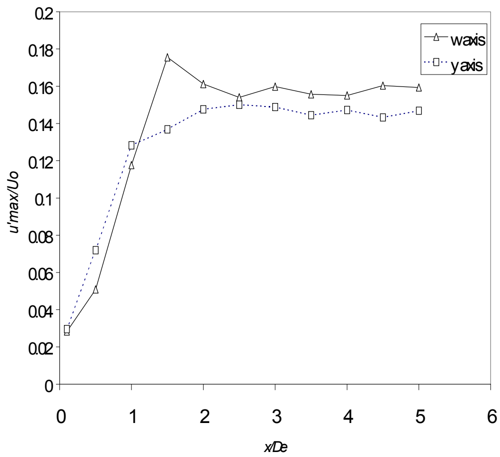


Figure 3. Comparison of maximum turbulent intensities in the shear layer along the *y*- and *w*-axes

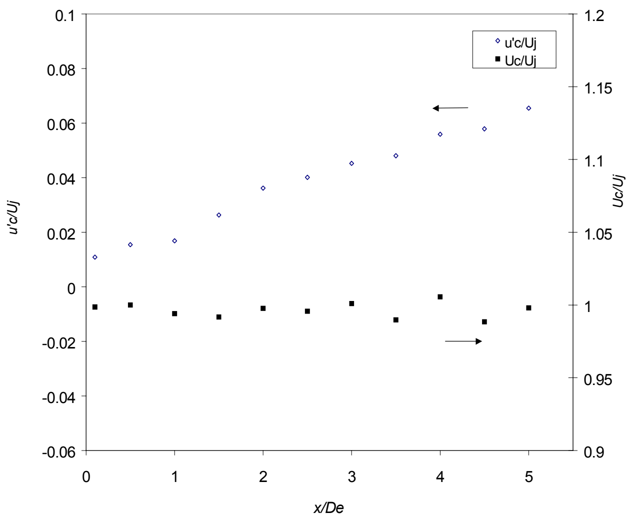


Figure 4. Centerline variations of mean velocity and normal shear stress in the potential core

To further investigate the axis-switching of the present jet, the mean velocity profiles at the cross-section of x/De= 0.5, 2.0, 4.0, 6.0 20.0 and 30.0 are measured and the corresponding velocity contours are presented in Figure 5a, b, c, d, e and f respectively. It can be observed in Figure 5a that at x=0.5*De* the velocity contours maintain the original orientation of the jet. Further downstream at x=2*De* (see Figure 5b), there is a change in orientation of the velocity contours for Um/Uo (Um is axial mean velocity) less than 0.5, although the higher level velocity contours (for Um/Uo greater than 0.8) still maintain the original orientation. It is then obvious in Figure 5c that there is a clear switching of the axis with the velocity contours are now resembling a square rotated 45°. It should be noted that it is not quite possible to have the distributions of the velocity contours with all the sides straight and resemble a perfect rotated square. The velocity contours of OU1 (see Figure 10 of [1]) although looked perfect, it were obtained with the assumptions of symmetric and joining the locations of the selected level of contours with straight lines. For the velocity contour at 6*De*, the upper half of the contour has become more circular in shape as compared to those of the lower half. It seems that the contour has slowly shifted from vague square shape to slightly irregular polygon shape. At further downstream of 20*De* and 30*De*, it can be observed in Figure 5e and f, the contours have become more circular in shape, indicating the flow has reached the self-preservation state.

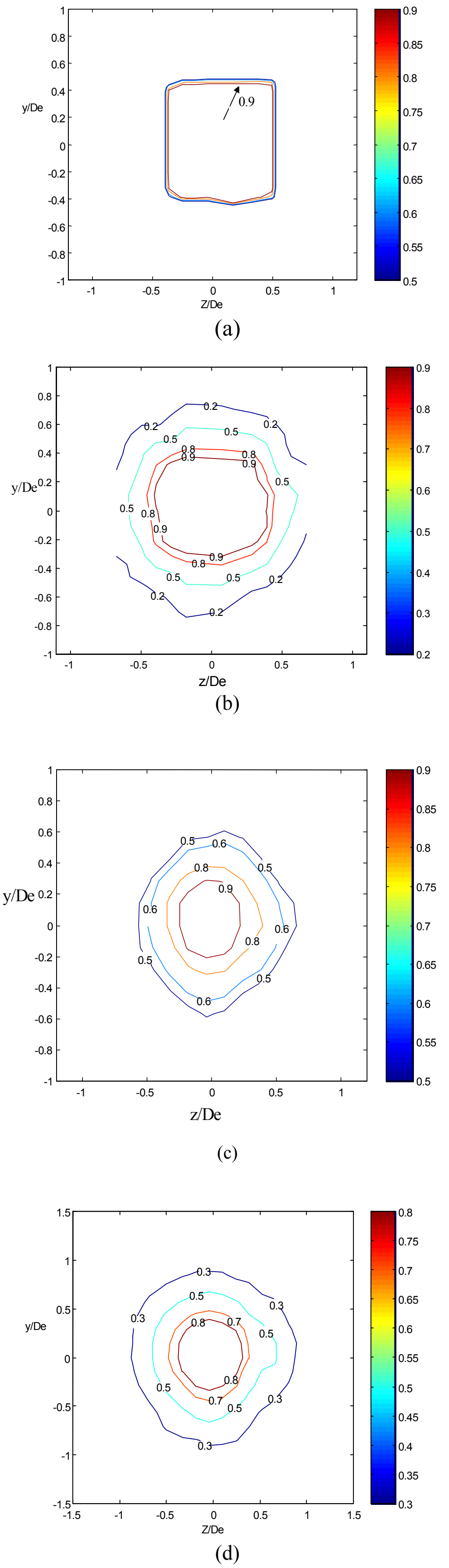
The shapes of the velocity contours at 2*De* and 4*De* may explain why it is difficult to have an accurate measurement on half-width and thus difficult to find out the corresponding axis-switching locations. Besides the possible dynamics characteristics of the axis-switching, i.e. it may not happen at fixed locations but deviate slightly from time to time, as were experienced by most of the researchers. The main reason should be that the mean velocity profile is not a critical indicator; it is thus required to have measurement on the streamwise vorticity and the corresponding contours. These are under process in our laboratory and will report elsewhere once it is carefully done.

Conclusions

Under the present jet initial conditions (see Table 1), there are axis-switching at 1.75*De*, 5*De* and 17.5*De* in the present contoured nozzle square jet. The large De/δ_{my}, low initial turbulent intensity but strong growth of the centerline normal shear stress and strong amplification of turbulence along the shear layers at both the side and diagonal of the jet should have overcome the adverse effect of the large δ_{mw}/δ_{my}. However, to provide a better comprehension of axis-switching, further measurement on the streamwise vorticity is still required.

Jet	Re	δ_{mw}/δ_{my}	D_e/δ_{my}	u'/U_0	Crossovers at x locations (in terms of De)
OU1 (orifice jet)	42000	1.58	164	0.003	0.3 and 14
OU2 (slot jet)	9300	1.08	60	0.1	0.6, 3.6 and 5.0
PU1 (pipe jet)	9300	1.34	40	0.1	None
Present (contour jet)	57500	3.5	245	0.01	1.75, 5.0 and 17.5

Table 1. Comparison of jet initial conditions with those of [1]



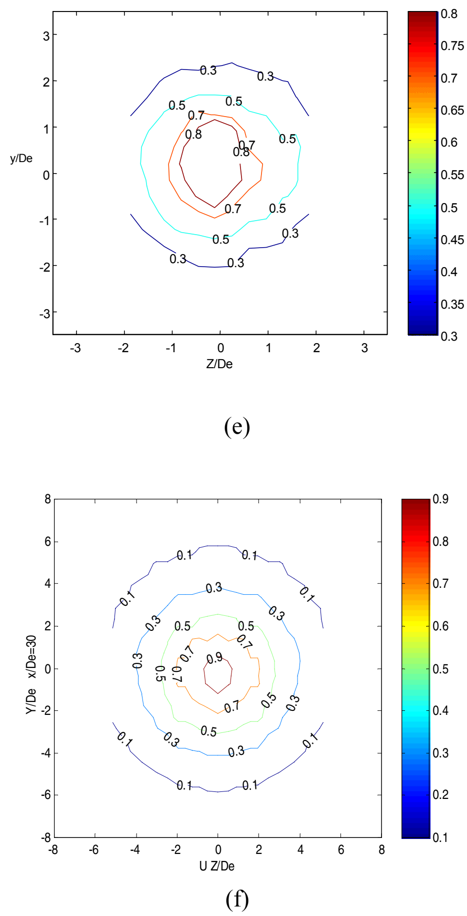


Figure 5: Contours of normalized mean velocity (*Um/Uo*) at streamwise locations of (a) 0.5*De* with 0.3<*Um*/*Uo*<0.9 at the interval of 0.3, (b) 2*De* (c) 4*De* (d) 6*De* (e) 20*De* and (f) 30*De*

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