Simultaneous Measurements of Velocity and Concentration Fields in An Inclined Jet in Crossflow

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ABSTRACT

Jet in crossflow (JICF) is a sophisticated phenomenon that commonly exists in many industrial applications such as gas turbine combustors and film cooling. Interaction and mixing between the jet and the crossflow are especially concerned in corresponding designs and hence need to be investigated and understood to improve the design efficiency. In this paper, simultaneous PIV (particle-image-velocimetry) and PLIF (planar laser-induced fluorescence) measurements were conducted in a water tunnel to study the velocity and concentration fields of an inclined JICF. Three jet-to-crossflow velocity ratios were studied and compared ($R = 0.4, 0.8$ and $1.2$). Turbulent normal stresses $\langle u'u' \rangle$, $\langle v'v' \rangle$ and turbulent shear stress $\langle u'v' \rangle$ were presented and discussed. Proper orthogonal decomposition (POD) was used to analyze the simultaneous velocity and concentration fields and revealed a certain degree of similarity between the concentration and the wall-normal component of velocity. Turbulent scalar fluxes $\langle u'C' \rangle$ and $\langle v'C' \rangle$ were obtained and their features in the windward shear layer were discussed and interpreted. This paper provides experimental data of simultaneous velocity and concentration fields in an inclined JICF and helps to deeper understand the interaction and mixing process, thus might be instructive in relevant applications.

1. INTRODUCTION

The term jet in crossflow (also known as transverse jet) refers to a jet of fluid that exits an orifice to interact with the surrounding fluid that is flowing across the orifice (Mahesh, 2013). JICF is a very common phenomenon in many industrial devices, such as pollutants issuing from chimneys, thrust vector control, gas turbine combustors and film cooling. In many of these applications, interaction and mixing between the jet and the crossflow is concerned. Therefore, it is very important to understand the responsible mechanisms, both qualitatively and quantitatively.

A lot of previous studies have been carried out to qualitatively understand the vortex structures of JICF. Four dominant vortical structures for JICF at high velocity ratios (nominally $R > 1$) have been identified (Fric and Roshko, 1994; New, Lim and Luo, 2003): (1) the counter-rotating vortex pair (CRVP), (2) jet shear layer vortices or roll-up vortices, (3) wake vortices and (4) horseshoe vortices. Among them, the most significant structure for the mixture and entrainment between the jet and cross flow is the counter-rotating vortex pair (Dai et al., 2016). However, it was found that at low velocity ratios (nominally $R < 1$), the interaction of the jet with the crossflow is dominated by hairpin vortices (Mahesh, 2013).

Besides revealing and understanding flow structures of JICF, quantitative studies also need to be carried out in order to more accurately design or control the JICF in corresponding applications. Early quantitative studies measured pointwise velocity data using hot wires and Laser-Doppler anemometry (Crabb, Durao and Whitelaw, 1980; Andreopoulos and Rodi,
1984). However, these techniques are pointwise and unable to provide information of an instantaneous field. Particle Image Velocimetry (PIV) is a non-intrusive laser diagnostic method, and can provide accurate, quantitative measurement of fluid velocity vectors in a plane (Adrian, 2005). Therefore, PIV has been used to obtain the velocity field of JICF and offered the possibility to quantify the vortex structures (Kim, Kim and Yoon, 2000; Gordon and Soria, 2002; Earl et al., 2016; Wen, Liu and Tang, 2018). Planar laser-induced fluorescence (PLIF), which is also a non-intrusive measurement technique, is widely used in providing structural visualizations (New, Lim and Luo, 2003; Wen, Liu and Tang, 2018) as well as concentration or mixing quantifications (Gordon, Cater and Soria, 2004; Shan and Dimotakis, 2006; Sadanandan et al., 2012) of JICF.

Since the scalar transport between the jet and the crossflow is deeply combined with the velocity field according to the governing equations, simultaneous velocity and scalar field measurements could provide more comprehensive insights into the interaction and mixing process of JICF. By applying PIV and PLIF techniques simultaneously, turbulent scalar fluxes as well as turbulent stresses could be obtained and analyzed. Su and Mungal (2004) discovered that the scalar variance and the magnitude of turbulent scalar fluxes were initially higher in the windward shear layer, but eventually became higher in the leeward shear layer (Su and Mungal, 2004). Cárdenas et al. (2007) indicated that the counter-rotating vortex pair influences the magnitude of the fluctuating quantities and consequently the mixing behavior of JICF according to their measurement results as well as a Large Eddy Simulation (Cárdenas et al., 2007). Moreover, proper orthogonal decomposition (POD) technique has been applied to analyse both PLIF and PIV data. Shoji (2017) found a good correspondence between the dynamics of the velocity and scalar fields using POD analyses (Shoji, 2017). Gervorkyan et al. (2018) applied proper orthogonal decomposition to both scalar and velocity fields and revealed strengthening dominance of the jet’s upstream shear layer instabilities with a reduction in momentum flux ratio J (Gervorkyan et al., 2018).

Inclined JICF (jet issued into the crossflow with a streamwise inclination) is widely used in film cooling, which is a common practice in modern gas turbines to protect the turbine blades and vanes from high-temperature incoming flow. However, most previous studies focused on normal JICF (jet issued into the crossflow perpendicularly) and only a few articles have shown results on an inclined JICF for velocity ratio \( R < 2.0 \), which is the most common situation in film cooling. Therefore, in order to efficiently design the film cooling configuration, more quantitative studies of the interaction and mixing process between the inclined jet and the crossflow should be conducted.

The present work aims to obtain the simultaneous velocity and scalar fields in an inclined JICF using PIV and PLIF techniques. The measurements were conducted in a water tunnel at three different jet-to-crossflow velocity ratios: \( R = 0.4, 0.8 \) and 1.2. The velocity fields and scalar fields were measured simultaneously using two high-speed cameras. 2000 instantaneous velocity fields and 2000 simultaneous concentration fields were obtained for each case, with the sampling frequency of 1000 Hz. Turbulent transport terms and POD modes based on the experimental data were determined and discussed, and further insights into the interaction and mixing process in JICF are offered in this paper.

2. EXPERIMENTAL SETUP

The experiments were performed in a water tank measuring 3000 mm (length) × 550 mm (width) × 700 mm (depth), which contains a water tunnel with a test section of 600 mm (length) × 80 mm (width) × 50 mm (height) as shown in figure 1 (a) and (c). With honeycombs and contraction section, the water tunnel can supply uniform oncoming flow into the test section. Figure 1 (b) shows the side view of the injection hole and the region of interest in this study. The jet was injected from a circular hole with a diameter of \( D \). Figure 1 (b) shows the side view of the injection hole and the region of interest in this study. The jet was injected from a circular hole with a diameter of \( D = 8.0 \) mm, a length-to-diameter ratio of \( L_{\text{hole}}/D = 5 \), and an injection angle of \( \alpha = 30^\circ \). The region of interest is 2D in height and 6D in width (1.5D before the hole centre and 4.5D after the hole centre). During the experiments, the mainstream flow velocity was fixed at \( U_x = 0.376 \) m/s, and the corresponding Reynolds number was \( \text{Re} = 1.5 \times 10^5 \), based on the distance between the leading edge of the test section and the coolant injection hole. The working fluid is water at ambient temperature for both the crossflow and the jet flow, resulting in a jet-to-crossflow density ratio, \( S = \rho_j/\rho_x = 1 \). The jet flow was supplied by a constant-head tank placed above the water tunnel. By tuning the flow meter to control the jet flow rate, three jet-to-cross-flow velocity ratios, \( R = u_j/U_x \) were achieved: 0.4, 0.8, 1.2. The origin of the coordinate system is set at the center of the jet orifice, with the X-axis pointing in the cross-flow direction and the Y-axis pointing in the wall-normal direction, as indicated in figure 1 (a).

The planar LIF technique was used to measure the two-dimensional distribution of the concentration field of the inclined jet-in-crossflow. Rhodamine-B was used as the fluorescent dye, and 100 L Rhodamine-B solution was prepared as the source of jet fluid with a concentration of \( C_j = 0.05 \) mg/L, below which the linear dependence of the fluorescence intensity on the dye was maintained (He and Liu, 2017). Thus the normalized concentration can be determined as:

\[
\frac{C}{C_j} = \frac{I(C) - I(C_0)}{I(C) - I(C_0)}
\]  

(1)

where \( I(C) \) means the origin images with jet, crossflow and laser on, \( I(C_0) \) denotes the background image which was recorded before each measurement with the laser turned on and the jet and crossflow off. \( I(C) \) denotes the reference image, which was obtained after the whole experiment. After adding more Rhodamine-B into the water tank and achieve a
homogeneous distribution of concentration $C = C_J = 0.05 \text{mg/L}$, the reference image was recorded with the jet and crossflow off and the laser on.

PIV technique was used to obtain the two-dimensional distribution of the velocity field. Both the water tank and the Rhodamine-B solution were seeded with silver coated hollow glass spheres ($\rho \approx 1050 \text{kg/m}^3, d \approx 10 \mu\text{m}$) as tracer particles. Instantaneous velocity vectors were obtained using a PIV software package, Micro-Vec. An interrogation window size of $32 \times 32$ pixels was applied to process the acquired PIV images. The overlap of the interrogation windows was set as 50%, leading to a spatial resolution of 0.4 mm (i.e., 0.05D) for PIV measurement results.

An 8 W continuous-wave semiconductor laser ($\lambda_{ex} = 532 \text{nm}$) was used to generate a laser sheet and illuminate the vertical plane through the jet centreline during the experiment. Two high-speed cameras (Dimax HS, PCO) were used to acquire PIV and LIF images simultaneously, as shown in figure 1 (c). One camera was installed with a long-wave-pass filter (570 nm) on the lens (focal length = 35 mm) to remove the laser light and obtain the LIF images. The spatial resolution of LIF images was about 0.12 mm (i.e., 0.015D). Another camera was installed with a short-wave-pass filter (550 nm) on the lens (focal length = 200 mm) to remove fluorescence light and obtain the PIV images. The two cameras were synchronized using a signal generator. The sampling rates are 1000 Hz for the LIF camera and 2000 Hz for the PIV camera separately since the PIV processing needs two images to obtain each instantaneous velocity field. Therefore, the sampling frequency of simultaneous concentration and velocity fields was 1000 Hz. The sampling duration was 2 seconds, beyond which the ensemble-averaged concentration field and velocity field converged (The root mean square of the difference between the ensemble-averaged field of 2000 images and that of 4000 images were less than 5% of the mean value of the 4000 images).

![Schematic of the experimental system](image1.jpg)

![Side view of the injection hole](image2.jpg)

![Water tunnel with laser on](image3.jpg)

![Configuration of the cameras](image4.jpg)

**Figure 1 Experimental setup**

3. RESULTS AND DISCUSSION

### 3.1 Results of velocity fields

Figure 2 shows the ensemble-averaged velocity fields (normalized by mainstream velocity) at different jet-to-crossflow velocity ratios. It is shown that when $R = 0.8$ or 1.2 the streamwise velocity penetrates further into the crossflow than the wall-normal component of velocity. This might indicate that the momentum interaction between jet and crossflow is more intense in Y direction. Moreover, when the jet-to-crossflow velocity ratio is low ($R = 0.4$), there is no obvious boundary in the streamwise velocity field between the jet and the crossflow.

Figure 3 shows the contours of the turbulent normal stress components (equivalently, components of the turbulent kinetic energy), normalized by the square of crossflow velocity, $\langle u'^2/u'^2 \rangle$ and $\langle v'^2/v'^2 \rangle$ at different jet-to-crossflow velocity ratios. $u'$ and $v'$ denote fluctuating components of velocity $u$ and $v$ respectively. The symbol $\langle \cdot \rangle$ indicates the ensemble average over the measured 2000 velocity fields. As shown in the figure, turbulent normal stresses mainly occur in the windward and leeward shear layers and become more intense with the increase of velocity ratio. These reflect the dominance of the jet shear layer instability in the near field (Su and Mungal, 2004). Moreover, according to the figure, the turbulent normal stress in X direction shows higher values in the leeward shear layer than in the windward shear layer. On
the contrary, the turbulent normal stress in Y direction is more strong on the windward side than on the leeward side of the shear layer.

Figure 2 Ensemble-averaged velocity fields

(a) Velocity in X direction at $R = 0.4$
(b) Velocity in Y direction at $R = 0.4$
(c) Velocity in X direction at $R = 0.8$
(d) Velocity in Y direction at $R = 0.8$
(e) Velocity in X direction at $R = 1.2$
(f) Velocity in Y direction at $R = 1.2$

(a) $\langle u'u'_x/u_\infty^2 \rangle$ at $R = 0.4$
(b) $\langle v'v'_y/u_\infty^2 \rangle$ at $R = 0.4$
(c) $\langle u'u'_x/u_\infty^2 \rangle$ at $R = 0.8$
(d) $\langle v'v'_y/u_\infty^2 \rangle$ at $R = 0.8$
Figure 3 Turbulent normal stress field

Figure 4 shows the contours of the turbulent shear stress at different jet-to-crossflow velocity ratios. As shown in the figure, the turbulent shear stress is dominated by shear layer structures and becomes stronger with the increase of velocity ratio. When the jet-to-crossflow velocity ratio $R \geq 0.8$, the turbulent shear stress in the windward shear layer is positive. That means fluctuations of $u$ and $v$ are likely to have the same sign. This phenomenon could be explained as the high-velocity jet that propagates into the crossflow and slow crossflow that is mixed into the jet (Schreivogel et al., 2016). When the velocity ratio is low (e.g., $R = 0.4$), the turbulent shear stress is negative in the windward shear layer. This is also reasonable based on the above interpretation because the jet velocity is lower than the crossflow velocity. It might be confusing that the jet velocity should be lower than the mainstream velocity when $R = 0.8$ but the turbulent shear stress is mainly positive in the upstream shear layer. In fact, in this study, the jet velocity in velocity ratio $R$ was defined as the bulk velocity of the injection hole. Due to the boundary layers of the jet and crossflow, the velocity of jet flow could be higher than that of the crossflow when $R = 0.8$, as shown in the ensemble-averaged velocity fields in figure 2. In the downstream shear layer, a sign change of $u'v'$ can be observed at about $X/D = 1.5$, which is similar to the results of Schreivogel et al. and might be explained as the deflection of the jet (Schreivogel et al., 2016).

Figure 4 Turbulent shear stress field

3.2 Results of concentration fields

Figure 5 shows the ensemble-averaged concentration fields at different velocity ratios. Consistent with the findings of Wen et al. (2018), the inclined jet barely detaches from the wall at low velocity ratios (typically at $R = 0.4$) and fully detaches from the wall at high velocity ratios (typically at $R = 1.2$).

Figure 5 Ensemble-averaged concentration field
3.3 Correlation between the velocity and concentration fields

Due to the similarity between governing equations for vorticity transport and scalar transport, the fields of vorticity and scalar might be similar to some extent. As expected, remarkable correspondence between the concentration gradient magnitude field and vorticity field was revealed in the normal JICF configuration (Gevorkyan et al., 2018).

In the present study, instantaneous concentration fields and vorticity fields were compared. As a representative, the results at velocity ratio \( R = 1.2 \) are shown in figure 6. There are indeed some correlations between the two fields. However, the similarity in the studied inclined JICF configuration was not as obvious as that shown in the normal JICF studied by Gevorkyan et al. (2018).

![Figure 6 Instantaneous concentration field and vorticity field at \( R = 1.2 \)](image)

Proper orthogonal decomposition (POD) has been applied to extract the most dominant mode structures in a turbulent flow field for decades (Berkooz, Holmes and Lumley, 1993). A main advantage of POD analysis is that the extracted mode structures are ordered according to fluctuation energy, hence the important flow features could be revealed from noisy or highly chaotic data (Gevorkyan et al., 2018).

In this paper, POD analysis was conducted based on the simultaneous PIV and PLIF measurement results. Figure 7 shows the first four POD modes of velocity \( u, v \) and concentration \( C \) at velocity ratio \( R = 1.2 \). It should be noted that in the presented POD analysis, velocity \( u \) and \( v \) are normalized by the mainstream flow velocity. Concentration fields are normalized by the jet concentration \( C_j \) and are linearly interpolated in order to have the same spatial resolution as the measured velocity fields. Then the simultaneous fluctuating components of velocity data and concentration data are combined into one matrix for the POD analysis. As shown in the figure, the modes of \( u, v, \) and \( C \) are dominated by shear layer structures, especially the windward shear layer. Interestingly, there are some similarities between the spatial distribution of main structures in the modes of velocity \( v \) and concentration \( C \). However, no apparent relevance between the modes of \( C \) and \( u \) was discovered. This may indicate that there is some correlation between the fluctuation components of \( C \) and that of wall-normal velocity \( v \). For other velocity ratios, the POD modes are not shown here, but the findings are similar.

![Figure 7 POD modes of velocity \( u, v \) and concentration \( C \)](image)
Figure 7 First 4 POD modes at $R = 1.2$

Figure 8 (a) and (b) show the energy level and accumulated energy level of the first ten POD modes respectively. It can be indicated from the figures that the fluctuation energy is more concentrated in the first few modes at low velocity ratios and more uniformly distributed at high velocity ratios.

Figure 8 Energy level of POD modes

In order to better understand the relationship between the velocity and concentration fields, turbulent scalar flux needs to be studied. The streamwise and wall-normal components of the turbulent scalar flux $<u'C'>$ and $<v'C'>$ in the centreplane can be determined using the simultaneous velocity and concentration data. Figure 9 shows contours of normalized $<u'C'>$ and $<v'C'>$ at different velocity ratios.

As shown in the figure, when velocity ratio $R = 0.4$, the streamwise turbulent scalar flux $<u'C'>$ is mainly dominated by the upstream shear layer with negative values. While with the increase of velocity ratio, $<u'C'>$ is dominated by both the upstream and downstream shear layer as well as a region near the downstream plate, and turns to be positive in the windward shear layer. However, for the wall-normal component of the turbulent scalar flux $<v'C'>$, it is clear that at all velocity ratios studied, this term is mainly dominated by the upstream shear layer with positive values and is weak in the downstream shear layer with negative values.

In the upstream shear layer, the crossflow and jet interact for the first time and have not experienced strong mixing. Thus it is not very difficult to interpret the turbulent scalar flux in the windward shear layer by the interaction between the jet and the crossflow. When velocity ratio is low, the streamwise component of mainstream velocity is higher than that of jet velocity, but the concentration of the crossflow is lower than that of the jet. The jet and the crossflow dominate on the windward side of the shear layer alternately and thus leads to the negative value of $<u'C'>$. The wall-normal component of the turbulent scalar flux could be explained in a similar way. Moreover, the wide region of positive $<v'C'>$ in the windward shear layer reveals that there is to some extent a positive correlation between the concentration and the velocity in $Y$ direction on the windward side of the shear layer. However, in the downstream shear layer, the interaction and mixing between the jet and the crossflow have become very complex, hence efforts to explain the turbulent scalar flux in this region still remain to be made.
Figure 9 Turbulent scalar flux fields of centreplane

CONCLUSIONS

Simultaneous measurements of velocity and concentration fields were conducted to study an inclined JICF within a water tunnel at three different velocity ratios ($R = 0.4, 0.8$ and $1.2$). PIV technique was used to obtain the velocity data and PLIF technique was applied to capture the concentration fields. The sampling frequency was 1000 Hz and the measurement duration was 2 seconds. The velocity fields and concentration fields were analyzed and some viewpoints about the correlation between them were provided in this paper.

The velocity fields revealed that both components of the turbulent normal stresses $\langle u'u' \rangle$ and $\langle v'v' \rangle$ dominate in the shear layers and get stronger with the increase of jet-to-crossflow velocity ratio $R$. However, streamwise component of the turbulent normal stress shows higher values on the leeward side than on the windward side. On the contrary, the wall-normal component of turbulent normal stress is more intense in the windward shear layer.

Based on the simultaneous PIV and PLIF technique, the correlation between the instantaneous velocity and concentration fields was able to be studied in this paper. POD analysis was carried out for combined simultaneous velocity and concentration data. As expected, the POD modes of $u$, $v$, and $C$ are mainly dominated by shear layer structures. But what’s interesting is that the POD modes of $v$ and $C$ show a certain degree of similarity, which is not obvious between $u$ and $C$. It might be inferred that the correlation between the concentration and the wall-normal component of velocity is stronger than that between the concentration and the velocity in streamwise direction.

Two components of turbulent scalar flux, $\langle u'C' \rangle$ and $\langle v'C' \rangle$, were determined to better understand the relationship between the velocity and concentration fields based on the measurement results. It was found that in the windward shear layer, $\langle v'C' \rangle$ is positive for all the studied cases while values of $\langle u'C' \rangle$ changed from negative to positive with the increase of velocity ratio $R$. These might be interpreted as the alternative dominance of the crossflow and the jet in the windward shear layer since they interact for the first time and has not experienced strong mixing in this region. On the leeward side of the shear layer, however, the concentration and velocity fields became complicated after a certain degree
of interaction and mixing. Therefore, the turbulent scalar flux in this region may not be directly explained in a similar way, and more works need to be conducted in the future.

NOMENCLATURE

\( C \)  
Concentration  \( \text{kg/m}^3 \)

\( C_j \)  
Concentration of the jet  \( \text{kg/m}^3 \)

\( \bar{C} \)  
Spatial-averaged concentration  \( \text{kg/m}^3 \)

\( C' \)  
Fluctuating component of \( C \)  \( \text{kg/m}^3 \)

\( D \)  
Hole diameter  \( \text{m} \)

\( L_{\text{hole}} \)  
Length of the injection hole  \( \text{m} \)

\( S \)  
Jet-to-crossflow velocity ratio -

\( R \)  
Jet-to-crossflow density ratio -

\( u \)  
Velocity in X direction  \( \text{m/s} \)

\( u_\infty \)  
Crossflow velocity  \( \text{m/s} \)

\( u_j \)  
Velocity of injection jet  \( \text{m/s} \)

\( u' \)  
Fluctuating component of \( u \)  \( \text{m/s} \)

\( U_{xy} \)  
Centreplane unmixedness -

\( v \)  
Velocity in Y direction  \( \text{m/s} \)

\( v' \)  
Fluctuating component of \( v \)  \( \text{m/s} \)

\( \rho_\infty \)  
Density of crossflow fluid  \( \text{kg/m}^3 \)

\( \rho_j \)  
Density of jet fluid  \( \text{kg/m}^3 \)

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