



Experimental Investigation on Plain Circular and 2:1 Rectangular Jets at Low Speed

Dr. A. Arokkiaswamy

Professor, Department of Aeronautical Engineering,
Dayananda Sagar College of Engineering
Bangalore – 560 078, Karnataka, INDIA

Abstract: The plane jet and circular jet are two fundamental classes of symmetrical jet. The symmetrical nature of the plane and circular jet has broad significance, for example, to reduce computational time in numerical modeling. These jets have received significant research attention both in experimental and numerical investigations. Exhaustive amount of research have been carried out in the past on these types of jets [1-3]. An experimental investigation was carried out to study the flow characteristics of jet issuing from a circular and an equivalent diameter 2:1 rectangular nozzle using two-component hotwire anemometry. Tests were conducted for a nominal jet exit velocity of 20ms^{-1} corresponding to a Reynolds number based on nozzle equivalent diameter of 5.02×10^4 . Relative to the jet issuing from circular nozzle, the jet issuing from rectangular nozzle shows a significant reduction in potential core-length from $3.2D_e$ (for circular jet) to $2.13D_e$ (33% reduction). Plain circular jet does not switch its axis, while the 2:1 rectangular jet switches its axis at approximately $X/D_e=4.0$. Hence, the application of rectangular nozzle enhances the mixing with the ambient jet.

Key Words: circular jet, rectangular jet, axis-switch, potential core length

D_e	= equivalent diameter of the rectangular nozzle, mm
Re_{D_e}	= Reynolds number based on equivalent diameter of the rectangular nozzle
u'/U_e	= non-dimensional streamwise velocity fluctuation
$u'v'/U_e^2$	= Reynolds shear stress
U_e	= mean streamwise jet exit velocity, ms^{-1}
U	= local mean streamwise jet velocity, ms^{-1}
V	= local mean jet velocity along Y-direction, ms^{-1}
X	= streamwise distance along the jet centerline, mm
Y	= cross-stream distance along minor-axis plane, mm
Z	= cross-stream distance along major-axis plane, mm
$Y_{0.5}$	= jet half-width growth along minor-axis plane, mm
$Z_{0.5}$	= jet half-width growth along major-axis plane, mm
δ_{mi}	= jet exit shear-layer thickness along minor-axis plane, mm
δ_{mj}	= jet exit shear-layer thickness along major-axis plane, mm

I. Introduction

Mixing enhancement in jet flows is of paramount importance in many engineering applications and therefore, has been the subject of continuing research. Frequently the jet geometry is dictated by the nature of application since jet characteristics are known to be closely related to the dynamics of shear flow originating at the nozzle exit and hence, are strongly affected by the shape of the nozzle from which they issue. As a result one of the most commonly used methods of shear flow control in jets is the use of nozzles with non-circular exit cross-sections which significantly changes the jet flow development as compared to a jet issuing from a circular nozzle. Jets from non-circular nozzle geometries spread and mix faster thereby providing a unique capability to control the jet development (both fine- and large-scale).

In the case of a plain circular jet, the laminar flow from exit of the nozzle becomes unstable and breaks up into turbulence and forms a thin shear-layer. The instability of the thin shear-layer leads to roll-up of vortex and turbulence subsequently becomes a three-dimensional disorganized complex large scale coherent structure [4]. Plain

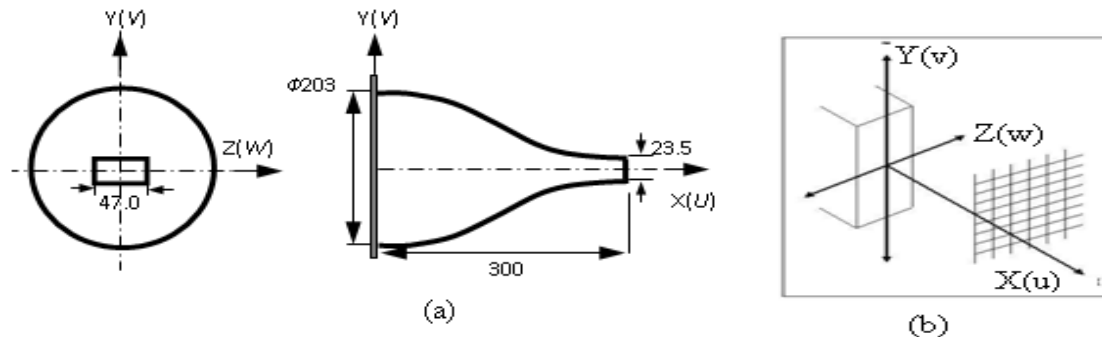
rectangular jets, on the other hand, exhibit superior mixing characteristics relative to the circular jet. The vertices of the rectangular jet reduce the coherence of the large-scale vortical structures, thus weakening the self-induction process which promotes large spreading rates [5, 6]. The small-scale mixing is also more intense in the rectangular jet due to the effect of streamwise vorticity generated at the vertices [7, 8]. Rectangular nozzles are of particular interest because they offer passively improved mixing due to axis-switching and enhanced small-scale mixing near corner regions and farther downstream due to faster breakdown of vortex ring coherence and hence faster transition to turbulence.

II. Experimental Set Up and Procedure

A. Test Facility and Models

Experiments were carried out to investigate the jet flow development from a 2:1 rectangular nozzle, with and without tabs, Figure 1 (a). The nozzle has a circular section of $203 \pm 0.1 \text{ mm}$ diameter, smoothly contoured to a rectangular section ($2a = 47.0 \pm 0.1 \text{ mm}$ and $2b = 23.5 \pm 0.1 \text{ mm}$) over a length of $300 \pm 0.1 \text{ mm}$, where $2a$ and $2b$ are major-and minor-axis lengths, respectively. The equivalent diameter (D_e) of the rectangular nozzle is $37.5 \pm 0.1 \text{ mm}$. The measurements are carried out at a nominal jet exit velocity (U_e) of $20 \pm 0.5 \text{ ms}^{-1}$ and the Reynolds number based on the equivalent diameter of the jet (Re) is $5.02 \pm 0.13 \times 10^4$.

Figure 1: Schematic of (a) 2:1 rectangular nozzle, (b) Grid measurement plane (Y-Z) for overall jet, all dimensions are in mm



Further, the jet exit shear-layer thickness ($U = 0.99 U_e$) along the minor-axis side, δ_{mi} , was about 1.25 mm, along the major-axis side of the nozzle, δ_{mj} , was about 1.75 mm, respectively. The corresponding displacement thickness along each nozzle axis is 0.381 mm and 0.534 mm, respectively. The jet flow longitudinal turbulence (u'/U_e) at the nozzle exit was about 0.3% at 20 m/s.

B. Instrumentation

Hot-wire measurements were carried out at several axial locations in the Y-Z plane by means of a 99N10 DANTEC anemometry system using a Dantec 55P11 2-component probe. The probe has platinum plated tungsten wires (1.25 mm long and $5 \mu\text{m}$ diameter) and can be used for air applications with turbulent intensities up to 5-10. The X-wire was positioned in the flow in such a way that it allowed to measure the fluctuations of streamwise velocity (u') and transverse velocity (v'). The positioning of the sensor was performed by using a PC controlled DANTEC 3-dimensional precision traverse (Model # 41T33). The probe was calibrated using Dantec 9054H01 calibrator with 120 mm^2 nozzle in the velocity range between 0-25 m/s. The signals from the probe were acquired at a sampling rate of 3 kHz with 10000 samples. The anemometer analog output was acquired by using a differential mode National Instruments PCI-6036E having 16-Bit resolution, operating range of $\pm 10 \text{ V}$ and maximum scan rate of 200 Ks/samples. The linearization and processing of the hot wire signal was then carried out digitally. The actual streamwise velocity U and perpendicular velocity V were calculated from the hotwire anemometer output according to King's law equation and equation procedure by Jorgenson (1971). The uncertainty in the jet exit velocity U_e and in the positioning of the hotwire X-probe is $\pm 0.5 \text{ ms}^{-1}$ (2.5%) and $\pm 0.5 \text{ mm}$ (2%), respectively. The projected dimension of the sensor elements to the oncoming flow is 0.8 mm and the uncertainty in measurements with regards to the probe dimensions is approximately 2%.

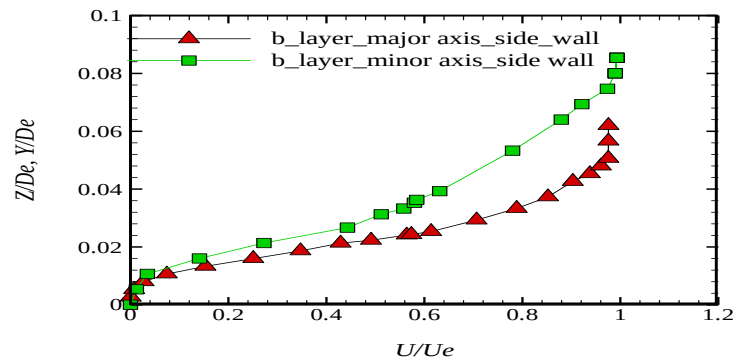
III. Results and Discussions

A. Boundary Layer thickness

Figure 2 shows the boundary-layer profile (U/U_e) along the Y and Z planes of the 2:1 rectangular plain nozzle. The thickness of the boundary layer is seen to be $0.048 D_e$ and $0.075 D_e$ which corresponds to the absolute value of 1.8 mm on the major-axis side wall and about 2.8 mm on the minor-axis side wall, respectively. The tab heights tested were well outside the boundary layer thickness. Therefore, the experimental data measured to investigate the

effects of various cases considered in the present study were the true representation of variation of different parameters in this experimental work.

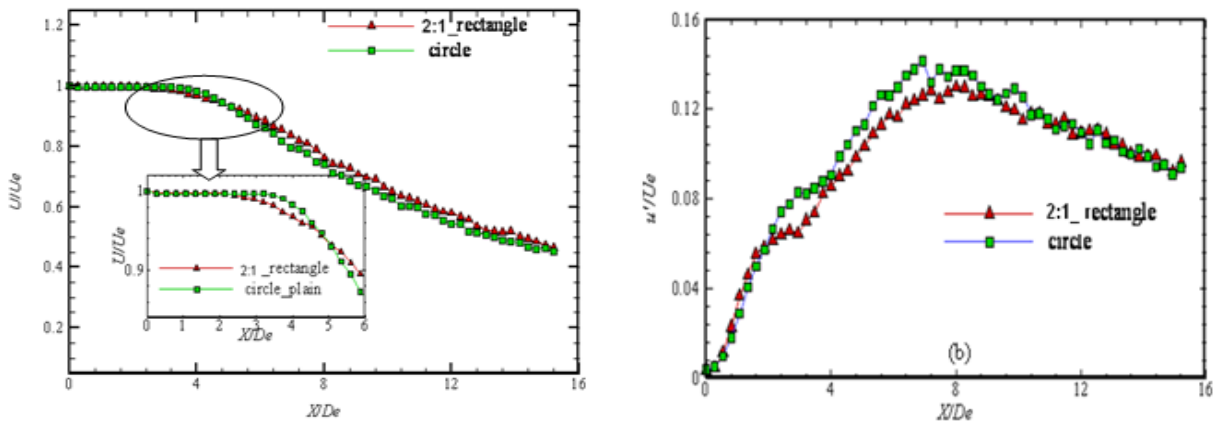
Figure 2: Boundary layer velocity profile on the nozzle exit plane: major and minor axis side walls



B. Comparison of Centerline Velocity and Turbulence Intensity

Figure 3 (a) shows a comparison of the centerline velocity decay (U/U_e) for a jet issuing from rectangular and circular nozzles. It may be noted that, relative to the jet issuing from circular nozzle, the jet issuing from rectangular nozzle shows a significant reduction in potential core length from $3.2D_e$ (for circular jet) to $2.13D_e$ (33% reduction). The above trends show enhancement of small-scale activity for jets with rectangular nozzle geometry.

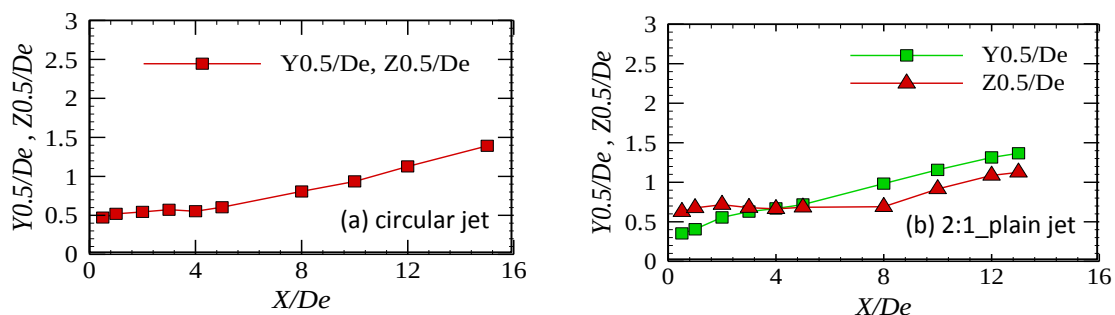
Figure 3: (a) Comparison of jet centerline velocity decay (U/U_e), and (b) turbulence intensity (u'/U_e) distribution



C. Comparison of Jet – Half Width Growth

Figure 4 (a) and (b) shows a comparison of the jet half-width growth for the cases of plain circular and rectangular jet, respectively. Relative to plain circular jet, the jet issuing from rectangular nozzle is seen to grow along its minor-axis plane while it shrinks along the major-axis plane. At approximately $X/D_e=4.0$, the jet half-width plots along the two planes cross each other indicating the axis-switching location of the jet, Fig. 4 (a)-(b). The axis-switching phenomenon observed in non-circular jets is responsible for the improved the mixing process.

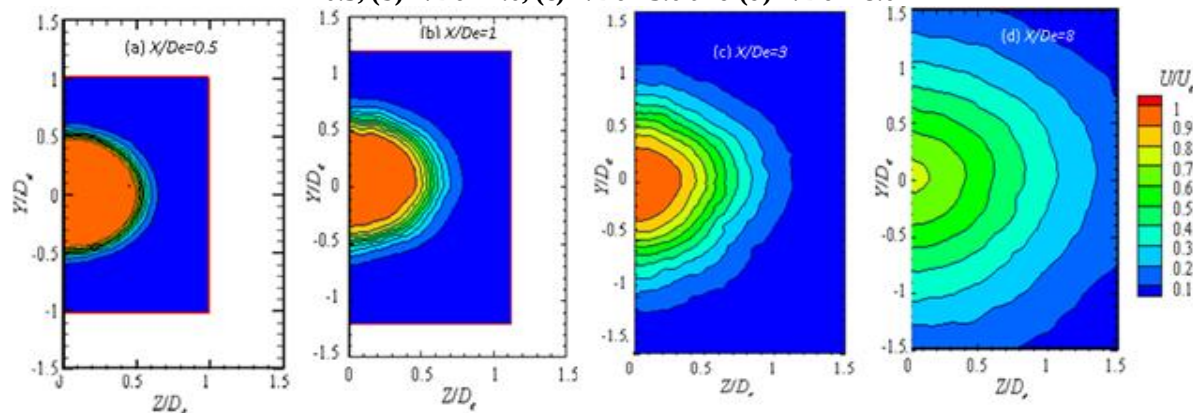
Figure 4: Half-width plots showing the variation in jet growth along Z- and Y-planes for the (a) plain circular and (b) 2:1 plain rectangular jet



D. Overall Jet Development - Mean Velocity Distribution Contours

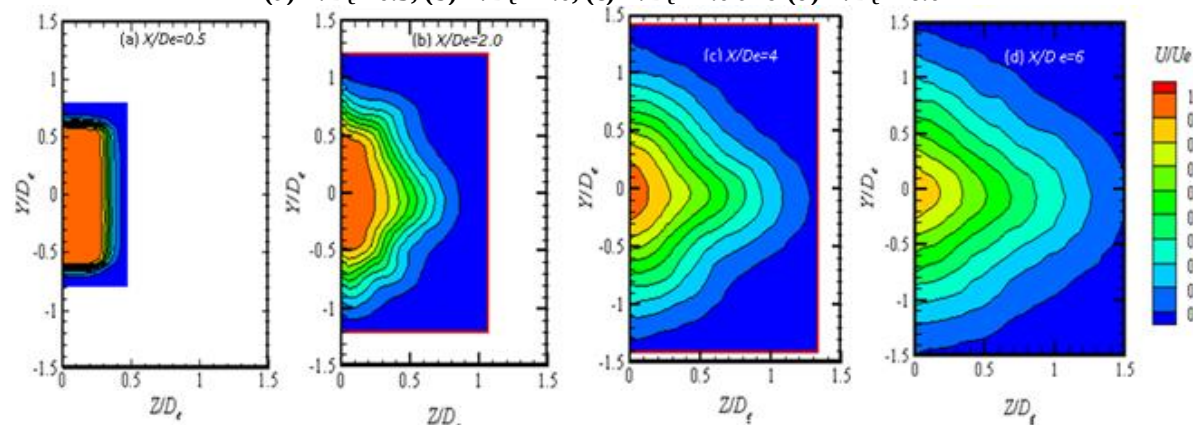
Figure 5 (a) – (d) and Fig. 6 (a)-(d) show the contours of normalized streamwise mean velocity (U/U_e) for the circular and rectangular plain jets at four axial locations of $X/D_e = 0.5, 1.0, 3.0$ and 8.0 , respectively. Extensive grid measurements were made in one-half Y-Z plane of the jet with a step size of $\Delta Z = \Delta Y = 1.0 \pm 0.1 \text{ mm}$ or $0.026 D_e$ for $X/D_e = 0.5, 1.0, 3.0$ and 8.0 (2926, 3913, 6786, and 3740 data points, respectively). It may be observed that the jet issuing from a plain circular nozzle develops symmetrically along both Y- and Z- planes and the shear-layer thickness increases as mixing is initiated between the jet and ambient fluid. However for the jet issuing from a rectangular nozzle, the jet does not develop symmetrically along Y- and Z - planes. On the other hand, for the jet issuing from a rectangular nozzle, jet is seen to retain its original rectangular shape and shows a thin mixing-layer initially [9], as is evident from the closely spaced contours, Fig. 5 (a). As the mixing between the jet and the ambient mass is initiated and the shear-layer grows, the jet begins to gradually deform due to non- uniform induction of velocity [10], along the nozzle azimuth, while a outward bump in contours in the vicinity of the jet corners suggests the presence of corner vortices, Fig. 6 (b). Further downstream, the mixing layer begins to thicken and the jet cross section begins to change its shape as is indicated by a higher growth along minor-axis side (Fig. 6(a) - 6 (e)). The spacing between the contour levels is seen to increase with increase in downstream distance.

Figure 5: Contours of mean velocity at different axial locations in Y-Z plane for a plain circular jet (a) $X/D_e = 0.5$, (b) $X/D_e = 1.0$, (c) $X/D_e = 3.0$ and (d) $X/D_e = 8.0$



As a result, the jet is seen to undergo a three-dimensional deformation process associated with the azimuthal distortion and bending of the rectangular vortex ring wherein ambient mass is brought in towards the jet centerline along the major-axis side, and jet mass is thrown out along the minor-axis side.

Figure 6: Contours of mean velocity at different axial locations in Y-Z plane for a plain 2:1 rectangular jet (a) $X/D_e = 0.5$, (b) $X/D_e = 2.0$, (c) $X/D_e = 4.0$ and (d) $X/D_e = 6.0$



IV. Conclusions

In this section the experimental results of 2:1 aspect-ratio plain rectangular nozzle and plain circular nozzle of identical equivalent diameter of 37.5mm is presented and the following observations may be made from the investigation:

Relative to the jet issuing from circular nozzle, the jet issuing from rectangular nozzle shows a significant reduction in potential core-length from $3.2 D_e$ (for circular jet) to $2.13 D_e$ (33% reduction). Comparison of the jet half-width

growth of plain circular and rectangular jet, shows that relative to plain circular jet, the jet issuing from rectangular nozzle is seen to grow along its minor-axis plane while it shrinks along the major-axis plane. At approximately $X/D_e=4.0$, the jet half-width plots indicates that the two planes cross each other indicating the axis-switching location of the jet, Fig. 4.5 (a)-(b). The axis-switching phenomenon observed in non-circular jets is responsible for the improved the mixing process compared to circular jets.

It may be observed that the jet issuing from a plain circular nozzle develops symmetrically along both the planes and the shear-layer thickness increases as mixing is initiated between the jet and ambient fluid. While the jet issuing from a rectangular nozzle, does not develop symmetrically along Y- and Z-planes and is seen to retain its original rectangular shape and shows a thin mixing-layer initially. The study reveals that rectangular nozzle significantly increases the mixing of jets.

Acknowledgements

The technical work reported here is carried out in the experimental Aerodynamics Division (EAD) at National Aerospace laboratories (CSIR), Bangalore. The author is thankful to Former Director, NAL, Dr. A.R. Upadhyaya, for granting permission to carry out the experiments as a part of his Ph.D work. The author also express his sincere thanks and gratitude to Dr. S.B. Verma, Principal Scientist, NAL for his technical guidance and to Mr. Sudhakar and Mr. Manisankar (scientists, EAD) for their assistance in conducting the experiments.

References

- [1] Bradshaw, P., "Effect of external disturbances on the spreading rate of a plane turbulence jet", *J. Fluid. Mech. Vol. 80*, (4), pp. 795 – 797, 1997.
- [2] Browne, L.W.B., Antonia, R.A. and Chambers, A.J., "The interaction region of a turbulence plane jet", *J. Fluid Mech. Vol.149*, pp.355-373, 1984.
- [3] Otugen, M.V., and Namer, I., "Velocity measurements in a Plane Turbulence Air Jet at Moderate Reynolds Number", *Expts in Fluids*, Vol.6: pp. 387 – 399, 1988.
- [4] Bradshaw, P., Ferriss, D.H., and Johnson, R.F., "Turbulence in the noise-producing region of a circular jet.", *J. Fluid Mech.*, vol.19, pp.591, 1964.
- [5] Sforza, P.M, Steiger, M.H, and Trentacoste, N. , "Studies on three dimensional viscous jets", *AIAA J.* , Vol.4 , No.5, pp. 800 – 806, 1966.
- [6] James H. Bell and Rabindra D. Mehta, "Measurement of Streamwise Vortical Structures in a Plane Mixing Layer", *J. Fluid Mech.* Vol. 230, pp. 213 – 248, 1992.
- [7] Sfeir, A.A. , "Investigation of three dimensional turbulence rectangular jets", *AIAA Journal* , Vol.17(No.10):pp. 1055 – 1060, 1979.
- [8] Hsia, Y., Krothapalli, A., Baganoff, D.,and Karamcheti, K., "Effects of Mach Number on the Development of a Subsonic Rectangular Jet", *AIAA Journal*, Vol. 21, No. 2, pp. 176-177, 1982.
- [9] Krothapalli A., Baganoff D. and Karamcheti, "On the mixing of a rectangular jets", *J. Fluid. Mech.* Vol.107, pp. 201 – 220, 1981.
- [10] Pope, S.B., "Turbulence Flows", *Cambridge University Press*, UK, 2002.