

Three-Dimensional Penetration and Velocity Distribution of Liquid Jets Injected Transversely into a Swirling Crossflow

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Abstract

An experimental study has been conducted to study the effect of a swirling crossflow on transversely injected liquid jets. In-house designed axial swirlers with vane exit angles of 30°, 45° and 60° were used to generate the swirling crossflow. Laser Doppler Velocimetry (LDV) results indicate that the axial (U_x) and the tangential (U_θ) components of the crossflow velocity decrease with increasing radial distance from the center. Also, flow angle (ψ) of the crossflow is lesser than the swirler vane exit angle indicating that the swirlers did not impart sufficient tangential momentum for the flow to be parallel to the vanes at swirler exit. The deficit in flow angle increased with swirler angle. Water jets were injected from a 0.5 mm diameter orifice located on a cylindrical centerbody that protruded through the hub of the swirler. Particle Image Velocimetry (PIV) was used to study the behavior of the jets. PIV measurements were conducted in multiple cross-sectional and streamwise planes. Mie-Scattering images were collocated to create three-dimensional representation of the jet plume, which was used to study penetration. In cylindrical coordinate system, the penetration can be described in terms of radial and “circumferential” penetration, where circumferential penetration is defined as the difference in the circumferential displacement of the jet and the crossflow over the same streamwise displacement. Increasing the momentum flux ratio (q) resulted in a higher radial penetration. Increasing the swirl angle reduced radial penetration and increased circumferential penetration. PIV results of the cross-sectional and streamwise planes each yielded two velocity components which were merged to obtain three-dimensional droplet velocity distribution. The three-dimensional velocity distribution yielded further insight into the evolution of the jet plume.

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Introduction

The transversely injected liquid jet in crossflow has numerous applications including fuel injection [1], thrust vector control of rockets [2], and lubrication of the bearing chamber [3]. The injection of a liquid fuel jet into crossflow is also one of several possible concepts of a premix module for lean, premixed, prevaporized (LPP) combustion for aviation gas turbines. The demands for higher efficiency of power production and smaller engines lead to an increase in the operating temperatures and pressures. This leads to increase in the production of effluents like oxides of nitrogen (NO_x) since NO_x formation rates increase with temperature [4]. With the increasingly stricter ICAO regulations on engine emissions, there is a strong emphasis on the development of low-emission combustion techniques. One technique is the LPP combustion, where lean, homogeneous fuel-air mixture is created just upstream of the combustor inlet. The presence of excess air throughout the primary zone ensures that the combustion temperature is low enough to suppress NO_x formation. The LPP model requires a premix duct where fuel and air are mixed together. To achieve good homogeneous mixture and to avoid coking, fine atomization and careful fuel placement are needed. Liquid jet in crossflow has characteristics of rapid atomization and controllable penetration [1], which make it a good choice for LPP fuel injection.

Jet-in-crossflow is a fundamental flow field and has been the subject of numerous experimental as well as computational studies. Tambe [5] and Elshamy [6] have conducted detailed literature reviews of the work done in this area. However, most of the studies feature uniform crossflows, i.e. where crossflow velocity does not change in the transverse direction. Only a few studies have utilized crossflows with steady-state non-uniform velocity profiles. Becker and Hassa [7, 8] injected liquid jets into a counter-swirling double-annular crossflow and studied the effect of momentum flux ratio and air pressure on the jet behavior. Gong et al [9] published a preliminary report on studies conducted for the Lean Direct Wall Injection (LDWI) concept, where they injected liquid jets into a swirling flow at different injection angles. The authors previously conducted a study where jets were injected transversely into a crossflow laden with a shear layer [10, 11]. The shear layer was generated by creating a slip plane between two co-flowing airstreams, creating a quasi-linear velocity gradient in the transverse direction. The strength of the shear layer and the sense of the velocity gradient had a significant impact on the jet penetration and the post-breakup spray.

The objective of the present work is to study the behavior of a liquid jet injected transversely into a swirling crossflow. The effect of swirl strength, in addition to typical jet parameters, on the jet penetration and

the droplet velocity distribution was investigated. The swirl strength was varied by using three different axial swirlers with different vane exit angles. Experimental techniques used include Laser Doppler Velocimetry (LDV) and 2-D Particle Image Velocimetry (PIV). The study was divided into a thorough investigation of the crossflow before looking at jets and the impact of this crossflow on their behavior. A part of this study [12] was reported previously. This paper serves to extend the findings from the previous paper.

In this study, LDV was used to study the crossflow to avoid the signal-to-noise issues experienced during PIV measurements [12]. PIV measurements were conducted on the jet at multiple cross-sectional as well as streamwise planes. The Mie-Scattering images from the cross-sectional planes led to an improved penetration prediction. Also, as each plane yielded two components of droplet velocity, the results were combined to create three-dimensional droplet velocity distribution.

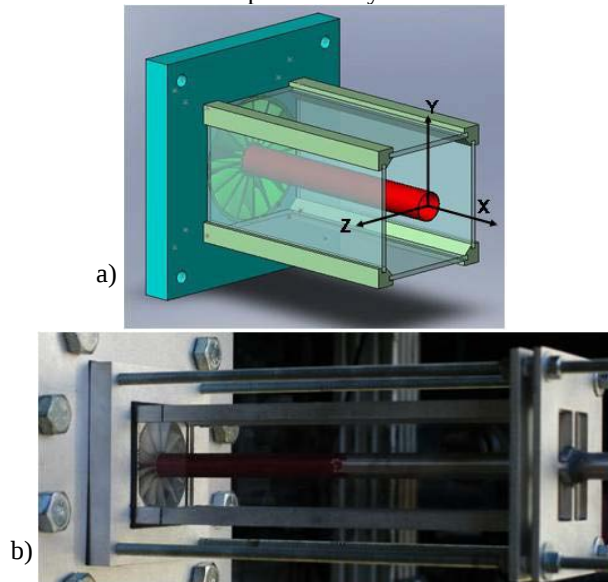


Figure 1. Test Chamber, a) Model, b) Test Chamber.

Experimental Setup

Test Chamber

The test chamber has a square cross-section with an internal dimension of 7.62 cm (3") and is 30.48 cm (12") long. The walls of the test chamber are constructed of 3.175 mm (1/8") thick acrylic material for maximum optical access. The walls are mounted on aluminum corner struts, which also provide a chamfer to suppress corner recirculation zones.

Figure 1a shows a model of the test chamber assembly and also indicates the coordinate frame of reference used for all analysis. Figure 1b shows the test chamber. The origin of the coordinate frame is located on the axis of the centerbody at the streamwise location of the center of the jet orifice. X-axis is aligned with the

streamwise direction, Y-axis points vertically upwards and Z-axis points to the left as viewed from downstream.

The test chamber assembly is mounted onto the Horizontal Rig, which is one of the experimental rigs available at the Combustion Diagnostics Research Laboratory at the University of Cincinnati's Center Hill Facility. The Horizontal Rig is a long pipe 15.24 cm (6") in diameter, and is equipped with a 72 kW inline air heater (not used for this study). A computer controlled 3-axis Lintech traverse is provided for precise positioning of diagnostic equipment. Air is provided from a Kaesar variable speed rotary compressor capable of maximum flow rate of 0.907 kg/s (2 lb/s) at a pressure of 7.9 bars (100 psig), connected to a dryer and tanks. A network of 10.16 cm (4") and 5.08 cm (2") diameter pipes connects the air tanks to the Horizontal Rig. Air flow rate is metered by a Micro Motion CMF300 coriolis flowmeter and controlled by a standard gate valve.

Jet injection is carried out through a centerbody, which protrudes from the swirler hub and extends through the length of the test chamber. The centerbody is a 1.91 cm (3/4") outer diameter stainless steel tube with wall thickness of 1.65 mm (0.065"). Thus the radius of the centerbody, $r_{cb} = 0.96$ cm. A water jet is injected from a 0.5 mm orifice located 2.54 cm (1") downstream of the swirler exit. The centerbody is aligned so that the jet orifice is centered on the Y-axis. Thus the coordinates of the center of the orifice are (0, r_{cb} , 0). The injected liquid is water, and is housed in a water tank. A nitrogen cylinder is used to pressurize the water tank, in order to drive the flow, as well as maintain a constant flow rate. The water flow rate is measured by a Micro Motion CMF010 coriolis flowmeter. A Parker metering valve is used for precise control of the water flow rate. Figure 2 shows a schematic of the experimental setup.

Swirlers

The axial swirlers used for the study were designed in-house and were fabricated by Rapid Prototyping SLA technology. The swirlers feature a hub diameter of 2.22 cm (0.875") and a tip diameter of 7.62 cm (3"). A 1.91 cm (3/4") diameter hole is provided in the hub to accommodate the centerbody. Three different swirlers were used, with vane exit angles of 30°, 45° and 60°.

The swirlers have a streamwise depth of 2.54 cm (1") with 12 vanes each for the 45° and 60° swirlers. To achieve reasonable solidity, the number of vanes was increased to 16 for the 30° swirler. The vanes were radial, and designed to provide a smooth transition from axial direction to the vane exit angle. Figure 3 shows a cutout of the 45° swirler design model as well as a fabricated swirler. All swirlers induce a swirl in the clockwise direction, as viewed from downstream.

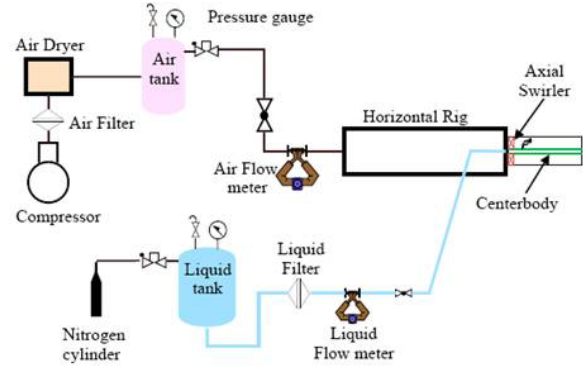


Figure 2. Schematic of Experimental Setup.

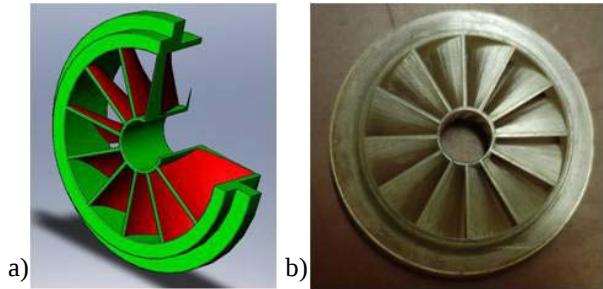


Figure 3. 45° Axial Swirler, a) Model, b) Swirler.

Measurement Techniques

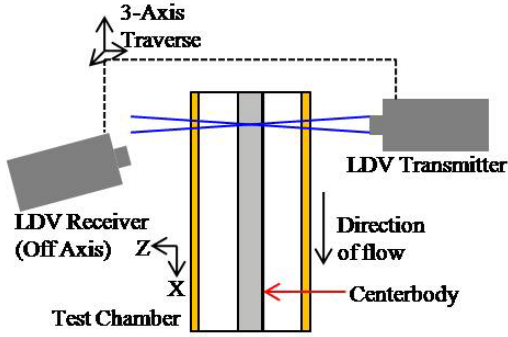
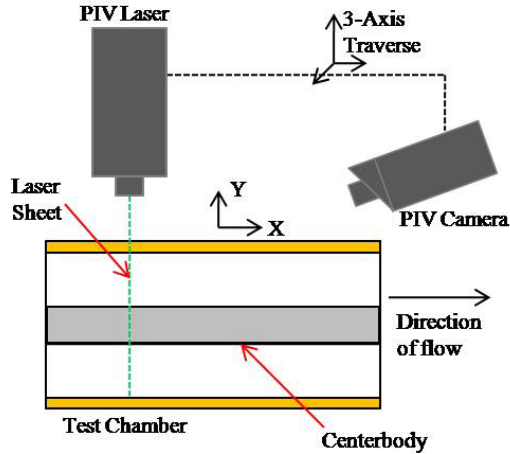
LDV measurements were conducted to characterize the crossflow. The equipment used for LDV measurements is the PDI-200 from Artium Inc. The PDI-200 series consists of a transmitter, a receiver, a power supply for the transmitter, and signal processing system. The special feature of the PDI-200 system is that the lasers are housed within the transmitter itself, so that there is no need for fiber optic systems, and the related alignment issues. The lasers used are Diode Pumped Solid State (DPSS) lasers, which do not require active cooling, and hence can be housed within a compact transmitter body. The PDI system was operated in LDV mode with forward scatter at an angle of 15°. The crossflow was seeded with olive oil droplets to enable measurement. For each test case, measurements were conducted in a cross-sectional plane 2.54 cm (1") downstream of the jet injection ($x = 2.54$ cm). Figure 4 shows a schematic of the setup for the LDV measurements.

2-D PIV was used for jet flow measurements. The PIV system is a LaVision commercial PIV system. A NewWave Solo PIV, double-pulsed Nd:YAG laser emits laser pulses at a wavelength of 532 nm with a maximum energy of 120 mJ/pulse. A LaVision Image Intense, double frame - double exposure CCD camera acquires images at the rate of 5 image pairs per second. A bandpass filter at 532 ± 3 nm is used to restrict the

Case no	Swirler	We	m_{cf} (kg/s)	U_x (m/s)	U_θ (m/s)	U (m/s)	ψ (deg)	$\psi = f(r)$	$\phi_{cf,20}$ (deg), $r = 20$ mm, $\Delta x = 20$ mm
C1	30	32.55	0.226	54.28	31.35	62.69	30	$\psi = 0.9721 \cdot r + 8.6$, $R^2 = 0.9883$	30.5
C2 (base)	45	33.91	0.222	50.67	38.95	63.91	37.5	$\psi = 1.2054 \cdot r + 9.7$, $R^2 = 0.5018$	38.4
C3	60	25.98	0.175	40.37	39.13	56.22	44.1	$\psi = 1.538 \cdot r + 11$, $R^2 = 0.9437$	51.2
C4	60	49.35	0.24	55.41	54.12	77.46	44.3	$\psi = 1.4937 \cdot r + 12.2$, $R^2 = 0.9234$	51.8

Table 1. Test conditions and relevant parameters for crossflow studies.

light absorbed to the laser wavelength. For more details on the PIV system, please refer to Elshamy [6].


Figure 4. Schematic of LDV Setup.

Figure 5. Schematic of PIV Setup.

PIV measurements were conducted in cross-sectional planes, i.e. parallel to the YZ plane ($x = \text{constant}$). Measurement was conducted over a range of $x = 0:25$ mm, with a spacing of 2.5 mm between measurement planes. Additionally, a few of the cases were repeated with measurements in streamwise planes, i.e. parallel to the XY plane ($z = \text{constant}$). The measured domain was $z = 0:-30$ with the planes separated by 2.5 mm.

The centerbody was coated with a fluorescent paint to reduce noise due to reflection. The paint converts about 30% of the green laser light into red fluorescent light, which gets blocked by the bandpass filter on the camera. Figure 5 shows the schematic of the PIV for measurement in the $x = \text{constant}$ planes.

Test conditions

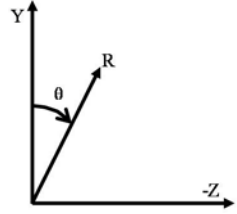
The 45° swirler was considered as the base swirler. Table 1 lists the test conditions used for crossflow studies. Table 2 lists the test conditions for jet measurements for cross-sectional ($x = \text{constant}$) as well as streamwise ($z = \text{constant}$) planes. The test cases for jets were designed so that the streamwise planes would repeat the test conditions for the cross-sectional planes. Thus cross-sectional and streamwise measurements for case J3 are represented by cases J3c and J3s respectively. The base cases for the crossflow and the jet are cases C2 and J3. The Weber number (We) and the momentum flux ratio (q) described in the test conditions were calculated based on total crossflow velocity, which was obtained from LDV results as explained in the results section. For water, a density of 996 kg/m³ and a surface tension of 0.0072 N/m have been assumed.

Results and Discussion

Note on Polar domain

Since the nature of the crossflow is axisymmetric, it was considered more useful to analyze the flow in a cylindrical domain. However, since all measurements are conducted in cartesian planes, the measured domains need to be transformed. The process occurs in a $x = \text{constant}$ plane, where (y, z) coordinates are transformed into (r, θ) coordinates (Figure 6). A new polar grid was created, and properties at the new grid points were obtained by interpolation. The polar grid, along with the X-axis, completes the cylindrical domain. Also, since the jet orifice is located on the 12 o'clock position on the centerbody, the circumferential coordinate is oriented such that $\theta = 0^\circ$ at the positive Y-axis and increases in the clockwise direction, as seen from downstream.

Case No	Swirler	We	q	m_{cf} (kg/s)	U_x (m/s)	U_θ (m/s)	U (m/s)	m_j (kg/min)	V (m/s)	Measurement Plane	r_p , $x = 20$ mm	$\phi_{p,20}$, (deg), $x = 20$ mm
J1c	30	106.16	9.42	0.401	99.59	57.5	114.99	0.141	12.02	cross-sectional	18.3	4
J2c	45	42.27	12.05	0.245	57.14	43.92	72.07	0.101	8.58	cross-sectional	16.3	6.5
J3c (base)	45	83.72	12.02	0.345	80.42	61.82	101.41	0.142	12.06	cross-sectional	19.3	6.5
J4c	45	83.72	24.01	0.345	80.42	61.82	101.43	0.2	17.05	cross-sectional	21.3	7.5
J5c	60	51.66	19.6	0.243	57.38	56.06	80.22	0.142	12.1	cross-sectional	20.3	9.3
J6c	30	106.16	18.94	0.401	99.59	57.5	114.99	0.2	17.05	cross-sectional	22.8	5
J7c	60	51.56	39.16	0.243	57.28	55.95	80.07	0.201	17.09	cross-sectional	26.3	11.3
J1s	30	106.35	9.4	0.401	99.77	57.6	115.21	0.141	12.02	streamwise	-	-
J2s	45	42.76	11.91	0.245	57.8	44.43	72.9	0.101	8.58	streamwise	-	-
J3s (base)	45	84.69	11.96	0.345	81.35	62.53	102.61	0.142	12.1	streamwise	-	-
J4s	45	84.69	23.84	0.345	81.35	62.53	102.61	0.2	17.09	streamwise	-	-
J5s	60	52.08	19.44	0.245	57.31	55.99	80.12	0.142	12.1	streamwise	-	-

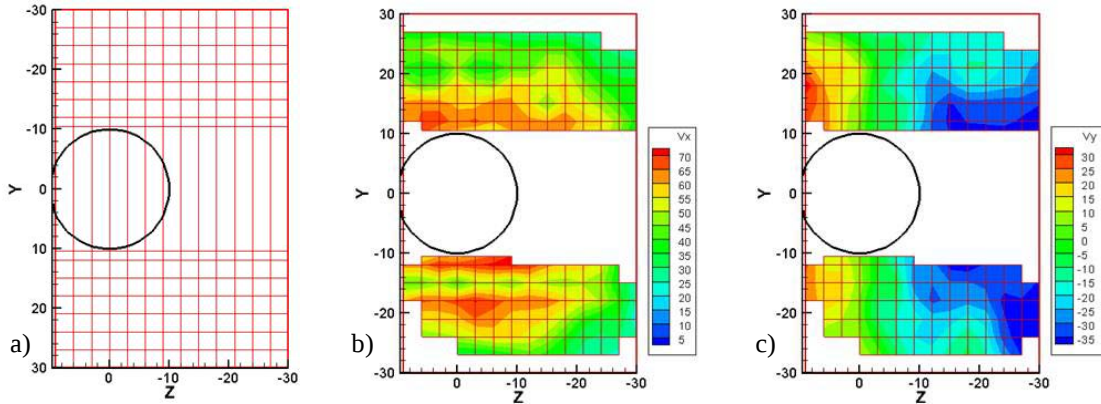
Table 2. Test conditions and relevant parameters for jet studies.

Figure 6. Transformation to Polar coordinates.

Now, if the data is contained within a cross-sectional plane, the properties at the locations of the new domain can be obtained by interpolation without any significant loss of information. However, for measurements in streamwise planes, a slice of the dataset at $x = \text{constant}$ contains data only at discrete locations. In this case, carrying out interpolations for the new polar

grid may omit significant information due to the incompleteness of data. In the previous report [12], intensity (Mie-Scattering) measurements along streamwise planes were converted into polar domain for penetration studies. While this yielded relatively good results in the radial direction, the circumferential coordinates clearly exhibited a lack of good resolution due to interpolation between measurement planes. To avoid this issue in this study, the conversion to cylindrical domain was conducted only for measurements in cross-sectional planes.

Crossflow Structure

It is important to characterize the crossflow in order to study its effects on the jets. This was achieved by conducting LDV measurements at the $x = 25.4$ mm


Figure 7. LDV results, Crossflow case C2 (45°, We = 33.91); a) Measurement grid, b) U_x contours, c) U_y contours.

plane. Figure 7a shows the measurement grid. Figures 7b and 7c show the contours of the streamwise (U_x) and the vertical (U_y) components of the velocity, respectively, for case C2, the base crossflow. Case C2 features the 45° swirler with $We = 33.91$. The centerbody is represented by the black circle in Figure 7. We observe that U_x is high near the centerbody, while the absolute magnitude of U_y is low near the Y-axis, but high near the Z-axis. U_y is negative in the right half plane due to the clockwise sense of rotation imparted by the swirler.

A polar grid was created, and the U_x and U_y components were mapped to the new grid by interpolation. Now, since the flow issuing from the swirler is axisymmetric, we can predict the z-component of the crossflow velocity, U_z , by rotating the domain by 90°. In this process, U_y at a location (r, θ) gets mapped to U_z at $(r, \theta \pm 90^\circ)$. Due to gaps in the LDV measurement, the circumferential extent of the region where both U_y and U_z are known is limited to $30^\circ \leq \theta \leq 60^\circ$. The total velocity, U was obtained as a vector sum of the three velocity components. Using trigonometric relations, U_y and U_z were transformed into polar velocity components, U_r and U_θ . A detailed description of this procedure is given in Tambe [13].

Figure 8 plots the variation of the total velocity, and its cylindrical components, with r for case C2. From Figure 8 we observe that both U_x and U_r decrease monotonically with r while U_θ initially increases with r though it starts decreasing at high r . The total crossflow velocity, U decreases monotonically with increasing r . The magnitude of U_r was observed to be very small compared to the other components, and will be neglected from further discussion.

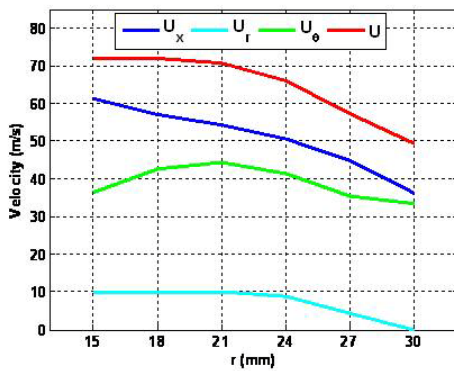


Figure 8. Total velocity and cylindrical velocity components for crossflow case C2 (45°, $We = 33.91$).

Figure 9 plots U_x and U_θ for cases C1- C4. The calculated We for cases C1 (30°), C2 (45°), C3 (60°) and C4 (60°) were 33, 34, 26 and 49 respectively. From Figure 9, we observe that as swirl angle increases, U_θ

increases while U_x decreases. As swirl angle increases, higher tangential momentum is imparted to the crossflow causing U_θ to increase. Now since We for cases C1 and C2 are almost equal, C2 will have smaller U_x in order to maintain the same total velocity. We note that U_θ for case C3 is slightly lower than that for case C2, though this occurs mainly because We of case C3 is less than that for case C2. Comparing the velocities for cases C3 and C4, we observe that increasing We leads to increase in both U_x and U_θ .

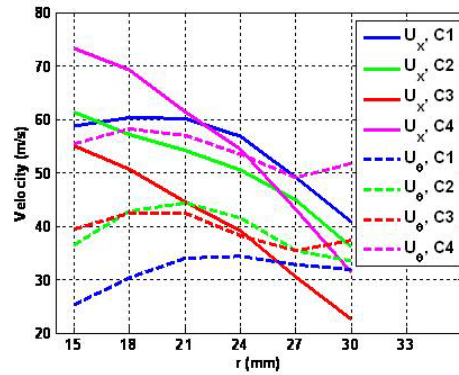


Figure 9. U_x and U_θ distributions for crossflow cases.

From the total and axial velocities, we can calculate the local flow angle, ψ , from equation 1. The flow angle is the angle made by the velocity vector with the streamwise direction (positive X-axis). Figure 10 plots the flow angles for cases C1- C4. For each swirler, the flow angle increases with r even though both U_x and U_θ decrease. Linear fits were obtained to describe the variation of ψ with r and have been included in Table 1. Mean ψ were determined based on mean U_x and U_θ and are also listed in Table 1. We observe that the mean ψ for the 30°, 45° and 60° swirlers are 30°, 37.5° and 44.3° respectively. Thus, only the 30° swirler generates enough flow turn from the crossflow. Thus, at the exit

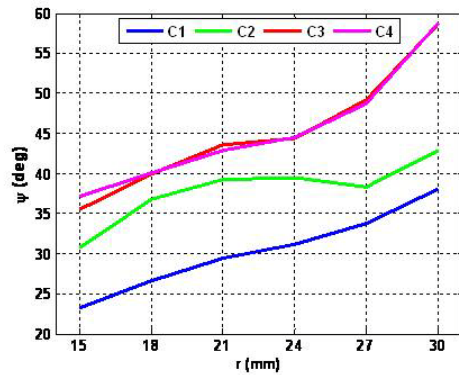


Figure 10. Flow angles (ψ) for crossflow cases.

of the swirler, the flow velocity is not tangent to the vanes, indicating that the 45° and 60° swirlers could not impart sufficient flow turn to the crossflow.

$$\psi = \tan^{-1}(U_\theta/U_x) \quad (1)$$

From Table 1 and Figure 10, we observe that We does not have any effect on the flow angle, ψ (Cases C3, C4). The only change is an increase in the magnitudes of the velocity components.

Another parameter of importance is the circumferential displacement (ϕ), which is the shift in the circumferential (θ) position of a particle for a given displacement in x . We have observed that the flow angle, ψ depends upon r . Then at any radius, ϕ for a given Δx will also depend upon r and can be calculated from equation 2. The magnitudes of $\phi_{cf,x}$ for cases C1-C4 at mean $r = 20$ mm and $\Delta x = 20$ mm have been calculated and are listed in Table 1. Thus for case C2, a particle located at $r = 20$ mm undergoes a circumferential displacement of 38.4° as it moves 20 mm downstream.

$$\phi_{cf,x} = (180/\pi r) \Delta x \cdot \tan \psi \quad (2)$$

Jet Measurements

The difficulty with studying jets in a swirling flow is that we do not know the trajectory of the jet. The path followed by the jet is curved, so that its cross-section is no longer parallel to the YZ plane. This was sought to be remedied by taking PIV measurements at several parallel planes and combining them together to create a 3-D measurement domain where we can re-create the jet plume. In the previous work [12], this was sought by conducting measurements in streamwise planes. However, as was shown earlier, when converting to cylindrical domain, interpolation occurs between measurement planes where no data is available. As a result, we are more likely to miss features of the jet that were present outside the measurement planes.

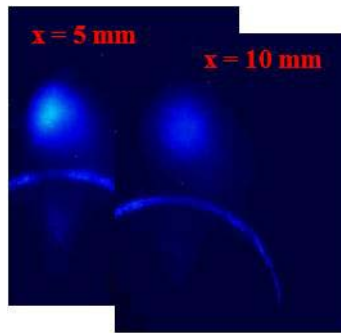


Figure 11. Mie-Scattering images for cross-sectional jet case J3c (45°, $We = 83.72$, $q = 12.02$).

To alleviate this problem, PIV measurements were conducted in cross-sectional ($x = \text{constant}$) planes. Then, all interpolations for the conversion to polar coordinates occur within the measurement plane, so that the risk of missing out on details of the jet is minimized. Additional tests were conducted with measurements in streamwise ($z = \text{constant}$) planes to match the test conditions of the cross-sectional planes cases. All these test conditions have been listed in Table 2.

Recreation of the Jet Plume

Case J3, with $We = 84$, $q = 12$ for the 45° swirler was considered as the base jet case. The corresponding case number for cross-sectional PIV is case J3c. We illustrate here the procedure for recreating the jet plume and obtaining the penetration for the jet.

From PIV results, we obtain an averaged Mie-Scattering image for each $x = \text{constant}$ plane (Figure 11). These can also be obtained as Tecplot data files, which are essentially intensity maps, i.e. they contain coordinate information with intensity values at these coordinates. A Matlab program was created to add the third (x) coordinate and combine all planes into a single data file. Additionally, the Mie-Scattering intensities in each measurement plane were normalized by the maximum intensity in that plane to provide comparable intensities across measured planes. Tecplot then renders this file as a 3-D plot of intensities, and can then be used to plot out the isosurfaces of the jet. An isosurface is the collection of all locations which have the same intensity value. The jet plume is thus represented by isosurfaces of the normalized Mie-Scattering intensity.

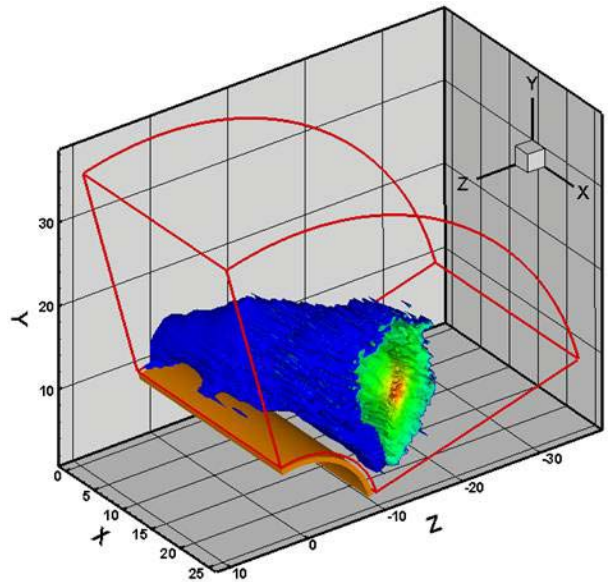


Figure 12. 3D Jet plume for case J3c (45°, $We = 83.72$, $q = 12.02$).

Jet Plume

Figure 12 shows the isosurfaces for the base jet, case J3c. Figures 13a, b, c show the projected views of the spray plume onto the XY , XZ , and YZ planes respectively. The edges of the cylindrical domain and the location of the centerbody are also illustrated in Figures 12 and 13. While the streamwise (x) momentum of the crossflow causes the jet to bend in the streamwise direction, the tangential (θ) momentum also induces a motion in the circumferential (θ) direction. Thus the trajectory of the jet is curved, forming an angle to the streamwise direction similar to the flow angle of the crossflow. This also means that the jet cross-section is at an angle to the measurement plane, causing its width to appear smaller. As a result, the shape of the jet plume appears to be elliptical (Figures 11, 12, 13c).

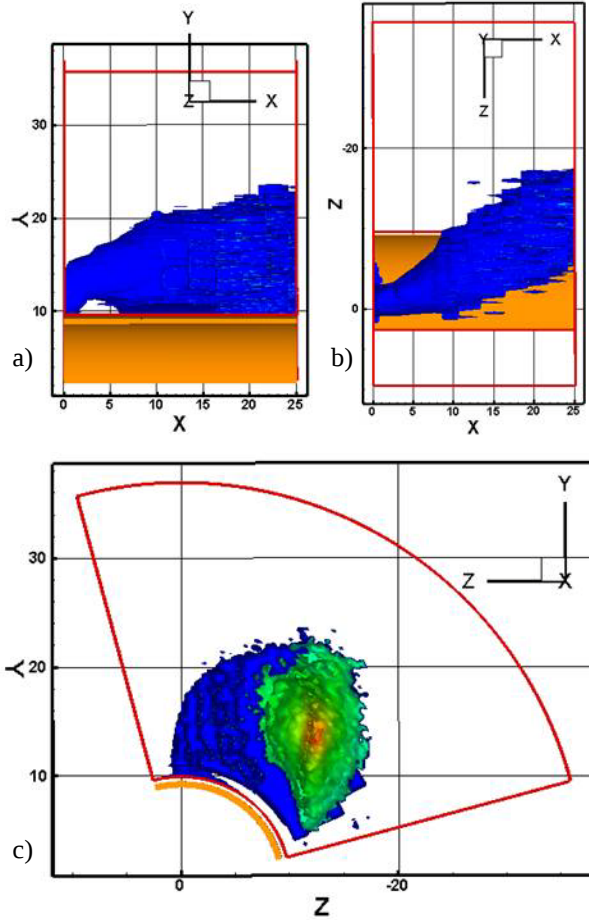


Figure 13. Projected views of spray plume for case J3c (45° , $We = 83.72$, $q = 12.02$), a) XY plane, b) XZ plane, c) YZ plane.

Detecting Jet Boundary

In order to detect the jet boundary, a threshold was applied to the Mie-Scattering images. The threshold was set at 10% of the maximum intensity of the plane, with all locations with higher intensity being considered

a part of the jet. A boundary detection algorithm was then used to trace the boundary of the jet plume at each measurement plane. From each boundary trace, 4 points were manually selected, marking the radial and circumferential extremities of the jet. The radial edges are the upper and lower edges of the jet while the circumferential edge on the advancing side is called the right edge and the other side is called the left edge, based on the appearance as viewed from downstream. Now, since the trajectory is three-dimensional, each edge location has r as well as θ coordinates. Both need to be taken into account while describing jet penetration.

Jet Penetration

We saw above that there are two dimensions to the jet trajectory, due to the presence of the radial and the circumferential coordinates of the edge.

To understand how this affects the jet, we first consider the case of a regular jet in crossflow, i.e. a jet injected transversely into a uniform crossflow. The aerodynamic forces exerted by the crossflow cause the jet to bend and it starts to move along the streamwise direction, so that the jet trajectory is aligned with the direction of the crossflow velocity. Note that this would still be valid if the streamwise direction (direction of crossflow velocity) was not aligned to any particular coordinate axis, i.e. if it had non-zero components along the X and Z axes. The jet trajectory would still be parallel to the direction of the crossflow velocity.

Now let us consider a simplified version of our crossflow in $R-\theta$ domain, assuming that U_x and U_θ do not vary with r . Due to axisymmetry, U_x and U_θ do not change with θ . Then, within this domain, the crossflow is similar to the previous example, and the jet trajectory would align with the direction of the crossflow velocity, i.e. it will have a flow angle equal to that of the crossflow. In this case, the jet trajectory has only one dimension, the radial height of the jet periphery, which can be referred to as the radial penetration (r_p). The circumferential coordinate, even though it exists, does not add any extra information about jet penetration and can be neglected under these conditions.

However, in the physical domain, a streamline of the crossflow is not a straight line, but follows a helical path. Thus the crossflow is subject to centripetal acceleration, which causes the streamline to curve in on itself, creating the helical nature of the streamline. Now, in addition to aerodynamic forces, tangent to the crossflow streamlines, the momentum of the jet also has to counter centripetal forces, directed radially inward. This has two effects. The first effect is an increase in radial penetration, akin to the effect of “centrifugal” forces. Secondly, this would also cause the jet trajectory to have a lower average flow angle as compared to the crossflow. This means that the circumferential displacement (ϕ) of the jet over a given streamwise displacement would be

lower than that of the crossflow. This difference in circumferential displacement is referred to as the circumferential penetration (ϕ_p).

Then, radial penetration (r_p) at any x -location is defined as the radial distance of the outer jet periphery from the surface of the centerbody. It is standard practice to scale the penetration by the jet diameter, d [1, 5, 6] to allow comparison across different datasets and different studies. Then r_p can be calculated as shown in equation 3.

$$r_p = (r - r_{cb})/d \quad (3)$$

The circumferential penetration ($\phi_{p,x}$) at any x -location is defined as the difference in the total circumferential displacements of the crossflow (ϕ_{cf}) and the jet (ϕ_j) over the streamwise range of $x = 0$ to the said x -location. $\phi_{p,x}$ can be obtained from equation 4, where ϕ for both jet and crossflow at $x = 0$ are assumed to be 0.

$$\phi_{p,x} = (\phi_{cf,x} - \phi_{cf,0}) - (\phi_{j,x} - \phi_{j,0}) = \phi_{cf,x} - \phi_{j,x} \quad (4)$$

Table 2 also lists r_p and $\phi_{p,x}$ for all the cross-sectional jet cases at $x = 40d$ (20 mm). For calculating ϕ_p , ϕ_{cf} was obtained based on ψ at $r = 20$ mm.

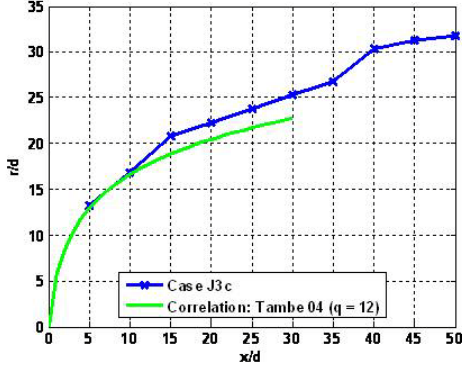


Figure 14. Radial penetration (r_p) for case J3c (45°, $We = 83.72$, $q = 12.02$).

Figure 14 shows radial penetration for the baseline jet, case J3c, and compares it to the penetration of an equivalent jet-in-uniform-crossflow ($q = 12$), obtained from the penetration correlation of Tambe [5]. We observe that in the near-field, the penetrations of both jets are similar. However as the jets move further downstream, the jet-in-swirling-crossflow continues to penetrate much higher as compared to the one from the correlation. As explained earlier, the jet in the current case experiences centrifugal acceleration, which might account for high radial penetration. Additionally, from Figure 9, we see that the crossflow velocity, U decreases with r . This creates a situation similar to the case in

Tambe et al [10], where crossflow velocity decreases with height. As the jet penetration increases, the aerodynamic force exerted by the crossflow decreases, allowing relatively higher incremental penetration as compared to a case with a constant crossflow velocity.

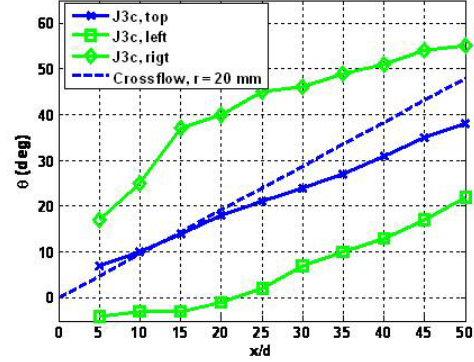


Figure 15. Circumferential progress of the jet, case J3c (45°, $We = 83.72$, $q = 12.02$).

We next consider the circumferential penetration of the jet. Figure 15 plots the circumferential (θ) coordinates of the top, left and right edges for the baseline jet case J3c. We observe that the top periphery is slightly closer to the left periphery as compared to the right; this occurs since the jet plane is at an angle to the measurement plane. Figure 15 also plots the circumferential progress of a particle in the crossflow located at a height of $r = 20$ mm. We observe that the circumferential displacement of the jet is indeed less than that of the crossflow, supporting the concept of circumferential penetration.

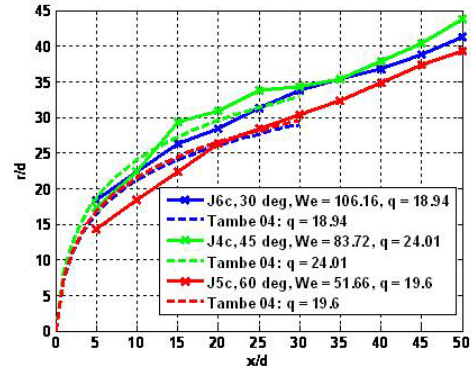


Figure 16. Effect of swirl angle on r_p .

We next study the effect of jet and crossflow parameters on jet penetration. Though not illustrated here, it was found that q affects only r_p , while We had no significant effect on penetration (Table 2). Here we consider the effect of swirl strength on radial penetration. Figure 16 plots the radial penetrations of cases J6c (30°), J4c (45°) and J5c (60°), along with the uniform

crossflow penetration correlations for the corresponding q values. We observe that the radial penetrations for all 3 cases are very close to the predicted penetrations from the correlation in the near region. However, beyond the initial region, the penetration for case J6c (30°) seems to be the highest, and is nearly equal to that for case J4c (45°), even though q for J4c is higher. An explanation for this could be that as swirler angle increases, more tangential momentum is imparted to the jet, causing reduced resistance in the radial direction, leading to lower penetration. From Figure 17, which plots the circumferential displacements for the same cases, we observe that the circumferential displacements do increase with swirl angle, thus supporting the previous claim. Figure 17 also plots the circumferential displacements of the crossflow. We observe that even though the circumferential displacement of the jets increase, the circumferential penetrations also increase with an increase in the swirl angle.

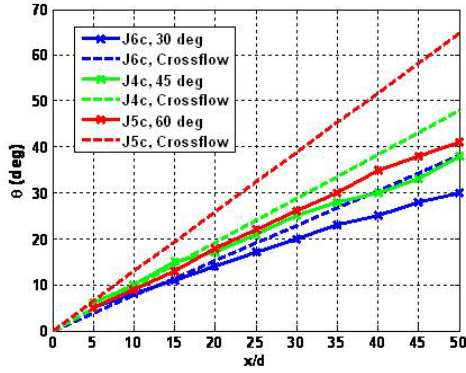


Figure 17. Effect of swirl angle on circumferential progress of jets.

Jet Velocities

For droplet velocities of the jet, we first consider the results from PIV measurements in the cross-sectional ($x = \text{constant}$) planes. Test conditions have been listed in Table 2. We select the baseline jet, case J3c for detailed analysis. Figure 18 shows PIV results for case J3c at two measurement planes, $x = 5, 10$ mm. The results from the different planes were collated in a manner similar to the Mie-Scattering images. Additionally, the measurement domain was converted into cylindrical domain, and the cartesian velocity components (V_y, V_z), were converted to polar velocities (V_r, V_θ).

Figure 19 shows the velocity vectors for case J3c at streamwise locations of 5, 10, 15 and 20 mm downstream of the nozzle. We can clearly observe the spread of the spray plume as the jet moves downstream. One of the surprising features of the jet is that most of the velocity seems to be directed in the tangential direction, even though we know that the jet grows in the radial as

well as the tangential direction. To understand this more clearly, we take a closer look at the radial (V_r) and the tangential (V_θ) velocity components for case J3c. Figures 20 and 21 plot V_r and V_θ respectively, at the same locations as Figure 19. From Figure 20, we observe a zone of positive V_r at the upper and upper-right portion of the plume, and a negative V_r region towards the bottom and bottom left. This accounts for the spread of the jet in the radial direction. From Figure 21, we observe high V_θ in the right half of the jet plume, while the left half has low, positive V_θ . This shows that the entire jet plume experiences positive circumferential displacement, and that it is also expanding in the tangential direction. We note here that the highest V_θ was approximately 63 m/s, while the average tangential velocity of the crossflow, U_θ was 62 m/s (Table 2, case C2). Thus, even though the jet plume moves circumferentially, the rate of circumferential displacement is lower than that of the crossflow, thereby reinforcing the concept of circumferential penetration.

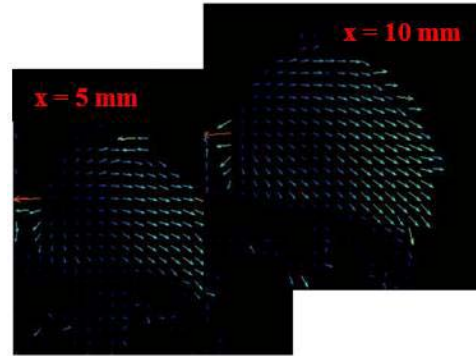


Figure 18. PIV results for cross-sectional planes, jet case J3c (45°, $We = 83.72$, $q = 12.02$).

Next, we consider the results from PIV measurements in the streamwise ($z = \text{constant}$) planes. The test conditions have been listed in Table 2. The test conditions were designed to be equivalent to the cases for cross-sectional measurement, and hence have similar case numbers, with the last letter 'c' being replaced by 's' to denote streamwise plane measurements. Thus the baseline jet for streamwise plane PIV is case J3s. The measurement domain for streamwise planes is the top right quarter of the test chamber, i.e. $z < 0, y > 0$ (Figure 1a). Figure 22 shows the PIV results for case J4s at two planes located at $z = -5, -10$ mm.

The velocity components in the streamwise plane (V_x, V_y) can be collated in a manner similar to the cross-sectional components to form a three-dimensional measurement domain. Figure 23 shows the velocity vector distribution at $z = -5, -10$ mm along with the location of the centerbody, which is visible at $z = -5$ mm. However, since V_z is not known, we cannot obtain polar velocity components for this data.

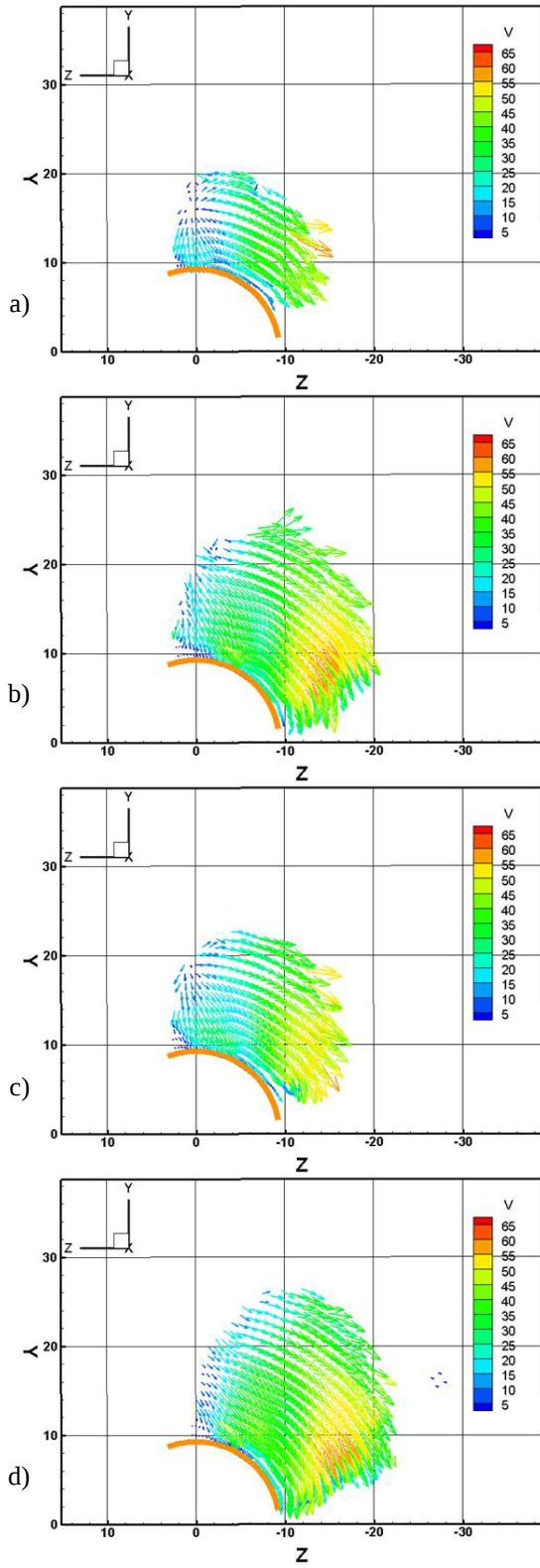


Figure 19. Droplet velocity distribution for case J3c (45° , $We = 83.72$, $q = 12.02$), a) $x = 5$ mm, b) $x = 10$ mm, c) $x = 15$ mm, d) $x = 20$ mm.

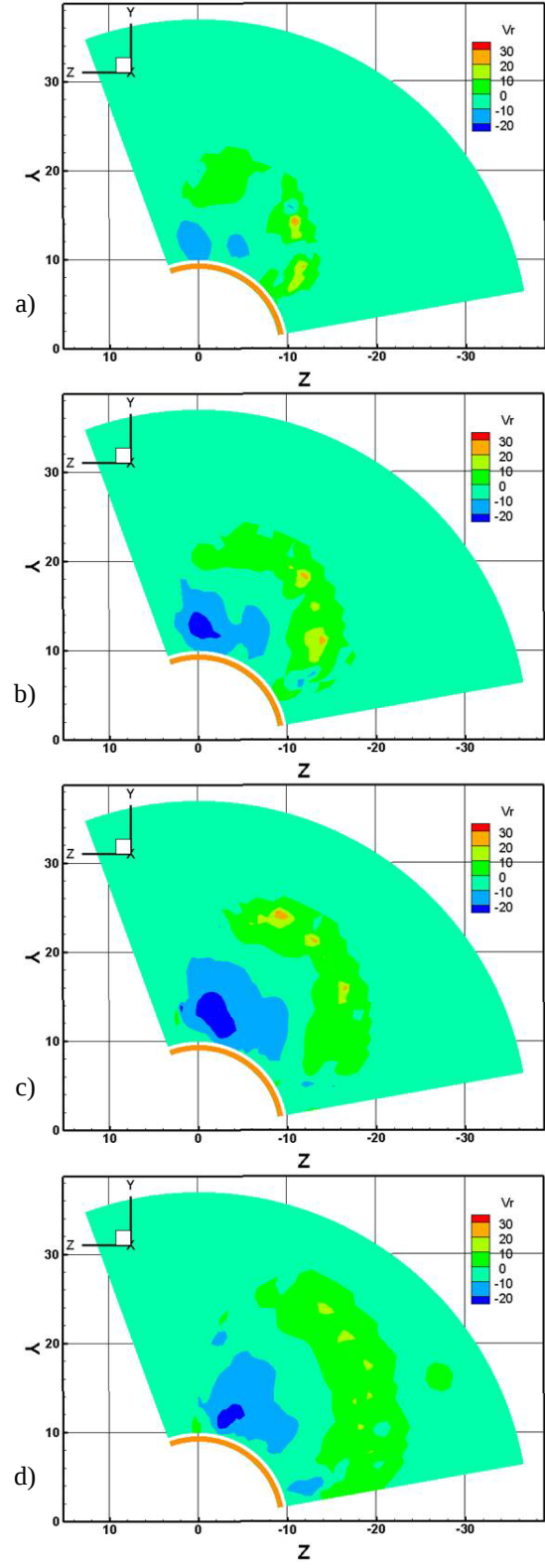


Figure 20. V_r distribution for case J3c (45° , $We = 83.72$, $q = 12.02$), a) $x = 5$ mm, b) $x = 10$ mm, c) $x = 15$ mm, d) $x = 20$ mm.

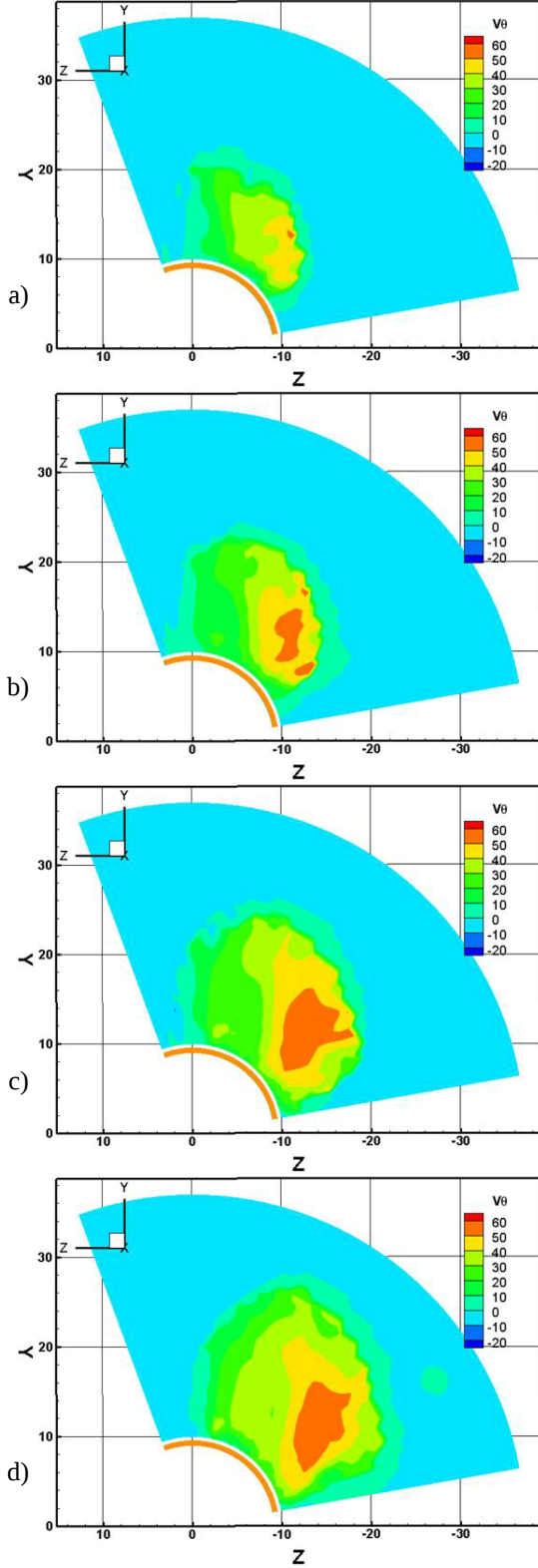


Figure 21. V_θ distribution for case J3c (45° , $We = 83.72$, $q = 12.02$), a) $x = 5$ mm, b) $x = 10$ mm, c) $x = 15$ mm, d) $x = 20$ mm.

Three-Dimensional Velocity Distribution

Since the test conditions for the measurements for the cross-sectional and streamwise planes were equivalent, it allows us to merge the two datasets. A 3D cartesian grid was defined, ensuring that it was coarser than the two measured domains to ensure smoother interpolation of data. Both datasets have a vertical velocity component, V_y . Upon comparing V_y for the two sets of data, it was observed that the magnitude of V_y for the streamwise planes was consistently higher than that for

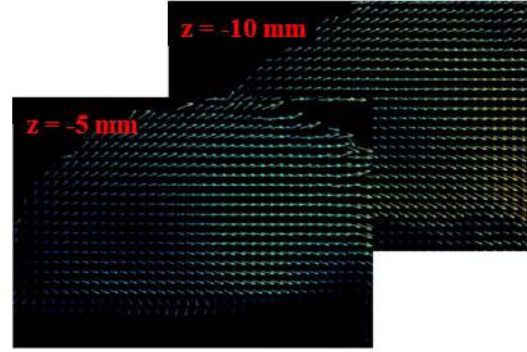


Figure 22. PIV results for streamwise planes, jet case J3s (45° , $We = 84.69$, $q = 11.96$).

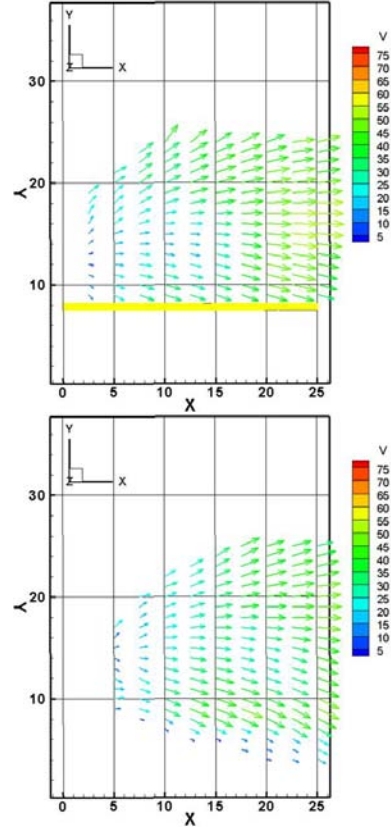


Figure 23. Droplet velocity distribution for case J3s (45° , $We = 84.69$, $q = 11.96$), a) $z = -5$ mm, b) $z = -10$ mm.

the cross-sectional planes, though the difference was not large [13]. The magnitude of final V_y was chosen to be the average of the magnitudes from the two data sets. V_x values were selected from the streamwise plane data and V_z values were selected from the cross-sectional planes. Figure 24 shows the three-dimensional velocity vectors for case J3, the baseline jet.

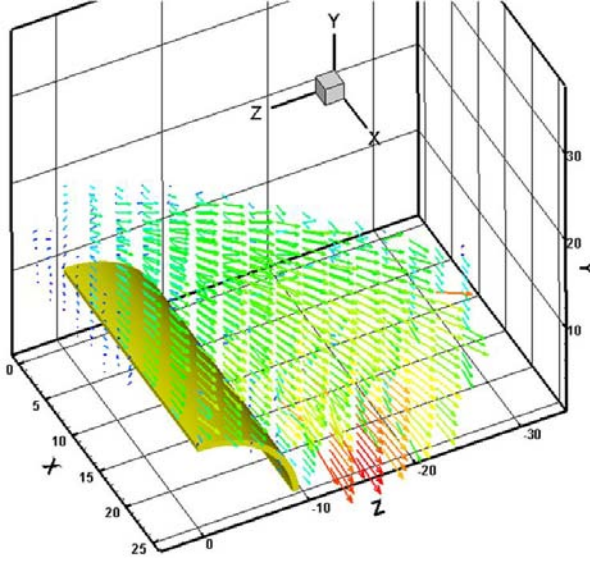


Figure 24. 3D droplet velocity vectors for combined jet J3 (45° , $We \cong 84$, $q \cong 12$).

The V_y and V_z components were then used to calculate the polar velocity components V_r and V_θ . We now study the evolution of the three cylindrical velocity components. Figure 25 shows contours of V_x for case J3 at $x = 5, 10, 15$ and 20 mm. We observe a low velocity region in the center surrounded by higher velocities on the side. This is similar to the typical axial velocity distribution for jets in a uniform crossflow [5], where the low velocity region represents the spray core. As the jet proceeds downstream, magnitudes of V_x increase, due to additional interaction with the crossflow.

Figure 26 shows the evolution of the radial component (V_r) of the velocity, by plotting the contours of V_r at $x = 5, 10, 15$ and 20 mm. The radial velocity distribution is similar to that observed for case J3c, with positive V_r at the upper periphery and negative V_r at the lower periphery of the jet. Also, we can observe that the magnitude of V_r at the upper periphery decreases with x , indicating that the tendency for incremental penetration of the jet decreases as the jet penetrates further into the crossflow.

Figure 27 plots contours of the tangential velocity, V_θ at $x = 5, 10, 15$ and 20 mm. The tangential velocity contours are also similar to that for the cross-sectional case J3c, with higher V_θ at the advancing side, and lower V_θ at the receding side.

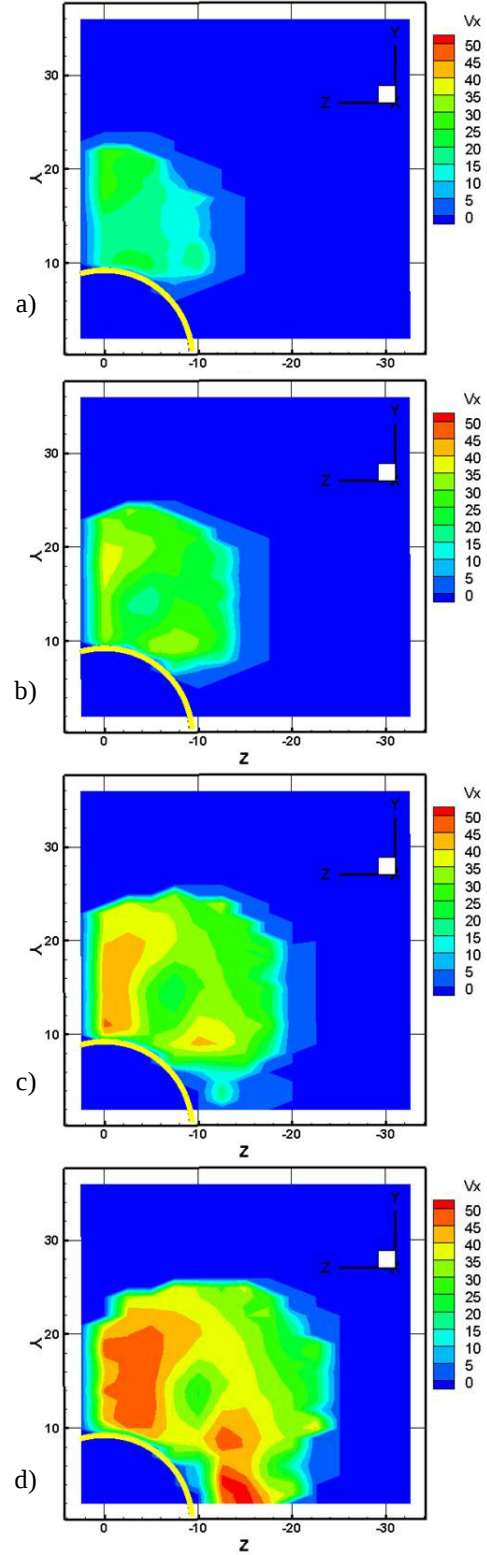


Figure 25. V_x distribution for combined jet J3 (45° , $We \cong 84$, $q \cong 12$), a) $x = 5$ mm, b) $x = 10$ mm, c) $x = 15$ mm, d) $x = 20$ mm.

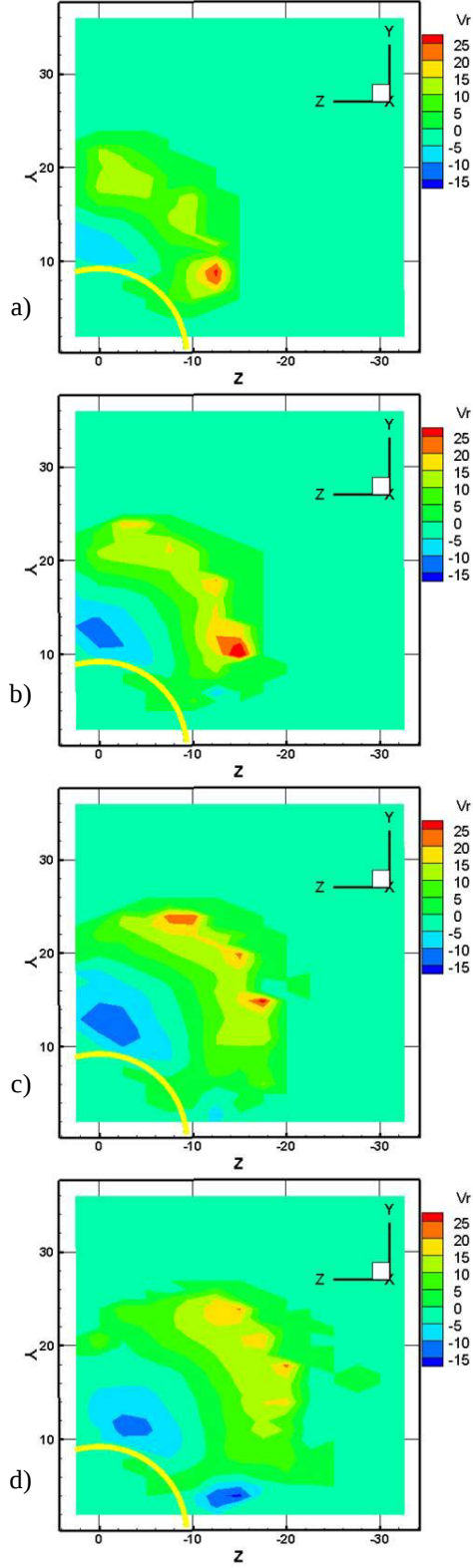


Figure 26. V_r distribution for combined jet J3 (45° , $We \cong 84$, $q \cong 12$), a) $x = 5$ mm, b) $x = 10$ mm, c) $x = 15$ mm, d) $x = 20$ mm.

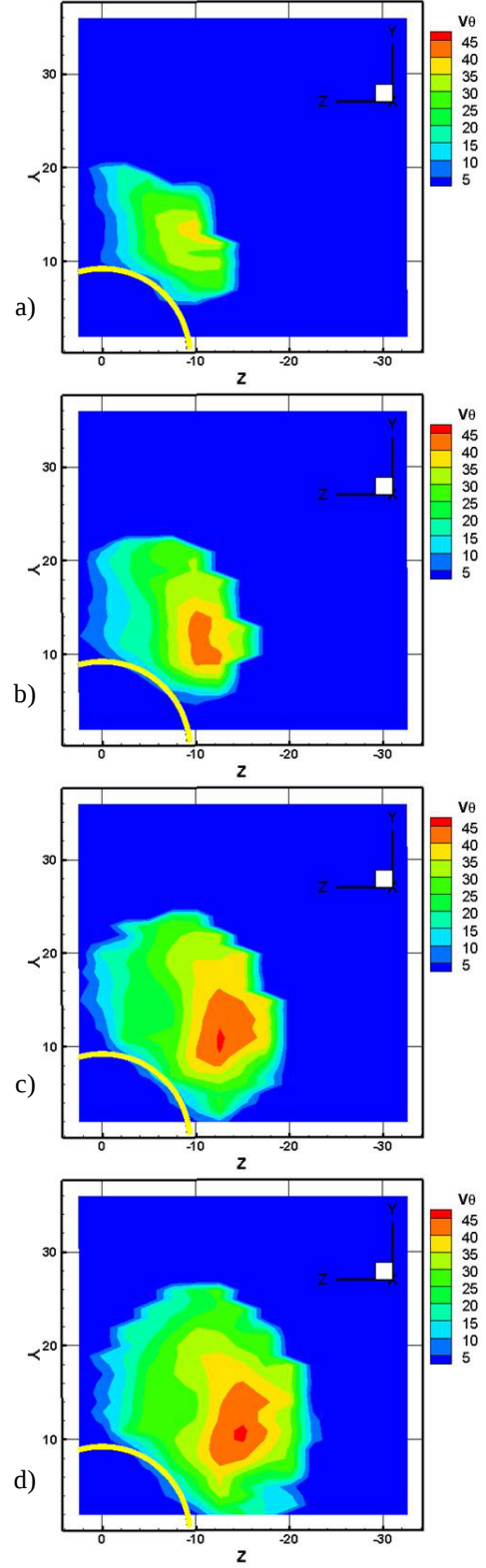


Figure 27. V_θ distribution for combined jet J3 (45° , $We \cong 84$, $q \cong 12$), a) $x = 5$ mm, b) $x = 10$ mm, c) $x = 15$ mm, d) $x = 20$ mm.

Conclusions

We have studied liquid jets injected into a swirling crossflow. The crossflow was non-recirculating, with both axial and tangential velocities decreasing with radius. We studied the jet penetration and observed that the penetration needs to be separated into radial and circumferential penetration to completely describe the jet trajectory. PIV velocity measurements were conducted in cross-sectional as well as streamwise planes, and the velocities were combined to generate a 3-D velocity distribution.

Nomenclature

d	jet diameter
m	mass flow rate
q	momentum flux ratio
r	radial coordinate
x	streamwise coordinate
y	vertical coordinate
z	lateral coordinate
R	radial axis
U	crossflow velocity
V	droplet velocity
X	streamwise axis
Y	vertical axis
Z	lateral axis
We	aerodynamic weber number
ϕ	circumferential displacement
θ	circumferential coordinate
ψ	flow angle
Θ	circumferential axis
Subscripts	
cf	crossflow
j	jet
r	radial component
x	streamwise component
y	vertical component
z	lateral component
θ	circumferential (tangential) component

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