Time-Resolved 3C-2D PIV Measurements in the Far-Field of a Turbulent Zero-Net-Mass-Flux Jet

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Abstract This paper presents mean flow and turbulence statistics for a turbulent zero-net-mass-flux (ZNMF) jet at high Reynolds and Strouhal numbers in the far-field in a plane perpendicular to the jet axis. The measurements were made using time-resolved stereo particle image velocimetry (TR-PIV). The jet is generated by the oscillation of a piston, which discharges filtered water to the quiescent fluid through a round orifice. Multigrid cross correlation digital particle image velocimetry algorithm (MCCDPIV) was used to compute the images from each camera that subsequently were combined to obtain the three components of the velocity. The axis of the jet was found to have a shift relative to the center of the field of view which meant that a correctional shift had to be applied in the data analysis. A comparative study was performed to determine the contribution to the spreading rate due to the displacement of the center of the jet. The criterion used to define instantaneous center of the jet was the center of mass or first moment of the axial component of the velocity. It was found the \( \bar{V} \) and \( \bar{W} \) components of the velocity are very small to compare with the axial velocity.

1. Introduction

A zero-net-mass-flux (ZNMF) jet is a pulsed jet generated by periodic oscillation of a fluid boundary within the fluid without injection of additional mass due to the ejection and suction of fluid through an orifice. The fact that no additional fluid is added to the domain makes ZNMF jets very attractive for different applications related to flow control like regulation of the lift and drag on airfoils, mixing in circular jets and control of cavity oscillations Glezer & Amitay (2002). There still remain some important questions that need to be answered regarding the ZNMF jet, including the full implication of similarity, the exact nature of the dissipation and its relation to local axisymmetry and far-field similarity and Reynolds number dependence.

Two dimensionless groups characterize the ZNMF jet flow; the Reynolds and Strouhal number:

\[
Re_0 = \frac{U_0 D_0}{v}
\]

\[
St = \frac{fD_0}{U_0}
\]

where \( D_0 \) is the orifice diameter, \( f \) is the frequency of oscillation of the piston, \( U_0 \) is the characteristic velocity scale and \( v \) is the kinematic viscosity.

Cater & Soria (2002) presented an experimental study of a ZNMF jet where the mean and turbulent statistics were studied in the far-field and near-field at high Reynolds numbers and low Strouhal numbers using planar PIV in both cases. Based on dye visualization experiments it was found that the Reynolds number and Strouhal number have a significant influence on the flow evolution. It
was revealed that for high Reynolds numbers (>10^3) the jet became turbulent. An appropriate characteristic velocity in terms of the momentum flow velocity, was suggested:

\[ U_0 = \left[ \frac{4}{\pi D_0^2 T_0} \int_0^{T_D / 2} 2\pi u(r,t)u(r,t)drdt \right]^{1/2} \]

where \( T_0 \) is the oscillation period, \( u \) is the axial velocity and \( r \) is the radial coordinate, both measured from the orifice centerline. The different behavior between a continuous jet and a ZNMF jet under the same conditions was studied. Further findings included that the round turbulent ZNMF jet has a cross-stream velocity distribution similar to that of a conventional continuous jet but with a larger spreading rate and decay constant.

Cui et al. (2011) presented a study of the mean flow and turbulent statistics for ZNMF jet in the near-field for a high Reynolds of 13322 and a high Strouhal of 0.03, using time-resolved planar particle image velocimetry (TR-PIV). The measurements revealed that the flow is self-similar in the mean axial velocity, mean vorticity and Reynolds shear stress for \( x > 3.5D_0 \) scaled with the local half-width \( \delta_{1/2} \) and the local mean centerline velocity \( U_{cl} \).

In the present work the ZNMF jet was generated by the periodic oscillation of a piston, which discharges the fluid through a round orifice as in Cater and Soria (2002). The goal of the present work is the measurement of the three components of the velocity in the far-field of an axisymmetric round ZNMF jet using TR-SPIV. Results presented in this paper correspond to measurements obtained in a plane perpendicular to the mean flow located at 40D_0. The objective was to study the ZNMF jet in the far-field at high Reynolds of 13322 and high Strouhal of 0.03. The examination is focused in the jet core, and for this reason, vector fields have been acquired with high spatial resolution at the expense of not being capable of including the whole jet cross section.

2. Experimental setup

The experimental measurements of the ZNMF jet were performed in an acrylic tank with a length of 1000mm, width of 500mm and depth of 500mm. The tank was filled with Perspex roof with filtered water. To remove the air/water interface within the tank, a riser tube with inner diameter of 56.5mm located on the Perspex roof at the far end of the tank from the piston normal to the jet axis was used. The riser tube alleviated the net mass injected during the ZNMF jet experiments.

The ZNMF jet was generated by a reciprocating piston within a cylinder with an inner diameter of 50mm which discharged water through a round orifice plate with a diameter of 10mm and thickness of 2mm. This plate was located in the center of the tank wall at the exit of the jet. The piston was connected to an AC motor through a flexible coupling and an eccentric plate. The rotation speed of the AC motor was fully adjustable through an AC motor drive which controlled the driving frequency of the ZNMF jet, which was set at 4Hz. The desired piston reciprocation amplitude of 15mm was achieved by the eccentric radius and the driving frequency. Both parameters provided the desired ZNMF jet with high Reynolds and Strouhal numbers.

The water in the tank was seeded with hollow glass spheres (Potter spherical, density 1100kg/m3) with an average diameter of 11μm. These seed particles have a relaxation time of 7.39μs and are thus expected to follow the fluid motion with high fidelity. Prior to the experiments the seeding particles were prepared following the process described in Soria & Parker (2005). A pump was used to homogenize the water and the particles inside the tank to reach the maximum uniformity.

The particles were illuminated with a Quantronix Nd:YLF twin cavity laser system at a wavelength of 527nm. The laser sheet thickness was adjusted to 2mm using the necessary optics and located
normal to the axis jet at a nominal 40D₀ downstream from the orifice plate.

The illuminated particles were recorded with PCO-DIMAX high speed cameras, with a CMOS size of 2016x2016px², placed symmetrically on either side of the tank. Both cameras were mounted on in-home designed Scheimpflug adapters. A prism of 40° containing filtered water was placed between each camera and the tank to reduce the radial distortion as described in Soria & Parker (2005). The lens used for this experiment was a 200mm Micro Nikkor set at f-stop of 8. The measurement area was 7D₀x5D₀.

Figure 1 shows the sketch of the top view of the set up and the main equipment used for the experiment while Figure 2 shows a photo of the side view of the set up with the laser sheet perpendicular to the mean jet flow.

The calibration process was performed according to Soloff et al (1997). Because of the fact that the laser sheet and the calibration target could not be aligned at the same time, the following procedure was applied: 1) the calibration target was placed at the desired location, 2) the camera was focused on the target at f-stop number of 4, 3) the calibration target was removed, 4) the laser sheet was displaced along the tank using a mirror mounted in a micrometer until it was precisely located in the same place of the target, indicated by the complete focusing of the image on the CMOS at the f-stop number of 4.

For the TR-SPIV experiments, the image pair acquisition frequency was set at 624 Hz, with a time delay between image pairs of 500µs. Due to the available memory it was possible to record 3149 vector fields per sequence, corresponding to 20 cycles of the ZNMF jet. A total of 22043 vector fields were obtained from the experiments. Both cameras and laser were synchronized by a pulse generator.

A small laser beam was used to find the geometric center of the jet pointing from the end of the tank to the center of the orifice plate on the opposite side. The images were analyzed independently for each camera with the multigrid cross correlation digital particle image velocimetry algorithm (MCCDPIV) developed by Soria (1996). For the first pass the size of the interrogation window was 64px, while for the second pass 32px was used. The sample spacing between the centers of the IW was 16px. The experimental parameters are summarized in Table 1. The vector fields were validated using a standard local median filter, Westerweel (1994), obtaining 4% of rejected vectors. Using the parameters calculated by the calibration and the method proposed by Willert (1997), the vector fields obtained from each camera were combined to calculate the three components of the velocity vector.
Table 1: Overview of relevant experimental parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Flow Piston Frequency</td>
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<tr>
<td>Piston Amplitude</td>
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</tr>
<tr>
<td>Orifice Diameter</td>
<td>10mm</td>
</tr>
<tr>
<td>Re₀</td>
<td>13322</td>
</tr>
<tr>
<td>St</td>
<td>0.03</td>
</tr>
<tr>
<td>U₀</td>
<td>1.3 m/s</td>
</tr>
<tr>
<td>Camera Type</td>
<td>CMOS</td>
</tr>
<tr>
<td>Resolution</td>
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</tr>
<tr>
<td>Acquisition rate</td>
<td>624Hz “Double Shutter”</td>
</tr>
<tr>
<td>Seeding Type</td>
<td>Hollow glass spheres</td>
</tr>
<tr>
<td>Diameter</td>
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<tr>
<td>Image Properties Lens focal length</td>
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</tr>
<tr>
<td>Field of view</td>
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</tr>
<tr>
<td>Time Delay</td>
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</tr>
<tr>
<td>Processing parameters Grid Spacing</td>
<td>16px</td>
</tr>
<tr>
<td>IW₀/IW₁</td>
<td>64px / 32px</td>
</tr>
</tbody>
</table>

### 3. Results

Figure 3 shows the contours of the mean axial velocity $\overline{U}$ obtained for the core of the jet, averaged over 22043 vector fields. This component corresponds to the axial velocity, placed at 40D₀ downstream from the jet exit. Velocity values are given in m/s.

![Figure1: Contours of the mean axial velocity $\overline{U}$](image)
The iso-contours in Figure 3 are not completely circular. As the jet is expected to be axisymmetric, this fact might suggest that the data have not converged sufficiently. In the calibration process a small laser beam was used to assure that the geometric center of the jet was coincident with the center of the field of view. The shape of the $\overline{U}$ contours reveals that the center of the jet is shifted with respect to the geometric center of the field of view. Mean flow and turbulence statistics have been calculated with respect to the point of maximum absolute value of the averaged axial velocity which has been designated as the local center of the jet.

Figure 4 shows the non-dimensional $\overline{V}$ and $\overline{W}$ profiles along the horizontal line crossing the jet center in Figure 3. Velocities have been non-dimensioned by the mean axial velocity in the center of the jet. Radii have been non-dimensioned with the orifice diameter. The magnitudes of both mean velocity components are small compared to the axial velocity. As a matter of fact, when calculating the average values, it can be seen that adding more images to the mean produces a progressive reduction of both $\overline{V}$ and $\overline{W}$ averaged components. As the convergence of the mean is
still not complete, a further reduction might be expected.

Figure 5 shows the profiles for the fluctuations of the three components of the velocity. In order to compare the magnitude of the mean velocity with respect to the fluctuations, the non-dimensional square root of the fluctuations is presented. The magnitudes of the fluctuations of the three components of the velocity are very similar. Large fluctuations for \( v' \) and \( w' \) compared to the mean magnitude of both reveal a random distribution. This feature suggests that increasing the amount of vector fields used for the averaging will, as indicated, decrease the mean velocity magnitude but could increase the fluctuations. Very similar fluctuation magnitudes are found for \( v' \) and \( w' \) component. This characteristic suggests that the flow is relatively isotropic for these directions.

Although the magnitude observed for the fluctuation in the preferential direction of the flow is larger, as expected.

Cater and Soria (2002) pointed out that the entrainment coefficient of a ZNMF was larger than that of a round turbulent continuous jet. The increase in the mean jet diameter with downstream distance is influenced by two effects, the ingestion of the quiescent ambient fluid in the proper jet and the displacement of the jet as a solid body. An analysis has been performed to determine the contribution due to the movement of the jet center. To this end, the center of mass (or first moment) of the axial velocity component has been considered as the magnitude that defines the jet center position in each one of the instantaneous images. After calculating the center of mass of the U velocity in each one of the images, all of them have been translated to a common coordinate origin chosen in the center of the field of view. The statistical velocity values have been calculated again.

Figure 6 shows the contours for the axial component over the field of view for the shifted coordinate system. The translated mean jet origin is not located in the (0,0) point because the jet is shifted to the left in most of the instantaneous images, and there is more “mass” in the right part of the image with respect to the jet center. This is evidenced in Figure 7 that presents the dispersion over the plane YZ of the points where the centers of mass are located. The points are accumulated in a specific region of the plane confirming the existence of a bias error. This is consistent with the fact observed in the contours shown in Figure 3.

Figure 8 shows the profiles of \( \bar{U} \) along the horizontal line across the jet center in Figures 3 and 7. Circles represent the profile of the mean axial velocity in Figure 3 and crosses show the profile of the mean axial velocity shifted to a common origin of the centers of mass. Both data sets have been fitted to Gaussian functions. Axial velocities have been normalized using the velocity in the center of the jet and the radii have been non-dimensionalized with the orifice diameter \( D_0 \). Half-widths extracted from both profiles are 5.15\( D_0 \) for the untreated data and 4.75\( D_0 \) for the profile obtained from the shifted coordinate system. This means that the contribution of the jet displacement as a solid body to the total ZNMF jet width accounts approximately for 0.35\( D_0 \).
4. Summary and conclusion.

Time-resolved stereo particle image velocimetry has been used to measure the core of a round zero-net-mass-flow jet at high Reynolds and Strouhal number in a perpendicular plane in the far-field to obtain the three components of the velocity. Although total convergence has not been achieved, the average axial velocity accurately fits to a Gaussian function, from which the jet half width can be derived. From the images acquired at a downstream distance of 40D₀, the calculated half width results to be 5.15D₀. The mean in-plane velocity components,  \( \overline{V} \) and  \( \overline{W} \), appear to tend to zero as the average progressively converges. The non-dimensional fluctuations \( v' \) and \( w' \) are very similar for both components, indicating a high isotropy in the far field perpendicular plane. As expected, fluctuations of the axial velocity are slightly higher.

The displacement of the core jet as a solid body has been studied considering the center of mass for the axial velocity the proper magnitude to define it. The accumulation of the points corresponding to the centers of mass in a specific region over the YZ plane reveals a bias error which has been resolved obtaining the mean flow and turbulent statistics subject to an origin of a coordinate system located at the point of maximum absolute value of the mean axial velocity corresponding to the jet center. The calculations of the center of mass have been used to determine the contribution of the displacement of the jet core to the spreading rate along the axis of the jet. This contribution has been determined in terms of half-width of the jet. The width of the jet produced by the displacement of the jet core has been found to be 0.35D₀.

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References


