

An experimental study on the near flow field characteristics of non-circular jets

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Abstract. Subsonic turbulent free jet, issuing from a lobed contoured nozzle in to quiescent air is investigated experimentally. Results are compared with a circular jet from a nozzle of the same exit area and same contraction profile. Mean flow characteristics, turbulence intensities and Reynolds shear stresses in the near field region are investigated by using Hot-wire Anemometry. An overall decrease in turbulence intensities and enhanced flow entrainment in the near field of lobed nozzle are observed.

1 Introduction

In many industrial applications, such as in ejectors, propulsive systems and HVAC systems, efficiency is strongly related to the mixing properties of the jet flow. Non-circular jet exit geometries can be used for various performance improvements, such as; noise reduction, combustion efficiency enhancement and heat transfer augmentation in many practical applications since they are capable of entraining large amount of surrounding fluids.

Jets issuing from non-circular nozzles as rectangular, elliptic, square etc. are subject of many studies in the literature. Gutmark and Grinstein [1] reviewed experimental, theoretical and numerical works on non-circular jet geometries and discussed physical mechanisms that control the flow development. Rectangular jets of different aspect ratios are investigated extensively and it is found out that introduction of sharp corners in the nozzle can increase significantly the fine-scale turbulence. Krothapalli et al. [2], emphasize that the flow details at the nozzle exit significantly affects the later development of the jet. Quinn's study [3] on low aspect ratio contoured rectangular nozzle points out that the mean streamwise velocity field changes from rectangular to an oval and finally to a circular shape in far field. Hussain and Hussain [4,5] examined, the vortex structure, switching process and vortex pairing phenomenon in elliptic jets. They found that the location and number of switchovers are strongly dependent on the initial conditions. Experimental results of Quinn, concentrated on sharp edged elliptical [6] and triangular [7] nozzles, show that the jet attains axisymmetric shape after one or two switches of major and minor axis. These studies reveal that, the shape of the exit nozzle is very important in mixing and entrainment phenomenon.

Lobed nozzles are widely used in turbofan engines to reduce jet noise, and in combustion chambers to improve combustion efficiency.

Belovich & Samimy [8], investigated coaxial jet geometry where the inner jet was a lobed mixer nozzle. The details of mixing process, for three different velocity ratios are explored by using LDV measurements. Hu et al. [9], used high resolution PIV system to analyze mixing process in lobed jet flow. They found that, the maximum effectiveness region of lobbed nozzles is about first two diameters. According to Hu et al., large scale streamwise vortices generated by the lobed nozzles break in to smaller but not weaker streamwise vortices as they travel downstream. Thus, beside the large scale mixing enhancement, mixing at a finer scale could also be achieved in the lobed jet mixing. Zaman et al. [10], investigated flow and noise field of rectangular lobed configurations. They examined the effect of number of lobes for a fixed nozzle exit area and shown that increasing the number of lobes results in a progressive reduction in the turbulence intensities and noise reduction in low frequency region. However increasing number of lobes involves diminution in thrust coefficient. Nastase & Meslem [11] studied experimentally 6-lobed air jets with and without lobe deflection angles. They investigated development of primary and secondary instabilities in the streamwise and transverse planes by means of flow visualization and hot-wire anemometry and revealed that the amount of flow entrained in lobed jet by the streamwise structures are amplified by the inclination of nozzle exit boundary.

In this study, subsonic free jets, issuing from circular and lobed nozzles in to quiescent air are investigated

experimentally. Three different Reynolds numbers, based on equivalent jet exit diameter, have been considered 4×10^5 , 6×10^5 and 9×10^5 . Mean flow characteristics, turbulence intensities and Reynolds shear stresses in the near field region are investigated by using HWA. Results are compared with the round jet experiments.

2 Experimental Setup

2.1 Jet Facility

Jet flow, is provided by pressurized air from 12 bar storage tanks through a pressure reducer placed at the inlet of the settling chamber. A converging nozzle is attached at the end of the settling chamber. Jet exit velocity is controlled by regulating stagnation pressure in the settling chamber. An electronic pressure controller (Tescom ER3000) drives the main pressure regulator exploiting pressure information from a pressure transducer mounted on the settling chamber wall. PID control is applied to maintain the system at a constant pressure / velocity. Interchangeable nozzle geometries have the same contraction profile (Figure 1). Nozzle contraction ratio is 7.4. Circular and 3-lobed nozzle exit geometries having same exit area are used. Equivalent diameter (D_e) based on the exit area of the lobed nozzle is 18mm. The ratio of wetted perimeter to equivalent diameter of the nozzle is 1.16π .

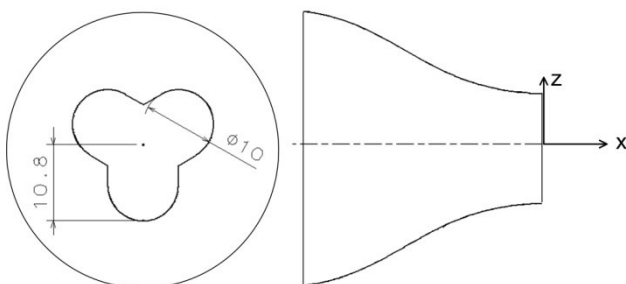


Fig. 1. Nozzle contraction profile and exit geometry.

2.1 Experimental Method

The mean velocity vector and turbulent quantities are measured by using hot-wire anemometry. A single hot-wire probe is successively positioned in the measurement point with different orientations relative to a fixed frame of reference. 55P02 type single slanted wire sensors with a diameter of $5 \mu\text{m}$ and an active length of 1.25 mm were used. Collected data is post processed by using general hot wire response equations for each probe orientation to obtain, mean velocity and Reynolds stress components. Details of measurement technique are discussed in Buresti & Di Cocco [12].

A positioning platform is designed and manufactured on which rotational component of traversing mechanism can be installed (Figure 2). The accuracy of positioning mechanism for point measurements is 0.2 mm. Hot-wire probe and positioning platform was moved together in the flow field by a Dantec Dynamics three directional traverse mechanism (Figure 3). The accuracy of linear motion was 0.016 mm.

Velocity measurements are performed by using a DANTEC 90C10 constant temperature anemometer. The hot-wire signal was digitized using a 16 bit A/D Board with 16 analog input channels. The mean velocity and turbulence data were obtained from averaged time series containing 8192 samples, obtained at a sampling rate of 4 kHz. Average values acquired from 7 probe orientations (Table 1) at the same coordinate, are used to calculate mean velocity and Reynolds stress components.

Data was acquired on a grid in y-z plane at several downstream locations. Total number of measurement points on a grid varies between 169 and 289. Grid spacing was 5mm.

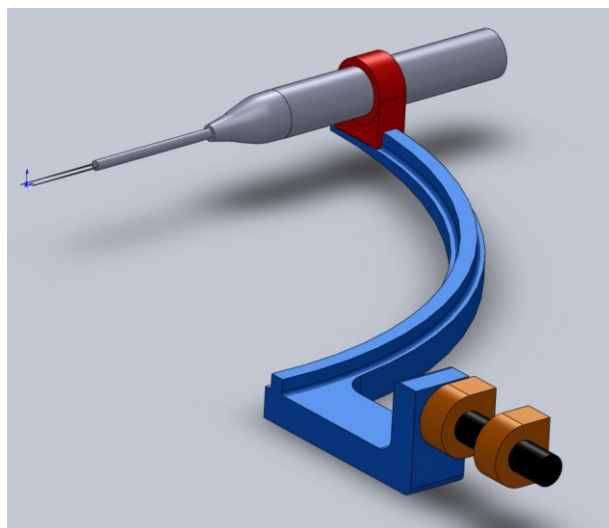


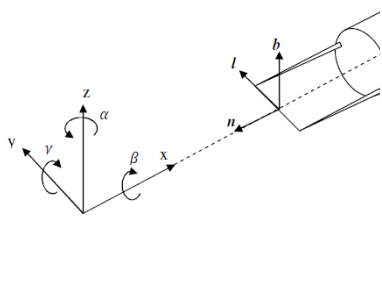
Fig. 2. Probe positioning platform



Fig. 3. Probe on the three directional traverse mechanism

Table 1. Probe positioning angles

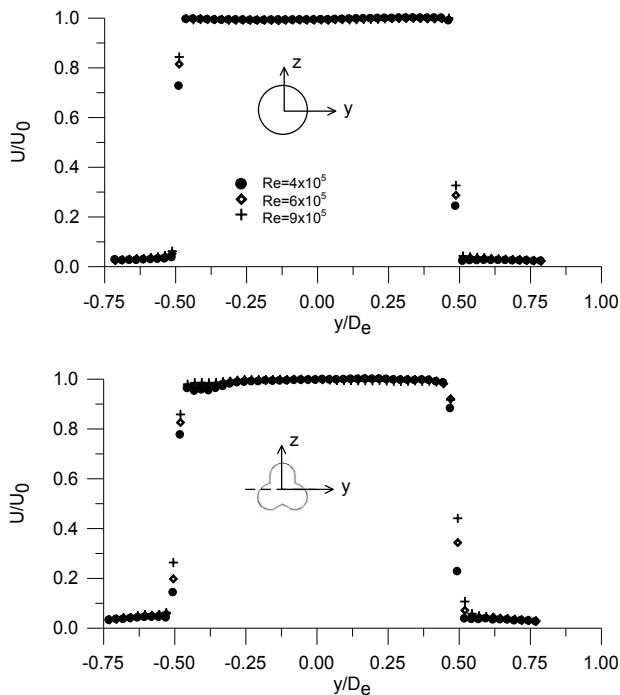
	α	β	γ
1	45	0	0
2	135	0	0
3	45	0	45
4	135	0	45
5	45	0	-45
6	135	0	-45
7	90	0	0



3 Experimental Results

3.1 Jet exit conditions

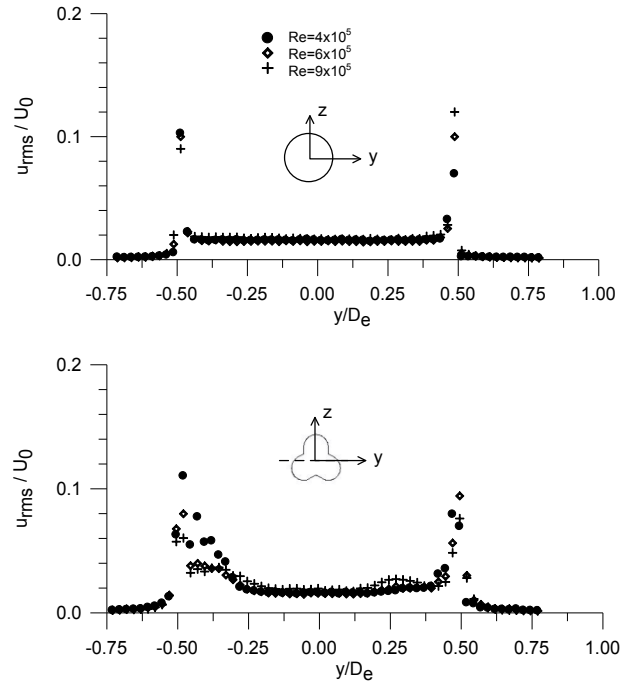
Hot-wire measurements were made at the exit plane to characterize the initial conditions. The exit velocity profiles (Figure 4) at $x/D_e=0.1$ shows uniform distribution. Non-dimensional velocity profiles are not affected by Reynolds number. Turbulence intensities in uniform velocity region are roughly 2% (Figure 5). Velocity and turbulence intensity profiles are not Reynolds dependent. Shear layer at the exit plane ($x/D_e=0.1$), affected by the nozzle shape, becomes thicker and non-uniform along the perimeter of lobed nozzle.

**Fig. 4.** Velocity profiles at $x/D_e=0.1$

3.2 Streamwise velocity contours

Hot wire measurements are performed in y - z planes at several x/D_e locations from jet exit up to $10D_e$. Plots of the axial mean velocity contours of circular and 3-lobed jets are presented in Figure 6. Mean velocities are

normalized with jet exit velocity (U_0). The shape of the velocity distribution in the near field of the jet keeps its exit nozzle form. The contours in near region are closely spaced which implies high velocity gradient and production of turbulence. In the near field region of lobed jet, higher velocity gradients in the lobe peaks, and lower gradients in the lobe troughs are observed. Farther downstream lobed jet velocity contours resemble to that of triangular and finally axisymmetric jet flow.

**Fig. 5.** Turbulence intensity profiles at $x/D_e=0.1$

Comparison of velocity contours at same downstream locations (x/D_e) show that the effective area occupied by the jet flow at the same downstream locations is increased by the lobed geometry. This result indicates higher spreading rates and enhanced mixing in lobed case.

3.3 Reynolds number effect

Jet flow field is strongly influenced by the initial conditions which are related to the jet exit Re number and inner wall nozzle contraction profile. Dependence of mixing field of round jets on the Reynolds number is quite well established by experimental studies. These studies indicated that at sufficiently high Reynolds numbers (>10000) velocity flow field is almost independent of Re number [13].

Reynolds dependency of lobed jet is investigated between 40000-90000 range with consecutive experiments at three different exit velocities. Both axial velocity and turbulence intensity contours show good agreement in near field region (Figure 7).

3.3 Entrainment rates

Volumetric flow rates at measurement planes (y - z) are calculated by integration of velocity data. Trapezoidal rule is applied for integration. The results are normalized

by the volumetric flow rate at the jet exit plane (Q_0) and presented in Figure 8. According to the Figure, 3-lobed nozzle entrains greater amount of mass from surroundings comparing with circular jet. Results are compared with Nastase & Meslem[11]'s 6-lobed jet and Quinn[7]'s triangular jet experiments. Mass flow entrained by the 3-lobed jet under investigation is lower than that of the 6-lobed jet. However it shows similar tendency to triangular jet results.

3.4 Axial velocity and turbulence intensities along the jet centerline

Axial velocity decay along the jet centerline is given in Figure 9. 3-lobed jet has lower velocities in near region. Centerline velocities of circular jet decay faster and attains the 3-lobed jet velocities at $x/D_e=8$.

The evolution of axial turbulence intensities along the jet centerline are presented in Figure 10. Turbulence intensities initially increase and reach a peak value in potential core region then diminishes gradually with increasing downstream distance. Lower turbulence intensities are measured for 3-lobed nozzle. Lower turbulence level in the source region of jet insures lower far field noise for the lobed nozzle.

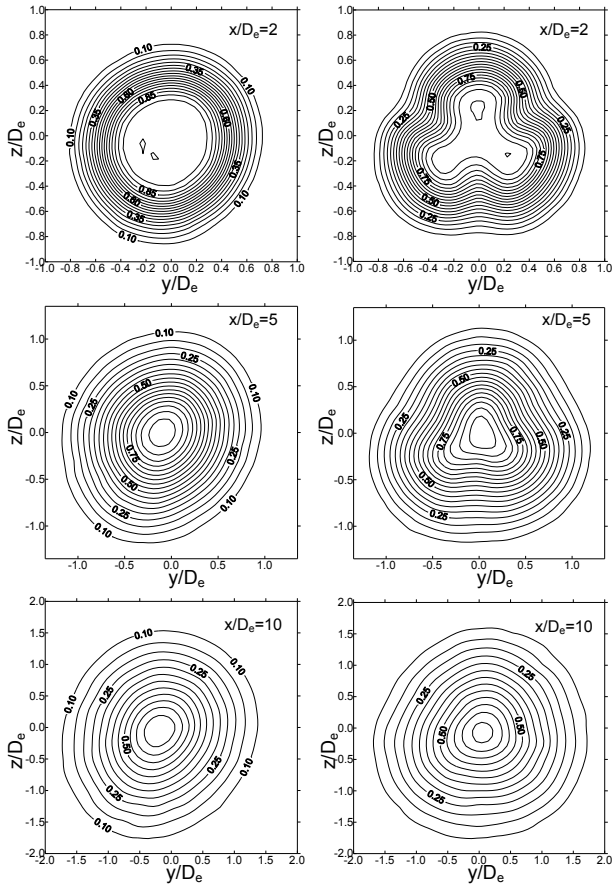


Fig. 6. Axial velocity (U/U_0) contours

3.5 Turbulent kinetic energy along the jet centerline

Turbulent kinetic energy measured along the jet centerline is normalized by the jet centerline velocity and presented in Figure 11. The turbulent kinetic energy

increases with increasing downstream distance x/D_e . Nearby the jet exit plane, slightly higher values of turbulent kinetic energy are acquired in 3-lobed jet. For $x/D_e > 4$, turbulent kinetic energy values on the centerline of circular jet flow are greater than the values measured in the lobed jet.

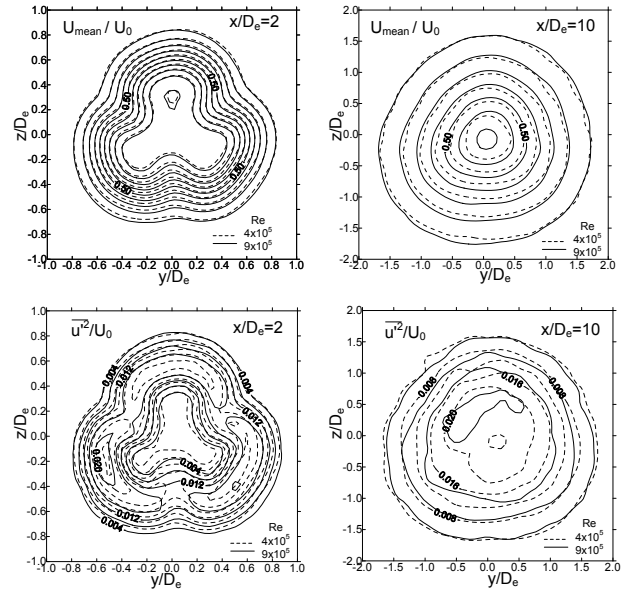


Fig. 7. Reynolds similarity of velocity and turbulence contours

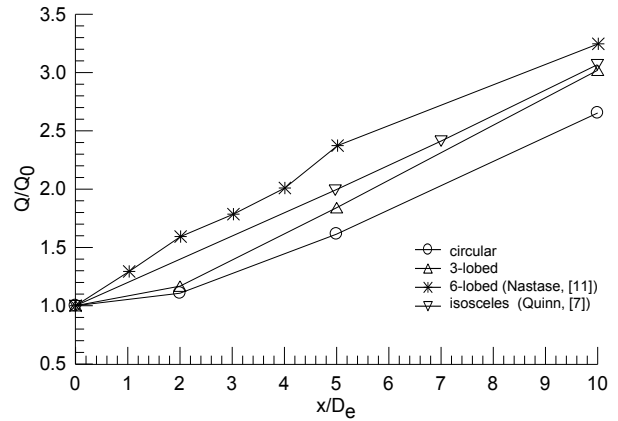


Fig. 8. Streamwise velocity decay along the jet centerline

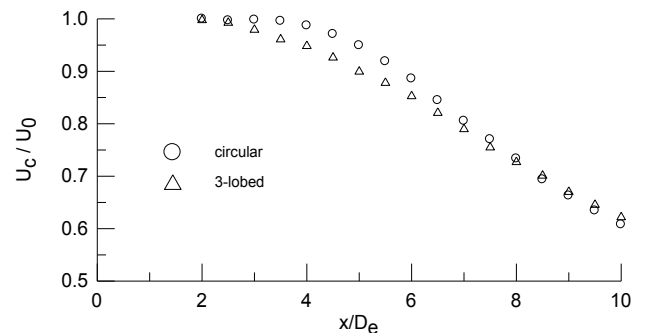


Fig. 9. Streamwise velocity decay along the jet centerline

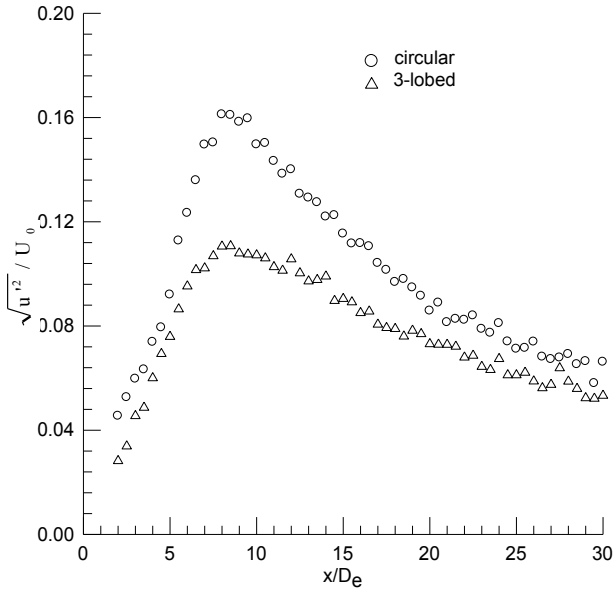


Fig. 10. Turbulence intensity along the jet centerline

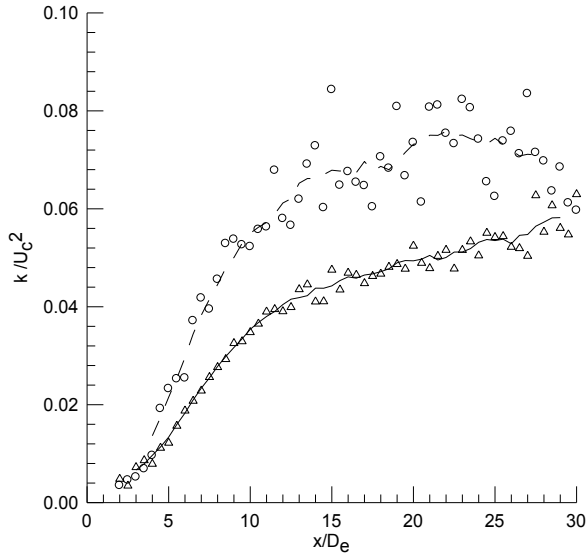


Fig. 11. Turbulent kinetic energy along the jet centerline

3.6 Reynolds stress contour maps

Reynolds normal stress $\overline{u'^2}$ contour maps are given in Figure 12. Positions of maximum turbulence intensity regions match maximum velocity gradients in Figure 6. Therefore Reynolds normal stress is related to local shear in axial mean velocity. Peak values in streamwise normal stress decrease in value and approach to the jet axis with increasing downstream distance. Maximum normal stresses measured in circular jet at each y-z plane are greater than lobed jet results.

Spanwise Reynolds shear stress $\overline{u'v'}$ contour maps are shown in Figure 13. At $x/D_e=2$ plane, while circular jet shear stress contours contain two peaks, 3-lobed jet contain six peak values. There exists a maximum and a minimum for each lobe. Location of peak values move towards the jet centerline with increasing distance from the exit.

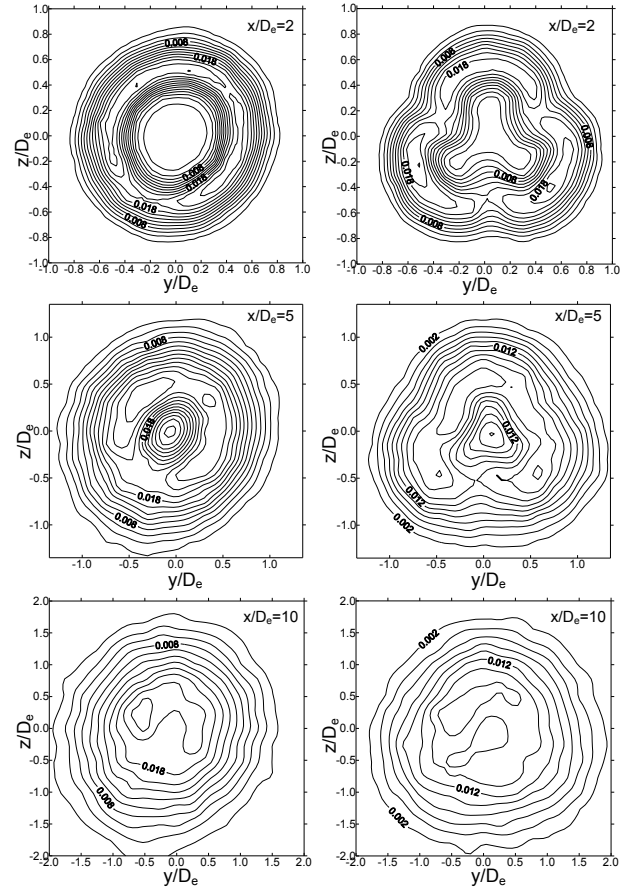


Fig. 12. Reynolds normal stress contours ($\overline{u'^2}/U_0^2$)

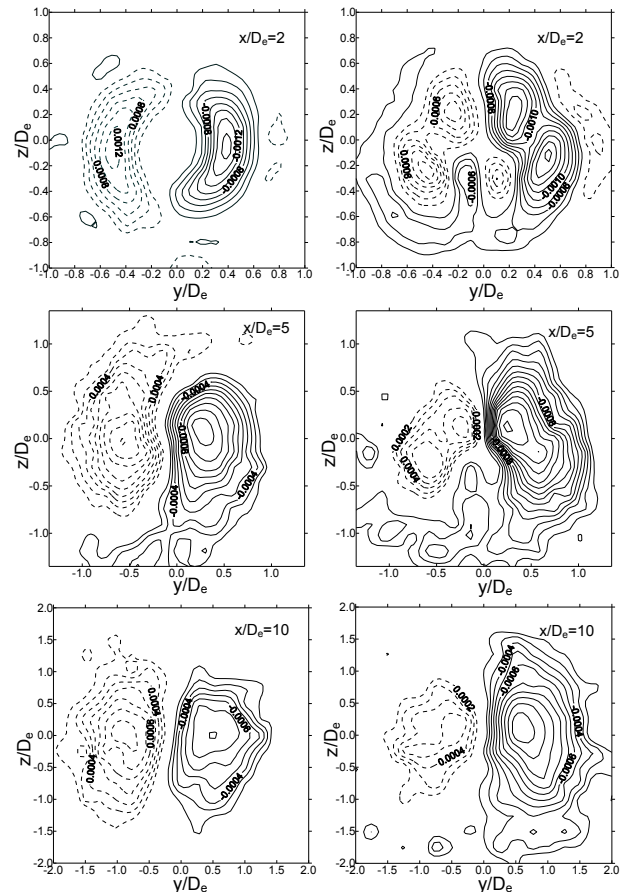


Fig. 13. Reynolds shear stress contours ($\overline{u'v'}/U_0^2$)

Number of shear stress peaks in the lobed case diminishes with increasing x/D_e and attains a form similar to the circular case at 10 equivalent diameters downstream of the exit plane.

4 Conclusions

The effect of lobed nozzle geometry on the flow characteristics of subsonic jets is examined experimentally. Measurements are performed for lobed and circular contoured nozzles having the same exit area.

Three different Reynolds numbers, based on equivalent jet exit diameter, 4×10^5 , 6×10^5 and 9×10^5 have been considered. It is shown that velocity and turbulence intensity fields are not Reynolds dependent in this Re range.

Evolution of volumetric flow rate along the jet axis is investigated. Flow rates are obtained by integration of velocity data. Lobed nozzle entrains greater amount of mass from surroundings comparing with circular jet.

On the centerline of the jet, turbulence intensities are maximized where outer shear layers merge. Even though the position of the peak is not strongly affected by nozzle geometry, turbulence intensities in the lobed case are diminished comparing with the circular case.

The turbulent kinetic energy measured along the jet axis increases with downstream distance x/D_e . For $x/D_e > 4$, turbulent kinetic energy values on the centerline of circular jet are greater than the values measured in the lobed jet.

An overall decrease of Reynolds normal stress in the flow field is observed for lobed nozzle.

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