The near-field structure of free jets from a contoured nozzle, a long pipe and an orifice plate

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ABSTRACT

Azimuthal vorticity fields generated from particle image velocimetry suggest that vortex pairs shed within 2 exit diameters from a contraction nozzle tend toward instantaneous axi-symmetry, while those shed from a sharp-edge orifice plate tend toward an asymmetric near-field structure. Relatively smaller scale and somewhat less organised structures are evident in the flow produced by a long upstream pipe.

1. INTRODUCTION

Numerous investigations of free turbulent jets from axisymmetric nozzles are available. However, most of these are performed using nozzles that produce uniform mean axial velocity distributions, that is, flow emerging from contoured nozzles, with a lower, but still significant number, performed for jets issuing from long pipes. In contrast, relatively little information is available for jets produced by sharp-edged orifice plates. This is notable, considering the fact that most practical flows are generated by the latter two devices due to their ease and economy of manufacture.

George (1989) performed a theoretical analysis on the effect of initial conditions on the asymptotic state of a jet and found that there exists a multiplicity of self-similar states, depending upon the initial conditions, or nozzle profile. There is growing experimental evidence in the literature that the downstream characteristics of free turbulent jets are altered by different inlet conditions. Recent work by Mi et al. (2001a) showed that initial conditions have an important influence on the mixing field of a free turbulent jet. They used planar laser induced fluorescence (PLIF) to show that the instantaneous structures exiting a contraction nozzle was highly symmetric and periodic. In contrast, the structures shed from a long upstream pipe produced structures that were less organised and non-periodic. Furthermore, Mi et al. (2001b) also demonstrated that the jet in the near-field from a sharp-edged orifice plate is structurally different from the contraction and pipe jets mentioned earlier. Ashforth-Frost & Jambunathan (1996), using laser-Doppler anemometry (LDA) to measure flow velocity, investigated the pipe jet and the orifice jet on the jet potential core and subsequent axial development of a turbulent axisymmetric air jet at \(Re=22,500\). They reported that the pipe inlet jet has a potential core of up to 7\% longer than the jet produced by the sharp-edge orifice plate. Recently, Wong et al. (2004), employing LDA, showed that varying the axisymmetric inlet to a fluidic precessing jet nozzle, by use of either a pipe, contraction or sharp-edged orifice nozzle, affected the exit velocity characteristics and the mode stability of the resulting precessing jet flow. A fluidic precessing jet (FPJ) is a naturally oscillating jet that is generated within a short nozzle with a large expansion ratio where the nozzle chamber is greater than 5 times the inlet jet diameter and is presently employed as a burner in rotary cement kilns (Manias & Nathan, 1994).

Although the literature reports on the abovementioned jets, the number of direct comparisons of the near-field of these three types of exit conditions is rare. To address this need, the present paper aims to directly compare the near-field flow structure using nozzles of equal diameters, and to discuss their likely effects on the downstream flow field.

2. EXPERIMENTAL TECHNIQUE

Particle image velocimetry (PIV) was employed in this investigation. The PIV experiments were conducted at the Turbulence, Energy & Combustion (TEC) laser laboratory of the University of Adelaide.

2.1 Experimental Apparatus

Figure 1 illustrates the apparatus used in the experiment. A compressor with an operating pressure of up to 650 KPa delivers conditioned supply air to the experimental nozzle with a central jet exit diameter, \(d=15.79\) mm issuing through a bluff body of 80.0 mm diameter. This bluff body is necessary to ensure consistency for the contoured nozzle and the orifice nozzle cases.

![Figure 1. PIV experimental arrangement.](image)

The compressed air is regulated and is divided into three sub-streams. The first sub-stream is fed into a TSI 6-jet particle generator while the second sub-stream is diverted to a by-pass valve. The two streams are re-combined at the exit of the TSI
particle generator and are transported via a flexible pipe into the brass pipe of the nozzle flow conditioner section. The bypass system allows the particle generator to function optimally, whilst providing a large air flow rate to the experimental nozzle. The third sub-stream is fed into a Laskin nozzle particle generator.

Both the TSI and Laskin nozzle particle generator produce olive oil seeding with a mean particle diameter of approximately 1μm. This type of seeding follows the bulk flow well and is suitable for the present velocity range (Raffel et al. 1998). Seed particles from the Laskin nozzle are used to seed the low-velocity co-flow around the jet nozzle and are distributed by means of a ring-type distributor located some distance below the nozzle. A cylindrical shroud of about 4.4 times the diameter of the jet nozzle is positioned such that the top edge is aligned at the same level as the exit plane of the nozzle. This is to confine the co-flow seeding within the region of interest. The whole rig is positioned under an extraction hood and is further surrounded by a curtain of black cloth to reduce the effects of room draughts and stray laser scattering.

To remove residual upstream swirl, to reduce the turbulence intensity level of the flow and to make the flow at the inlet uniform, the current investigation has adopted a flow conditioning system based on the recommendations of Bradshaw & Pankhurst (1964). Flow conditioning was first achieved by a development pipe of 30 diameters in length connected in series with a conical diffuser with a total cone angle of 9.1° and an area expansion ratio of 2:1. This was followed by a honeycomb section with a length-to-diameter ratio of 12 to reduce any upstream swirl. A series of 5 screens, each with an open area ratio of 61% and screen wire diameter of 0.355 mm was used to further improve the flow uniformity and to reduce the turbulence intensity of the flow. A development section equivalent to about 280 wire diameters followed immediately after the last screen to allow any vortical structures generated by the screens to dissipate. Further details can be obtained from Wong et al. (2003a).

To obtain a uniform velocity profile at the inlet plane, a nozzle with a 5th order polynomial profile having a zero derivative end conditions and a contraction area ratio of 10.03 was attached to the end of the development section. To obtain an orifice-type flow, a 5 mm thick sharp-edged orifice plate with a downstream chamfer of 45° was attached to the end of the development section. This type of flow is known to result in the formation of a vena contracta immediately downstream from the sharp edge.

To obtain a pipe flow inlet, an upstream development length of about 63 pipe diameters following a honeycomb flow straightener was used instead of the flow conditioner. This is longer than the minimum of 40 diameters suggested by Hinze (1975) to be necessary for ensuring a fully developed turbulent flow in a pipe. All the inlet diameters d were the same at 15.79 mm.

The PIV system consists of a light generation system, light delivery system, shaping optics, a pulse delay generator and a camera connected to a Nikkor 70-300mm f/4 5.6 ED zoom lens set at an f/# = 5.6. The f-stop ensures that the image distortion around the edges of the image was minimised and adequate light enters the camera. Light is generated by a Quantel Brilliant Twins pulsed Nd:YAG laser rated at 380mJ per pulse at a wavelength of 532nm. Each pulse has a pulse duration of 6ns at FWHM (full width at maximum half-height). The light produced is delivered to the shaping optics which are made up of a diverging cylindrical lens followed by a cylindrical focusing lens with a focal length of 260mm. Optimising this arrangement of lenses produces a suitable light sheet with a thickness between 1mm and 2mm (equivalent to 8 to 16 pixels) in the region of interest. The laser system comprises two independently controlled laser oscillators which fire at a rate of 10Hz each. The lasers are controlled by a Stanford Research Systems DG-535 pulse delay generator, which has a pulse-to-pulse jitter of less than +/- 5ns. The flashlamp-to-Q-switch delay for both lasers is set at 300μs and this gives a laser energy output of about 180mJ per oscillator, which is adequate for the present experiment.

The output signal from the internal timer is sent to the camera which, following an external trigger, has an internal delay of 20μs before exposing the first frame. The exposure time is determined by the transfer pulse width (TPW) which has been set to 300μs. The first laser pulse is synchronised to illuminate the region of interest during this period. Following this, a transfer pulse delay of 1μs occurs before the second exposure is activated for a fixed time period of up to 30ms. The second laser pulse fires at a time, εt, after the first pulse. After this period, frame two is still recording even after the second laser pulse has elapsed. Thus, for all experiments, the light windows were turned off to reduce the effects of background light to negligible levels. The camera is a Kodak Megaplus ES 1.0 and has a charged-coupled device (CCD) with a width and height of 1008 by 1018 pixels respectively. Each pixel has a full fill factor of 60% to improve the collection of light on it. A “triggered double exposure” mode was used and a total of 350 image pairs were recorded at a nominal rate of 10Hz for 35 seconds in each experimental batch. The data were downloaded onto a computer hard-drive for long-term storage and further post-processed by commercial software “PIV View 1.7” (Pivtec, DLR, Germany).

<table>
<thead>
<tr>
<th>Description</th>
<th>Contraction</th>
<th>Pipe</th>
<th>Orifice plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number (Re=υo,d/v)</td>
<td>31,900</td>
<td>37,100</td>
<td>28,400</td>
</tr>
<tr>
<td>Bulk Mean exit velocity (m/s)</td>
<td>29.7</td>
<td>34.5</td>
<td>26.4</td>
</tr>
<tr>
<td>Time between laser pulses, εt(μs)</td>
<td>12</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Dimensions of interrogation window (px. mm)</td>
<td>16×16, 32×32, 16×16, 1.80×1.80, 1.10×1.10, 1.48×1.48</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Summary of experimental conditions and analysis. υ is the kinematic viscosity of air at 5,STP.

Each image pair was cross correlated and a three-point Gaussian fit was employed to identify the correlation peak, while outliers were filtered using the global histogram method (Raffel et al. 1998). Improved vector yield was enabled by the use of an iterative two-pass interrogation with re-sampling based on the step size (Hart, 2000). Differences in the calibration and processing dimensions reported in Table 1 to match the physical interrogation windows of different experiments as closely as possible given a discrete range of interrogation windows (e.g. 16×16, 32×32, 64×64, etc) while having a reasonable spatial resolution for each experiment.

In general, vector yields of greater than 95% were obtained. Vorticity was calculated using “smart” cells which check the interrogation window overlap and determine optimal distances to calculate the differential value (Willert, 2002). Table 1
provides details regarding each experimental condition used in the experiments.

3. RESULTS

The results of vorticity plots within 2 jet diameters are shown in the left column of Fig. 2 for the contraction, pipe and orifice jets. Clear differences are evident in each. The features in the jet from the smooth contraction exhibit evidence of large-scale organised motion, while those in the pipe jet are thin and sheet-like. Larger features are also evident in the orifice jet, but these are less clear. To provide some more insight into these features, the right right column presents the size (nominally circular) and location of the 50% vorticity contour for each local maximum of vorticity. Although these features are not fully resolved by the present measurement, which has a spatial resolution of about 1.8mm (Table 1), it is clear that the size of these features is smallest for the pipe jet and comparable for the orifice and smooth contraction jets. It is also important to note that the features identified in these sets of images, vorticity images and peaks in Fig. 2 are not necessarily large-scale coherent structures themselves, although they are probably associated with such structures. For example the middle two and upper three pairs of circles identified in the right hand side of Figure 2a are probably features of the second and third pairs of large-scale coherent motions in this jet, respectively. They appear to be associated with the well-known vortex pairing processes in these jets (e.g. Meyer et al., 2001) although it is not possible to deduce this level of detail from these images alone.

Together, the right and left hand sets of images in Fig.2 are used to visually identify the most similar features on the two sides of the orifice and smooth contraction jets (note again, that this does not necessarily imply that these features are considered to correspond to specific large-scale coherent motions, although they may do so). Although qualitative and subjective, these images strongly suggest that there exists a qualitative difference in the axi-symmetry of the two jets. The contraction jet (Fig.2a) exhibits a strong tendency of axisymmetry. In contrast, the vorticity in the orifice suggest that structures in the jet exhibit a tendency toward anti-symmetry (e.g. a helical mode).

To provide a semi-quantitative assessment, the azimuthal vorticity ($\omega_r = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$), presented in Fig.3 for a typical instantaneous image from each nozzle, are normalised by $u_c$ and $d$, where $u_c$ is the average of the mean centreline velocity over the region $0.5 \leq x/d \leq 1.5$.

For the contoured nozzle jet, the fluid structures are highly organised and show some evidence of the vortex pairing as discussed, for example, by Meyer et al. (2001). This is illustrated by the cross-section through each vortex ring in the $x-r$ plane; that is, each vortex on one side of the axis is closely aligned with a matching vortex on the other side of approximately equal magnitude but opposite sign.

The presence of large-scale coherent motions in the pipe jet (Fig.2b) is not obvious, although groups of relatively smaller vortices appear to be clustered together. This evidence of reduced organization is consistent with earlier work [9]. For the orifice jet, large-scale vorticity regions are also evident from the vorticity plot. However, some vorticity regions seem to be aligned nearly axisymmetrically, while others are not.

Figure 2. Instantaneous vorticity fields from (a) Contraction, (b) Pipe and (c) Sharp-edge orifice plate. Left: Vorticity; Right: Location and size of the 50% vorticity contour.

A quantitative measure of large-scale coherent structures is further deduced from the cross-correlation of radial velocities, $v_1$, obtained from approximately 350 image pairs relative to the point at $x/d=0.64$ and $r/d=0.55$, and $v_2$ at other locations, i.e.,

$$R_{ij} = \frac{v_1 - v_0}{\sqrt{v_1 - v_1}} \frac{v_2 - v_0}{\sqrt{v_2 - v_2}}$$

The cross-correlation contours for the contoured nozzle and pipe jets are very similar, suggesting a high degree of axisymmetry in the large-scale structure for the contoured nozzle jet and the pipe jet. In contrast, the vorticity patches of the orifice jet (Fig.2c) are less axisymmetric. The large-scale vorticity patches near to $x/d=1$ are not aligned axisymmetrically and there is generally less evidence of organised motion. A higher degree of variability in the symmetry and location of the flow structures are also clear from the cross-correlation contours (Fig. 3c). The magnitude of the peak correlation on the opposite side of the jet (at $x/d=0.64$, $r/d=0.55$) is only about 20% of the other jets while the entire flow-field is much less correlated than the other jets. The departure from axisymmetry in the vorticity field of other instantaneous image pairs for the orifice jet (not shown here due to the lack of space) bears some resemblance to the near-field non-axisymmetric structures shed from unforced inclined nozzles reported by Webster & Longmire (1997). Oscillations in the separation bubble upstream from the orifice plate are most likely responsible for the high degree of variability in the symmetry and shape of the vorticity patches in the orifice jet.
Figure 3. Typical non-dimensionalised instantaneous azimuthal vorticity ($\omega_d / u_1$) and radial velocity fields for (a) Contoured jet, (b) Pipe and (c) Sharp-edged orifice plate. Solid lines of radial velocity plots indicate flow moving from left to right and vice versa for dotted lines. Difference between each vorticity level is 2. Coherence measurements taken relative to point at coherence value of 1.0. Re=$u_1d/v$, where $u_1$ is the mean centreline velocity within 1.5d for 350 image pairs.

Mi et al. (2001b) measured the normalised power spectrum at the shear layers (at $z/d=3$) of these three types of inlets and reported that the contoured nozzle generates a jet with a Strouhal number ($St=fd/\nu_1$), $St=0.4$, while the sharp-edged orifice plate jet has $St=0.7$. The present results are consistent with the findings of Mi et al. (2001b), in that the passage of fewer and moderately sized vorticity patches of a small size range in the contoured jet leads to a narrow cluster of frequencies about a particular $St$ value ($St=0.4$), while the passage of a larger number of vorticity patches with more variety in size for the orifice jet could be related to a broadening of frequencies clustered around a higher $St$ value ($St=0.7$). For the pipe case, however, there is no distinct peak present in the spectrum at any particular frequency. This is consistent with Fig 2b which shows the passage of many relatively smaller vorticity patches.

These results may be one physical reason to explain the broad differences reported by various experiments conducted in free turbulent jets. In addition, it may help to explain the sensitivity of axisymmetric inlet conditions in some applications (eg. Ashforth-Frost & Jambunathan 1996 and Wong et al. 2004).

In summary, the present analysis, although not conclusive, finds evidence of a differing degree of instantaneous differences in the jets from smooth contoured, orifice-type and pipe jet nozzles. The near-field large-scale vorticity distributions from the contoured nozzle are approximately axisymmetric and well-structured, as found previously. However, those from the orifice are in general not symmetric and less spatially correlated. The near-field flow field of the pipe jet is similar in coherence with the smooth contraction and there is also evidence to suggest some degree of instantaneous axisymmetry of the vorticity patches.

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REFERENCES