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Effect of flow parameters on an Obliquely Impinging Jet in a Cross Flow

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Abstract

The horseshoe vortex associated with an obliquely impinging jet in a cross flow was studied for various angles of pitch and yaw. Dye visualisation and Planar Laser Induced Fluorescence was used to locate various characteristic features of the horseshoe vortex and determine how these features were affected by pitch and yaw. Results show that an increase in pitch leads to an increase in leading vortex size and penetration upstream of impingement, a decrease in the vertical trajectory of the trailing vortices, and an increase in the distance between the trailing vortices. An increase in yaw also results in an increase in leading vortex size and penetration upstream of impingement, and also produces an asymmetry between the size and trajectory of the trailing vortices as the jet moves from parallel to the cross flow to normal to the cross flow.

Introduction

While much research has been done on the simple case of a jet impinging normally on to a surface with no cross flow involved, very little is known about the flow resulting from an obliquely impinging jet in a cross flow (OIJCF). Variations such as whether a cross flow is added or if the jet is applied at an oblique angle have been investigated separately but rarely in combination. Since an OIJCF is found in many applications, such as precessing jet burners and Vertical Take-Off and Landing (VTOL) aircraft, it is beneficial to have a better understanding of the flow. Hence a more thorough investigation of the effect of characteristic flow parameters, such as the angle of the jet relative to the cross flow (yaw), has been conducted. It is expected that knowledge of the quantitative effects of changing selected flow parameters will result in a more effective application of obliquely impinging jets in cross flows, ideally allowing designers to maximise desirable flow behaviours and minimise unwanted flow behaviours in their applications.

When a cross flow is applied to an obliquely impinging jet, it produces a horseshoe vortex (figures 1 and 2) with a parabolic shape upstream of impingement and two counter-rotating trailing vortices continuing downstream [1][2]. The dimensionless parameters which define the flow are the jet exit-to-impingement surface spacing, h/d, the jet Reynold's number based on the jet diameter, Re_j, the velocity ratio between the jet and the cross flow, VR, the angle of the jet relative to the impingement surface, pitch (θ), and the angle of the jet relative to the direction of the cross flow, yaw (ϕ). These parameters are highlighted in figures 1 and 2, where figure 1 shows a side view of a streamwise cross-section of the flow through the point of impingement, and figure 2 shows a top view of the horseshoe vortex formed by an OIJCF. Some of these parameters have already been extensively investigated and their effects on certain parameters and regions of the flow are well understood, and as such will not be discussed here. However, the effects of pitch and yaw are not as well documented and are therefore the focus of this research.

The effect of pitch when a cross flow is not present has been extensively researched, though there is significantly less data on the effect when a cross flow is present. When the angle of pitch is not normal to the impingement surface, more jet fluid flows in the direction of the jet [3][4][5]. This results in a change of the leading edge penetration and the spread of the trailing vortices. Changing the pitch so that the jet points further upstream (i.e. increasing pitch) will move the leading vortex upstream [3][4][5] and increase the spanwise spread of the trailing vortices [7]. This effect may be symmetric about 90° and non-linear [6], but this observation is based on a small data set and more studies are needed for verification.

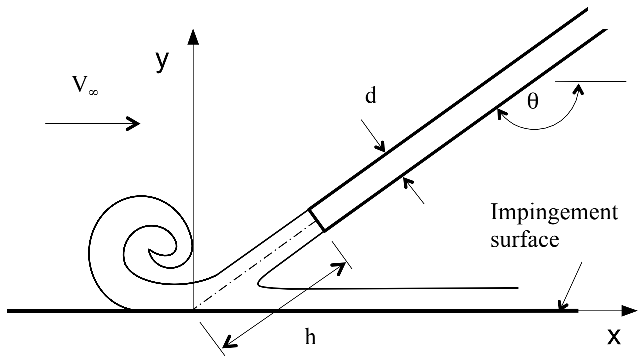

Figure 1. Side view of an OIJCF.

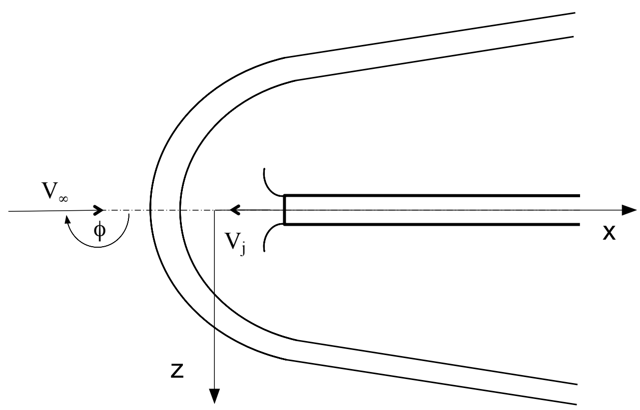

Figure 2. Top view of an OIJCF.

The effect of yaw is still poorly understood. Very few studies have been conducted with non-zero angles of yaw, and the studies that do exist have not examined the effect of changing yaw. Changing the yaw of the jet creates an asymmetry between the trailing vortices (figure 3), with more jet fluid flowing in the direction of the jet and hence one trailing vortex will be larger than the other [8]. No data currently exists to determine the extent of the asymmetry or to show how it changes with yaw.

It can been seen that further research is needed into the effect of impingement angle on the size and shape of the horseshoe vortex, especially the effect of yaw, for the flow to be more completely understood. This paper will show the results of such research into the effect of pitch and yaw on the flow of an OIJCF.

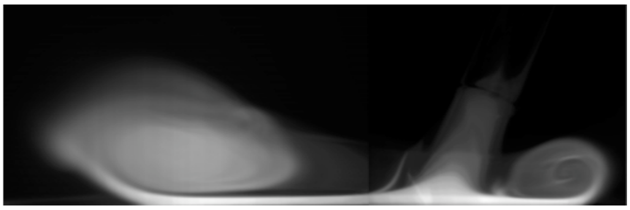

Figure 3. Asymmetric nature of trailing vortices at 45° yaw (VR=4, Re_j=910, pitch=60°).

Experimental procedure

Equipment and parameters

A 16mm diameter water jet was impinged onto the floor of a water tunnel 500mm wide and 400mm deep. The pitch of the jet was set to 45°, 60° or 90° from horizontal. The yaw was varied from 0° (in the same direction as the cross flow) to 180° (in the opposite direction to the cross flow) in increments of 45°. The jet Reynolds number based on the jet diameter (Re_j) was set to either 910 or 1390, and the jet-to-cross flow velocity ratio (*VR*) was set to 1, 2 or 4. The distance from the jet exit to the water tunnel floor along the jet centreline was kept constant at two jet diameters.

Dye visualisation was used to record all combinations of the chosen parameters, and Planar Laser Induced Fluorescence (PLIF) was used to visualise ten cases in greater detail, such that the effect of each parameter could be shown. The values of the parameters in each of these ten cases are shown in table 1.

	Values of VR	Values of Re_j	Values of Pitch	Values of Yaw
Pitch	4	910	45°, 60°, 90°, 120°	0°
Yaw	4	910	60°	0°, 45°, 90°, 135°, 180°

Table 1. Values of parameters used in the investigation of the effects of pitch and yaw on the flow resulting from an OIJCF. Note that a pitch of 120° is achieved by combining 180° yaw with 60° pitch.

Data collection and analysis

Dye visualisation was used to record the flow resulting from an OIJCF. Blue food colouring was introduced to the jet 3m upstream of the exit. A video camera captured the flow from the side of the tunnel at a frame rate of 25Hz, and Matlab was used to then create an average image of the flow. The image processing software ImageJ was used to visually analyse the images of the ten flows to be analysed in greater detail and record the locations of the characteristic features of the leading vortex, including vortex core and maximum vortex penetration. All measurements are given in terms of jet diameters.

Planar Laser Induced Fluorescence (PLIF) was used to visualise spanwise cross-sections of the horseshoe vortex resulting from an OIJCF. The water jet was marked with Rhodamine dye and illuminated using a Nd:YAG laser firing at 10Hz, and the images were recorded with a Megaplus camera. The laser beam was passed through sheet-forming optics to create a 100mm wide, 4mm thick vertical laser sheet. The laser sheet was oriented perpendicularly to the cross flow at five downstream locations, namely at 0, 1, 2, 5 and 10 jet diameters from the point of impingement. The image processing software Oma was used to create a mean image of the flow at each cross section, and ImageJ was used to visually analyse the images and record the characteristic dimensions of the trailing vortices, shown in figure 4. All measurements are given in terms of jet diameters.

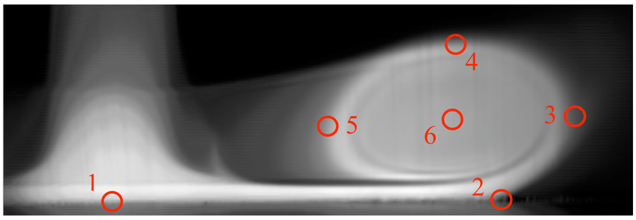

Figure 4. Example of mean PLIF image of spanwise cross-section of right trailing vortex at 0d downstream of impingement, with pitch=60°, yaw=0°, Re_j=910, VR=4, showing characteristic data points collected. 1:impingement, 2:separation, 3:outer edge, 4:upper edge, 5:inner edge, 6:vortex core.

Effect of Pitch

Leading vortex size and penetration

Qualitative comparison of dye visualization for all cases shows that as pitch increases (i.e. jet moves from pointing downstream to pointing upstream) the leading edge penetration increases (i.e. also moves upstream), and the leading vortex becomes larger and more turbulent. Closer analysis of mean dye images agrees with these observations. As indicated in previous research [7], the effect on penetration appears to be symmetric around 90°, but is not linear, as shown in figure 5. The rate of increase in penetration from 60° to 90° is almost double the rate of increase from 45° to 60°.

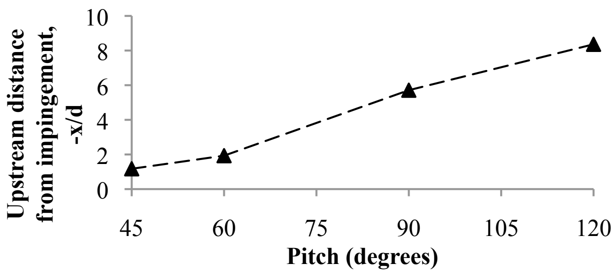

Figure 5. Effect of pitch on penetration of leading vortex.

Quantitative analysis of leading vortex size shows the same trend. As discussed above, the rate of increase of the leading vortex size with pitch increases from 45° to 90° in a non-linear fashion, and then decreases from 90° to 120° in the same non-linear relationship.

Vertical trajectory of trailing vortices

Qualitative comparison of dye visualization for all cases shows that as pitch increases, the vertical trajectory angle decreases. When pitch is less than 90° (i.e. jet is pointing downstream), the trajectory angle is positive (i.e. vortex rises away from floor as it moves downstream). When pitch is equal to 90° the trajectory angle is zero (i.e. parallel to floor). When pitch is greater than 90°, the trajectory angle is negative.

Closer analysis with PLIF data and mean dye images agrees with this observation, as shown in figure 6. The decrease in trajectory angle from 45° pitch to 60° pitch is less than that from 60° to 90° pitch and from 90° to 120° pitch, though the decrease from 90° to 120° pitch appears to be less than that from 60° to 90° pitch, suggesting this effect is not symmetric about 90° pitch.

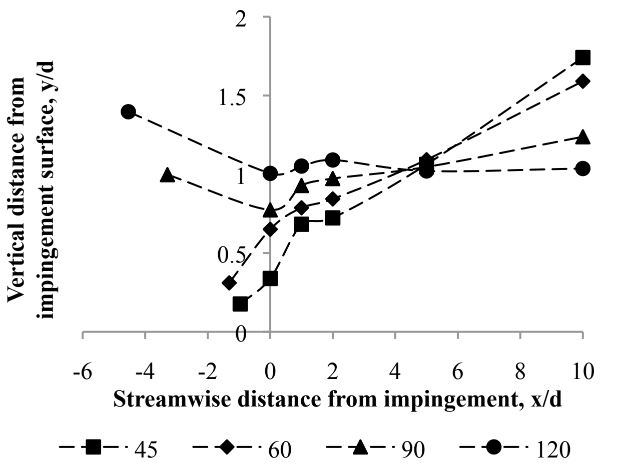

Figure 6. Effect of pitch on vertical trajectory of trailing vortex cores.

It is interesting to note the point of convergence at approximately 4.5d downstream of impingement for all values of pitch, at which point the vortex core is 1d above the impingement surface. It is unclear at this stage if this phenomenon is unique to this set of flow parameters or if a similar point of convergence occurs for all flow cases.

Horizontal trajectory of trailing vortices

Qualitative comparison of dye visualization for all cases does not show any clear trend in the effect of pitch. However, closer analysis with PLIF data and mean dye images shows a clear relationship between pitch and the horizontal trajectory of the trailing vortices, as shown in figure 7. As pitch increases, the distance between the vortex cores increases, though the overall shape of the horseshoe vortex appears to stay the same. The increase in spread from 45° pitch to 60° pitch is less than the spread from 60° to 90° pitch and 90° to 120° pitch, which is the same trend as for the other flow characteristics discussed above. As with the vertical trajectory of the trailing vortices, it is unclear if this effect is symmetric about 90°.

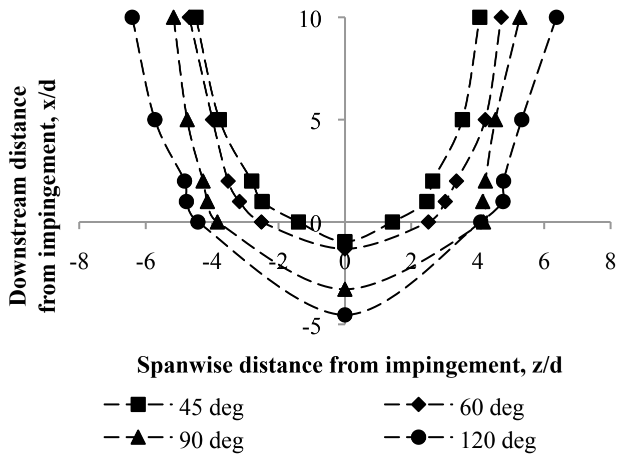

Figure 7. Effect of pitch on horizontal trajectory of trailing vortex cores.

Effect of Yaw

Leading vortex size and penetration

Qualitative comparison of dye visualization for all cases shows that as yaw increases (i.e. jet moves from pointing downstream to pointing upstream) the leading edge moves upstream and the leading vortex size increases and it becomes more turbulent. A quantitative analysis of the mean dye images shows a nearly linear relationship between yaw and leading edge penetration, as seen in figure 8. An analysis of the leading vortex size, using the distance between the vortex core and the leading edge as a measure of the vortex radius, shows a similar trend. The radius clearly increases in a nearly linear manner with increasing yaw, with a slight inflection at 90°.

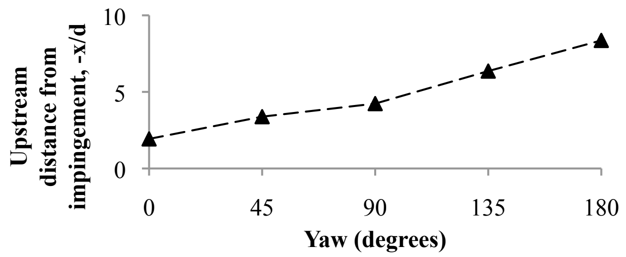

Figure 8. Effect of yaw on penetration of leading vortex.

Vertical trajectory of trailing vortices

Qualitative comparison of dye visualization for all cases does not show a clear trend, but changing yaw seems to have a similar effect as changing pitch. It appears that increasing yaw will decrease the vertical trajectory angle. When yaw is less than 90°, the trajectory angle is positive. When yaw is greater than 90°, the trajectory angle is negative. The effect on the relative height of the vortices is unclear from dye visualization.

PLIF data has been divided into 'left' and 'right' trailing vortices, as seen when looking at the horseshoe vortex from above with the cross flow direction being 'up'. When the jet is at 90° yaw it is seen from above to be pointing to the left (-z direction).

The vertical trajectories of the left and right trailing vortices are shown in figure 9. At 0° and 180° yaw the trajectories are similar, as expected of the symmetric flow seen in figure 7 (equivalent to pitch of 60° and 120°). As yaw moves from parallel to perpendicular to the cross flow, the difference between the heights of the vortex cores increases. The trajectory angles are similar for the left and right trailing vortices and this angle decreases as yaw increases, which is the same effect as changing pitch.

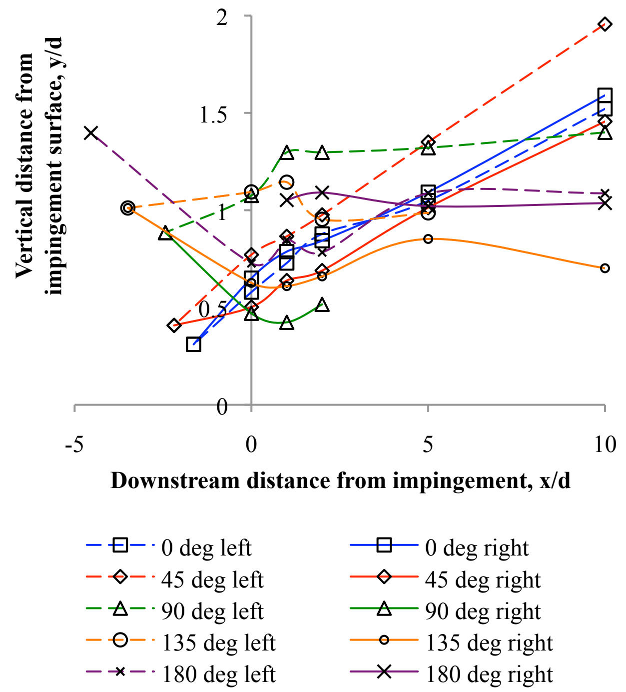

Figure 9. Effect of yaw on vertical trajectory of trailing vortices.

Horizontal trajectory of trailing vortices

Qualitative comparison of dye visualization for all cases shows that as yaw moves from parallel to the cross flow to perpendicular to the cross flow, the horseshoe vortex becomes more asymmetric. PLIF data agrees with this observation, and is used to determine the trajectory of the vortex core (figure 10) and the diameter of the trailing vortices (figure 11).

The asymmetry created when the yaw is not parallel to the cross flow is clearly shown in figure 10. As the yaw is increased from 0° to 90° the left and right vortex cores move to the left, though the change is greater in the left vortex than the right. As the yaw is increased from 90° to 180° the left and right vortex cores move to the right, though the change is greater in the right vortex than the left.

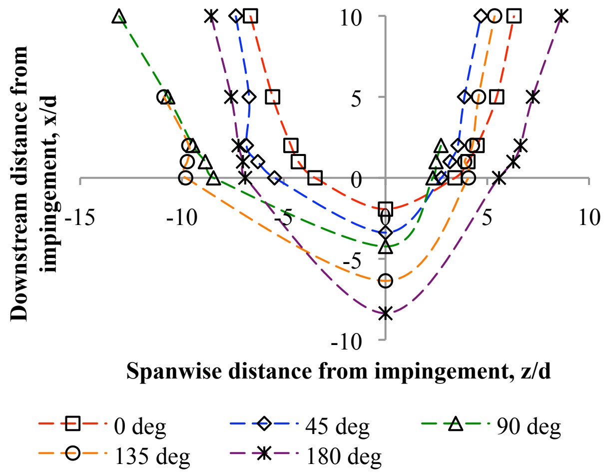

Figure 10. Effect of yaw on horizontal trajectory of trailing vortices.

The inner and outer edges of the trailing vortices are used to calculate their spanwise diameter and analyse the extent of the asymmetry in the flow, as shown in figure 11. As yaw increases from 0° to 90° the left vortex core diameter increases while the right vortex core diameter decreases, though only slightly. As yaw increases from 90° to 180° the left vortex core diameter decreases while the right vortex core diameter increases. For each trailing vortex, the rate of increase in diameter is greater than the rate of decrease.

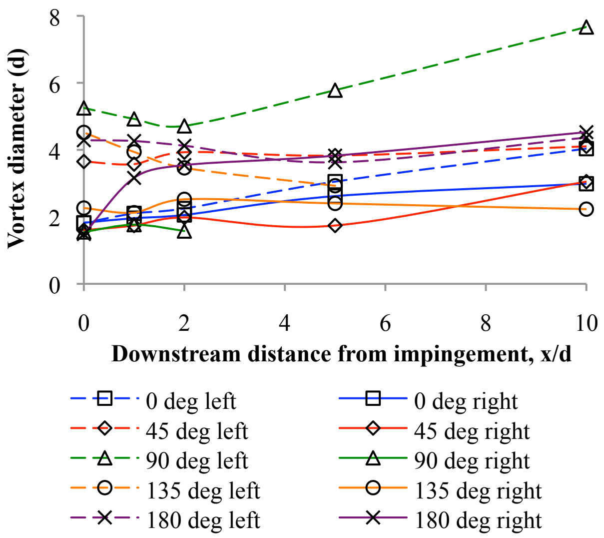

Figure 11. Effect of yaw on trailing vortex diameter.

Conclusions

An experimental investigation has been made into the effects of pitch and yaw on the flow produced by an obliquely impinging jet in a cross flow. Results of this study show agreement with previous research, and extend the knowledge of the effects of pitch and yaw on leading vortex size and penetration, and on vertical and horizontal trajectories of the trailing vortices.

The current study shows that an increase in pitch leads to an increase in leading vortex size and penetration upstream of impingement, an increase in the distance between the trailing vortices, and a decrease in the vertical trajectory of the trailing vortices. The investigation into the effect of yaw on the horseshoe vortex has shown the linear relationship between yaw and leading vortex size and penetration, and highlighted the significant asymmetry that occurs when the jet is not parallel to the cross flow.

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