Velocity and Scalar Measurement of a Low Swirl Jet
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ABSTRACT

This paper presents preliminary velocity and scalar measurements of low swirl intensity jets in air. Swirling jets were generated using a micro-injector swirl generator. Velocity fields of the jets were obtained using Multi-grid Cross Correlation Digital Particle Image Velocimetry. Initial flow visualizations were performed using planar laser induced fluorescence with acetone as tracer species.

1. INTRODUCTION

The large scale effects of swirl in fluid flow have been appreciated for decades. It affects the jet growth, entrainment and decay of non-reacting jets, and flame size, shape and stability of combusting jets. There are a number of studies conducted on swirling jets over the years, namely [1, 2, 3, 4] This literature concentrates mainly on high swirl jet, close to or at vortex breakdown. There is still much unknown on jets with low swirl intensity (S < 0.2). The aim of the present study is to produce both quantitative and qualitative measurements of properties of air jets with low swirl intensity.

In this study, a swirl velocity component is induced in an axial jet by micro-injectors. The combined flow is then discharged through an orifice. With proper calibration of the swirl generator, Reynolds number and Swirl number can be varied independently and precisely. Jets with different Reynolds numbers (Re) and swirl numbers (S), which define the characteristics of the flow, are investigated using Multi-grid Cross Correlation Digital Particle Image Velocimetry (MCCDPIV) and Planar Laser Induced Fluorescence (PLIF).

2. EXPERIMENTAL METHOD

Figure 1 shows the coordinate system used in this study, while Figure 2 shows the layout of swirl generator used and a general overview of the apparatus.

Velocity field in azimuthal plan (r-θ) and vertical plane (r-x) were obtained using MCCDPIV. This allowed flow conditions to be established accurately. Relevant PLIF experiments were then performed in the (r-x) plane.

The swirl generator (Figure 2) consists of two separate supplies, the main jet supply and micro-jets supply. This allowed the flow rate of the axial jet and the micro-jets to be varied independently. To enable PIV / PLIF measurements, the main axial jet supply was seeded. Olive oil droplets were used in PIV measurement, while acetone vapour was used in PLIF measurement. The unseeded micro-jets supply was directed into the reservoir, before it was injected tangentially into the settling chamber via eight 0.5 0.5mm square cross section micro-injectors. The combined flow then passed through a contraction with an area ratio of 25, thence through an 8mm diameter orifice at the exit of the nozzle.

The swirl nozzle was placed rigidly on its supplying pipeline. Swirling jets with tracer particles or species were discharged at the top of the nozzle. These oil droplets (for PIV) or acetone vapour (for PLIF) were illuminated using laser sources at their excitation frequencies (Nd:YAG for PIV and dye laser for PLIF). Illuminated particles or fluorescence were then recorded by a CCD camera. A mirror at 45° is placed at approximately 45 diameters downstream of the orifice to reflect the images in the azimuthal plane. The effect of the mirror on the flow field at nozzle should be negligible. Images collected are stored in an image acquisition computer. Timing of the laser and the camera were controlled by a timing computer that operated Real Time Linux.

A Quanta system dual Nd:YAG laser with the wavelength of 532nm was used to illuminate the olive oil particles. This laser is capable of producing two 200mJ pulses of 6 ns duration at a repetition rate of up to 10Hz. System timing was controlled by a computer running Real Time Linux. Time intervals between each laser pulse in a pulse pair ranged from 7-40µs depending on the experiment.

Acetone was used as tracer species for the PLIF experiment. According to Lozano (1992) [5], the absorption band of acetone ranges from 225-320nm, with a flat region between 270-280nm. This frequency was achieved using a frequency doubled Lambda Physik Scanmate dye laser with Rhondamine 6G dye that peaks at 283nm (second harmonic generation). Acetone fluorescence, on the other hand, extends from 350 to 550nm with peaks at 435 and 480nm. These frequencies appear to be pale blue, which can be picked up by an intensified CCD camera.

Images were acquired using a PCO Sensicam 12bit cooled CCD digital camera. Images obtained from the camera were stored in an image acquisition computer. Images in both the vertical (r-x) and azimuth plane (r-θ) were acquired for MCCDPIV measurements. Only images in the x-r plane were acquired for PLIF measurement. Orientation of the camera was such that a CCD array of 1280 1024pixels was used for images in vertical plane, while CCD array of 1024 1024pixels was used for images in azimuth plane. A 105mm Nikkor lens was used for images acquired in the vertical plane, while a 200mm Micro-Nikkor lens was used in the azimuth plane. Intensified 105mm lens was used to capture the acetone fluorescence. Intensifier used in this experiment was a DELFT Electronic image intensifier XX1450VD.
The image pairs were analysed using the MCCDPIV algorithm described in Soria et al [6], which has its origin in an iterative and adaptive cross-correlation algorithm introduced by Soria [7, 8]. Details of the performance, accuracy and uncertainty of the MCCDPIV algorithm with applications to the analysis of a single exposed PIV and holographic PIV (HPIV) images have been reported in [9, 10].

The present single exposed image acquisition experiments were designed for a two-pass MCCDPIV analysis. The first pass used typically an interrogation window IW = 32 pixels, while the second pass used an IW = 24 pixels with discrete IW offset to minimize the measurement uncertainty [11]. The sampling spacing between the centres of the IW was 24 pixels. The MCCDPIV algorithm incorporates the local cross-correlation function multiplication method by [12] to improve the search for the location of the maximum value of the cross-correlation function. For the sub-pixel peak calculation, a two dimensional Gaussian function model was used to find, in a least square sense, the location of the maximum of the cross-correlation function [7]. The MCCDPIV data field was subsequently validated by applying: (i) a global histogram operator check [13], (ii) a median test [12], and (iii) the dynamic mean value operator test described in [14]. The tests were applied in the specified order. Following data validation, the in-plane velocity components \((u,v)\) in the \((x,r)\) coordinate directions respectively were computed by dividing the measured MCCDPIV displacement in each interrogation window by the time between the exposures of the image pair. The uncertainty relative to the maximum velocity in the velocity components at the 95% confidence level for these measurements is 0.3%.

Two non-dimensional numbers can characterize a swirling jet: the Reynolds number and the swirl number. The Reynolds number used is based on the average axial velocity \((U_o)\) at the orifice and the orifice diameter \((D_o)\),

\[
Re = \frac{\rho U_o D_o}{\mu}.
\]  

The swirl number is normally defined as the axial flux of swirl momentum divided by the axial flux of axial momentum times the equivalent nozzle radius [1]:

\[
S = \frac{G_o}{G_D / 2}.
\]  

This characterization is often very difficult to measure with certainty. Thus, simplification of the equation is necessary. One common assumption made is to treat the flow as a solid body rotation plug flow at the nozzle. The turbulent stress term is also often neglected [1]. The swirl number can then be simplified to,

\[
S = \frac{G / 2}{1 - (G / 2)^2},
\]  

where \(G\) is the ratio of the maximum tangential velocity to maximum axial velocity measured at the nozzle. This equation is valid up to a swirl number of about \(S \approx 0.2\) [1].

Four experimental conditions were investigated. The Reynolds number for all four conditions ranges from 3773-3982. Swirl number was varied progressively from 0.0640-0.1465.

Table 1 shows the MCCDPIV parameters used.

<table>
<thead>
<tr>
<th>Position (axial)</th>
<th>0(D_o) - 5.8(D_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image area</td>
<td>46.7 - 37.4(mm^2)</td>
</tr>
<tr>
<td>5.8(D_o) - 4.7(D_o)</td>
<td></td>
</tr>
<tr>
<td>CCD array</td>
<td>1280 1024 pixe(l^2)</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>27.4pixels/mm 219.2pixels/(D_o)</td>
</tr>
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<td>Number of image pairs</td>
<td>1120</td>
</tr>
<tr>
<td>Vectors spacing</td>
<td>24pixels</td>
</tr>
<tr>
<td>First interrogation window size</td>
<td>32 32pixe(ls^2)</td>
</tr>
<tr>
<td>Second interrogation window size</td>
<td>24 24pixe(ls^2)</td>
</tr>
</tbody>
</table>

Table 1: MCCDPIV parameters (x – r plane).
3. RESULTS

Figure 3 shows an instantaneous uncorrected PLIF image with $S=0.0640$ and $Re=3832$. The jet is discharged from the orifice on the left. Wave-like pattern appears along the shear layer as the jet develops. Well-defined coherent structures can be clearly seen starting from about two orifice diameters downstream. These structures diffuse further downstream of the orifice.

**Figure 3**: Instantaneous uncorrected PLIF image with $S=0.0640$, $Re=3832$ ($x/D_o = 0$ to 9.6).

Figure 4 shows average velocity fields for obtained from MCCDPIV. Every vector in the $r$-direction and every second vector in the $x$-direction is shown. The velocity profiles in developed region appear to be in Gaussian profile. According to Chigier and Chervinsky [1], a low swirl jet reaches self similar region at approximately four orifice diameters downstream. Such velocity profile is expected as the swirl numbers of these jets are fairly low. From Figure 4, jet spread appears to be higher in higher swirl jet. Moreover, decay of the centreline velocity is also higher in jets with higher swirl number due to larger jet spread.

Figure 5 shows the corresponding normalised averaged PLIF images. Each image is an average of 64 instantaneous images. Signal intensity at each pixel is normalised by the average signal across the jet ($r$-direction) right at the nozzle exit. At this stage of the research, these images have not been corrected for laser power distribution and other non-uniformity. From these PLIF images, the potential core of the jet decreases as swirl number increases. The location where the jet starts to spread moves upstream as swirl number increases. For instance, the jet with $S=0.064$ starts to spread out at around $1.5D_o$ downstream, while jet with $S=0.1465$ starts to spread out as early as $0.5D_o$. Tracer species in jets with higher swirl number diffuse in a shorter distance compared to that of lower swirl number. This indicates that an increase in swirl will promote mixing of the jet with the surrounding air.

There is no recirculation observed in this experiment due to low swirl intensity nature of the jet. According to the literature [1], the critical swirl number where recirculation occurs is approximately $S \sim 0.6$.

4. CONCLUSION

Quantitative measurements of velocity fields were obtained using MCCDPIV. Acetone concentration field were measured using PLIF. Both measurements show that the jets spread increases with swirl intensity. Tracer concentration diffuses faster in higher swirl jets. All these findings are consistent with the literature [1, 2, 3]. These preliminary findings provide vital information for constructing detailed experiment to perform quantitative measurements of scalar transport of pre-vortex breakdown low swirl jet.

**Figure 4**: Average velocity fields. (a) $S=0.0640$, (b) $S=0.0692$, (c) $S=0.0968$, (d) $S=0.1465$. 
5. ACKNOWLEDGEMENT

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6. REFERENCES


