Near Field Structure of Flush-mounted and Elevated Transverse Jets
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ABSTRACT

The topological structure of the near field of a transverse jet is investigated for two jet configurations at one jet to cross-flow velocity ratio. In one configuration the jet exit is flush-mounted with the floor and in the other the jet exit is elevated off the floor. Particle Image Velocimetry (PIV) is used to investigate the mean velocity field of each configuration in two orthogonal planes. Mean velocity magnitude fields and integrated streamline patterns are used to identify flow features, in particular the node downstream of the deflected jet. Similarities and differences of the two configurations are discussed in light of previous works in the literature. Both configurations show the presence of a node downstream of the jet exit at slightly different locations. The major difference is in the jet interaction with the cross-flow in the vicinity of the jet exit.

1. INTRODUCTION

The jet in cross-flow (JICF) or transverse jet is a commonly occurring flow in both industry and nature. The JICF is basically a round jet issuing perpendicularly into a uniform flow. A thorough review of the topic is given by Margason [7] citing over 300 references. More recent considerations of the JICF have been Kelso, Lim and Perry [6], Hasselbrink and Mungal [5] and Cutler [2]. Jets in cross flow are primarily classified by the jet Reynolds number, Re, and the square root of the ratio of momentum fluxes from the jet and the cross flow. The latter term is usually referred to as the velocity ratio, R, because in the cases of same jet and cross flow fluids R is approximately equal to the ratio of the mean jet to cross-flow velocities. Figure 1 shows the jet and cross flow velocities, the coordinate system, the jet apparatus used in the experiment in the flush mounted configuration and definitions of Re, and R. The jet diameter is denoted as d and the kinematic viscosity of the fluid is v. The “z” coordinate is into the page.

Few studies have investigated the topological structure of the near field of either flush mounted or elevated transverse jets. Kelso et al. [6] investigated the flush-mounted JICF and identified mean topological features in the near field. Moussa et al. [8] noted the importance of the flat wall on the structure and development of the JICF. Eiff and Keiffer [3] investigated the interaction between the vortex shedding off an elevated jet pipe and the wake of the deflected jet. A characteristic feature of the near field of the JICF is an unstable node occurring downstream of the jet on the plane of symmetry. This feature was first identified in the flush-mounted JICF by Kelso et al. [6] and has since been verified in the flush-mounted elliptic JICF by New et al. [9]. Furthermore, Hasselbrink and Mungal [5] demonstrated the existence of a node in the elevated JICF.

This paper describes a comparative study where two jet configurations; one elevated and one flush-mounted; with essentially identical flow conditions are investigated and compared using PIV and dye visualisation. The results are discussed using the topological framework described by Perry & Chong [10].

2. EXPERIMENTAL TECHNIQUE

2.1 Experimental arrangement

The experiments were conducted in the 500 mm x 500 mm working section of a closed-return water channel located at the School of Mechanical Engineering, The University of Adelaide. The frequency-controlled pump allowed steady operation at velocities below 20 mm/s and up to 450 mm/s. Before issuing into the cross flow, the jet fluid passed through a flow conditioning section. This section, shown in figure 1, consisted of a 9:1 conical expansion, followed by a settling section and flow straightener and a 9:1 axisymmetric contraction. See Cutler and Kelso [1] for further details. The discharge pipe had a diameter of 50 mm and a length to diameter ratio, (L/d), of 4. This diameter was further reduced using an insert consisting of a smooth contraction and a 25 mm pipe of L/d=4. The elevated jet configuration was implemented by the addition of a nozzle of length 2.5 jet diameters that was affixed concentrically to jet exit. The outside of this nozzle was tapered at an angle of 7° to a sharp edge at the tip.

A Bellfram™ cylinder was used to generate the jet flow. Fluid expelled from the cylinder travelled along a 1.5 m long, 25 mm diameter hose into the settling chamber and eventually issued into the working section transversely to the cross flow. A stepper motor was used in conjunction with a lead screw to advance and retract the shaft of the piston in a controlled manner. The motor controller allowed various user inputs of motor speed, drive time, and direction.

Both the spatial and temporal jet centre-line velocities were investigated as a means of verification of the jet apparatus.
Hydrogen bubble visualisation was used to observe the spatial velocity profile of the jet. The results indicated a top hat velocity profile is obtained for the jet in absence of a cross flow. Three-dimensional Acoustic Doppler Velocimetry was used to measure the temporal velocity profile of the jets in the absence of a cross-flow. The measurements were conducted using a SonTek™ Acoustic Doppler Velocimeter (ADV). The measurement volume of the ADV was aligned with the centre of the jet and was located approximately one jet diameter upstream of the jet exit. It was found that the impulsively started jet attained and maintained a steady velocity after an initial short rise time. Further details of the jet generating apparatus and the velocity profiles can be found in Hassan et al. [4].

2.2 Particle Image Velocimetry
The entire flow was seeded with 8-micron mean diameter hollow glass spheres. The specific gravity of the spheres was approximately 1.1. The flow was illuminated by 532 nm wavelength 1.5 mm thick light sheet generated by a dual-cavity Quantel™ Brilliant B Nd:YAG pulsed laser with appropriate optics. The duration of each laser pulse was approximately 5 ns. The PIV images were recorded with a Kodak™ Megaplus ES 1.0 CCD camera with an array of 1008 by 1018 pixels and a Nikon™ 70-300mm zoom lens. The imaged region was approximately 100mm x 100mm which resulted in a spatial resolution of 10 px/mm. The data were collected at 10 Hz with a time delay of 20 ms between laser pulses. A Stanford DG535 pulse delay generator regulated the triggering of the laser pulses as well as the Flash lamp to Q-Switch delay for each cavity. The camera triggering and image acquisition were facilitated by XCAP-Plus for windows software. Images were saved as uncompressed 16 bit TIFF files.

The cross correlation of the image pairs was carried out using PIV View™ version 1.7. An interrogation window size of 32 px x 32 px was used with 50% overlap. A multi-pass double correlation, least squares Gaussian fit was used for the correlation peak detection. Vector outlier detection and replacement was conducted with PIV View™. The method used for identifying outliers was based on the difference between the magnitude of the vector in question and the eight surrounding vectors. If the pre-specified difference is exceeded by more than four of the surrounding neighbours then the vector is deemed as an outlier, Raffel et al. [11]. Outliers were replaced by vectors corresponding to the next highest correlation peak saved during the correlation calculation step. The outlier detection was then repeated for the replaced vector and if the criterion was not satisfied then the vector was disabled.

3. EXPERIMENT
PIV of transverse jets were conducted for both the flush mounted and elevated jet orientations. For all cases presented, the jet diameter is 25mm. The cross-flow velocity was held constant at approximately 12mm/s for all flow cases, thereby keeping the cross-flow boundary layer thickness at the jet exit constant at \( \delta^+ = 1.0 \). The jet velocity was held constant at a velocity of approximately 50mm/s resulting in a jet to cross-flow velocity ratio of \( R = 4.2 \) and a jet Reynolds number of 1250.
PIV was conducted first in the \( x-y \) plane. As the aim of this study was to investigate the structure of the flow in the vicinity of the node in the wake, this feature was then identified in the new data. The flow was repeated but with the PIV imaging plane being the \( y-z \) plane passing through the identified node. A mirror was placed 15 jet diameters downstream of the jet exit at an angle of 45° to the cross-flow. This mirror used in conjunction with appropriate laser illumination allowed for PIV measurements to be conducted in the \( y-z \) plane. Flow visualization tests were conducted to ensure that there was no adverse effect of the mirror on the near field of the jet. In-plane velocities were smaller in the \( y-z \) plane than the \( x-y \) plane, so a slightly longer duration between laser pulses of 25ms was used. This pulse delay also ensured that the maximum out of plane motion was confined to 25% of the light sheet thickness.

The mean velocity field for each of the flows was composed from a large number of independent vector fields. At some spatial locations where erroneous vectors have been disabled the vector population was less than the total number of vector fields. The total number of vector fields obtained as well the smallest population used in the calculation of the mean vector at any location are shown in table 1 for each configuration. Table 1 also shows the maximum velocity magnitude, \( U_{max} \), in each investigated plane. Standard dye visualisation techniques were used to visualise the flow at the same flow conditions. Here the entire jet was uniformly marked with dye.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>No. Vector fields</th>
<th>Min No. Vectors</th>
<th>In-plane ( U_{max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flush ( x-y )</td>
<td>723</td>
<td>631</td>
<td>72.3 mm/s</td>
</tr>
<tr>
<td>Flush ( y-z )</td>
<td>832</td>
<td>745</td>
<td>27.7 mm/s</td>
</tr>
<tr>
<td>Elevated ( x-y )</td>
<td>724</td>
<td>597</td>
<td>68.4 mm/s</td>
</tr>
<tr>
<td>Elevated ( y-z )</td>
<td>679</td>
<td>637</td>
<td>14.3 mm/s</td>
</tr>
</tbody>
</table>

Table 1. Sample population and velocity data for the cases investigated.

4. RESULTS AND DISCUSSION
Figures 2 and 3 show velocity magnitude normalized by bulk jet velocity, \( U_b \), in the \( x-y \) plane for the flush-mounted and elevated configurations respectively. Figures 2 and 3 also show streamline patterns integrated from the mean velocity field. Similarities include; the length of the potential core, an unstable node downstream of the jet exit; and a strong positive bifurcation line (BL) that separates flow entrained into the lee side of the deflected jet and fluid carried downstream by the cross-flow in the near field. The data of Hasselbrink and Mungal [5] also showed a bifurcation line in the near field of the elevated transverse jet although the authors did not comment on its existence. Figure 2 and 3 also show that bifurcation lines are also present at the upstream and downstream shear layers of the jet, similar to the observations of Kelso et al. [6]. A significant difference between the flush-mounted and elevated cases can be seen in the interaction of the cross-flow with the upstream shear layer of the jet. Whereas in the elevated case the streamlines turn upwards ahead of the entire jet shear layer, in the flush-mounted case the curvature of the cross-flow streamlines varies from downwards in the region of the nozzle to upwards away from the nozzle, with the result that the velocity difference across the shear layer is likely to differ at the jet exit for the two cases. Furthermore, dye visualization showed that the roll up of the shear layer of the elevated jet was delayed with respect to that of the flush-mounted jet. A similar observation was made by Cutler and Kelso [2] who attributed the delayed roll-up to the difference in the angle of the free stream flow at the jet exit. This reasoning is verified by the present results shown figures 2 and 3. Both configurations show a node downstream of the jet, although, the location of the node differs in each case. The location of the node in the flush-mounted case is \( (x/d, y/d) = (1.2, 0.8) \) and in the elevated case it is \( (x/d, y/d) = (1.6, 1.4) \). In the case of the elevated jet, the node clearly has the form of an unstable star node. However in the flush mounted case, the topology is similar to an unstable focus, although the results show very little vorticity to be associated with this feature. The occurrence of a focus in this region was also reported by New et al. [9] for a flush mounted JICF. The elevated jet data by Hasselbrink and Mungal [5] show a topology similar to a node in this region.
Figure 2. Normalized mean velocity for the flush-mounted orientation.

Figure 3. Normalized mean velocity magnitude for elevated orientation.

Figure 4. Dye visualisation of the flush-mounted JICF.

Figure 5. Normalized mean velocity magnitude for the flush-mounted orientation. The imaging plane is the y-z plane through the node at x/d=1.2.

Figure 6. Normalized mean velocity magnitude for the elevated orientation. The imaging plane is the y-z plane through the node at x/d=1.6.

Figure 7. Dye visualisation of the elevated JICF.
It is apparent from these results that the difference in topology is most likely due to the presence of the flat wall at the jet exit. Upstream of the nodes in Figures 2 and 3, the streamline patterns show regions of reversed flow, where fluid is induced towards the downstream shear layer of the jet. The superimposed velocity magnitude map shows clearly that the induced flow velocities are significantly higher than the surrounding flow in the "wake" region. Previous studies of similar flows (see references [6], [8] and [12]) indicate that the reversed flow occurs between the counter-rotating vortex pair (CVP) that begins to form near or within the jet exit. The different sizes and locations of the regions of highest induced velocity are consistent with a difference in the trajectories of the CVP in the two flow cases, with the elevated jet CVP appearing to have a lower trajectory. In addition, comparison of the curvature of the jet shear layers (and overall jet trajectory) shows that the elevated jet turns more rapidly with the cross-flow than does the flush-mounted jet. This would usually be interpreted as evidence of a higher mean rate of entrainment, although the induced velocities of other vortices and the low-pressure wake of the elevated jet pipe prevent such a simplistic conclusion from being drawn.

Figures 5 and 6 show the normalised mean velocity field of the flush-mounted and elevated jets in the y-z plane passing through the respective locations of the nodes as identified in Figures 2 and 3. Here, the velocity magnitudes are normalised relative to the corresponding maximum in-plane velocities $U_{max}$ and not by the bulk jet velocity $U_j$. Normalising by $U_j$ would obscure relevant details of the velocity fields because of the significant differences between $U_j$ and measured velocities in the y-z plane, as is evident from table 1. Here the mean streamline patterns (as projected onto these planes) are overlayed with the normalised velocity magnitude maps. Note that a slight asymmetry in the fields is possibly a result of a low frequency lateral oscillation in the flow combined with a relatively short data sampling time. The streamline patterns of Figures 5 and 6 show that the nodes observed in the x-y plane correspond to saddles (S) in y-z plane, as would be expected (see Perry and Chong [10]). They also show that the plane is populated by a number of stream-wise vortical features. These have been interpreted using flow visualization images and vorticity fields (not shown) and by reference to Kelso et al. [6]. The most prominent of the vortical features is the CVP. The CVP, which is a large-scale vortex system embedded in the jet, originates from the jet shear layer (see Kelso et al. [6]). The CVP is visible in figure 5, centred at approximately $y/d=3$, but is centred above the field of view in figure 6. It is important to note that the imaging plane does not cut the CVP orthogonally so the location and topology of the vortices are unlikely to be correctly represented by the streamlines.

Immediately above the saddle in both cases, at about $y/d=1.5$, there seem to be regions of elevated velocity. These correspond to peaks in the vorticity field (not shown). Flow visualisation show that these structures correspond to the lowest extent to which the cylindrical shear layer is stretched and folded as shown in figures 4 and 7.

Located near the exit plane, for both cases, there is a third pair of vortices. In the flush-mounted case of Figure 5 these features are not very prominent, although their structure is probably obscured due to their proximity to the edge row of data. They are more prominent in the elevated case of Figure 6. These vortices correspond to regions of low velocity in the y-z plane, which may suggest that they are wake structures generated by the cross-flow, not the jet flow. Comparison with Kelso et al. [6] confirms that these are the “wall” vortices that develop from the separation of the cross-flow boundary layer from the flat wall on the lee side of the jet. Comparison with the flow patterns of Cutler [2] indicates that stream-wise vortices of the same sign are formed near the exit of elevated pipe due to separation of cross-flow fluid from the external surface on the down-stream side of the pipe. Although the surface geometries are different, both cases generate similar pattern of stream-wise vortices downstream of the jet exit. This is confirmed by the present results.

5. CONCLUSIONS

PIV measurements of flush-mounted and elevated transverse jets were obtained in two orthogonal planes and are presented in the form of normalised mean velocity fields and streamline patterns. The results show that the two flows have a similar structure overall, although some differences are evident, including the curvature of the jet trajectory and the trajectory of the CVP vortices. Another difference that has not been noted before relates to the nature of the node located in the near wake region. Here the presence of the flat wall appears to change the feature from an unstable star node to an unstable focus. The y-z plane results also show that both flows generate a complex pattern of stream-wise vortices downstream of the jet exit. Nevertheless the overall patterns of stream-wise vortices are remarkably similar.

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REFERENCES