

A Study on the Effects of Cavitation and Orifice Geometry on Liquid Jets in Crossflow Using Laser Diagnostics

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Keywords: Liquid Jet in Crossflow, Cavitation, Interfacial Velocity, Optical Connectivity, Optical Flow Velocimetry, Droplet Sizing.

ABSTRACT

Injecting a liquid jet into a high-speed air crossflow, known as a liquid jet in crossflow (LJIC), causes the jet to break up into a cloud of fine droplets. LJIC systems have been widely used in applications such as agricultural spraying and combustion systems because the breakup length and droplet distribution can be controlled by adjusting the liquid and gas momentum ratios. Owing to these advantages, LJIC is attracting increasing interest, particularly for aircraft combustion systems. However, several key issues must be understood to fully control spray performance. First, as in most fuel-injection systems, cavitation may occur inside the nozzle before the liquid is discharged. Cavitation can lead to unpredictable jet-breakup behavior and may damage the nozzle due to bubble collapse. Direct observation of cavitation inside the nozzle is extremely difficult, and its corresponding intensity is challenging to evaluate. Therefore, it is important to develop a method that can evaluate cavitation intensity from LJIC features measured outside the nozzle. Moreover, almost all existing LJIC studies have focused on round-orifice nozzles. It is therefore of interest to investigate how LJIC breakup characteristics change when the orifice geometry is modified. In this study, we applied the OC-OFV method, which combines the Optical Connectivity (OC) and Optical Flow Velocimetry (OFV) techniques, to quantify the interfacial velocity of the LJIC. The results show that features of the measured interfacial velocity can serve as indicators of cavitation intensity inside the nozzle. Additionally, we investigated the effect of orifice geometry by comparing liquid jets issued from round and flat orifices using shadowgraphy, while near-nozzle droplet sizes were measured using planar laser-induced fluorescence (PLIF). The results demonstrate that liquid sheets from the flat orifice exhibit more pronounced bending and a different near-nozzle droplet-size distribution compared with the round-orifice case.

1. Introduction

Atomization systems, which break a continuous liquid jet into a cloud of fine droplets, have been widely used in applications such as inkjet printing, combustion systems, agricultural spraying, and coating processes, depending on the required performance [1-15]. Among various atomization methods, air-blast atomization uses high-speed air flow to shear and disintegrate the liquid jet. A particular form of air-blast atomization - the liquid jet in crossflow (LJIC), where a liquid jet is injected into a perpendicular air stream, has attracted increasing attention in liquid-fuel atomization systems. LJIC offers enhanced control over jet penetration and downstream droplet

distribution within combustors, which can improve combustion efficiency and reduce pollutant emissions [4, 8, 16-20].

However, to fully exploit the advantages of LJIC, several key issues still require investigation. For instance, as in many atomization systems, cavitation may occur inside the injection nozzle due to the rapid acceleration of the liquid around sharp inlet corners. Apart from the potential nozzle damage induced by cavitation, it has been shown that cavitation inside a nozzle, depending on its intensity, can significantly alter the geometry of the emerging liquid jet and consequently affect the downstream droplet size distribution [21-25]. In practical applications, it is difficult to determine whether cavitation has occurred or is contributing to nozzle damage. This highlights the need for a method that can measure specific features of the injected liquid jet which indirectly indicate both the presence and the intensity of cavitation within the nozzle.

Wang and Hardalupas [26, 27] combined Optical Connectivity (OC) and Optical Flow Velocimetry (OFV) as OC-OFV to measure detailed interfacial velocities on the surface of an injected liquid jet. OC introduces a laser beam through the continuous liquid jet and illuminates the jet interface based on local deformation. OFV then tracks the surface structures of the jet and computes the velocity field on the liquid-air interface. When cavitation occurs, vapour bubbles inside the nozzle may reduce the effective orifice cross-section, particularly when hydraulic flip takes place. This contraction changes the behaviour of the exiting jet, for example, by accelerating the flow, and these changes are reflected in the interfacial velocity field. Therefore, it is of interest to investigate whether OC-OFV measurements of interfacial velocity can be used to evaluate the onset and intensity of cavitation inside the nozzle during liquid ejection.

In addition, the effect of nozzle-orifice geometry remains an open question. No conclusion has been set on which orifice shape yields the best performance, and modifying the orifice geometry may offer an additional degree of control over LJIC behaviour [28-31]. Most LJIC system designs employ a circular micro-orifice that produces a cylindrical liquid jet injected into high-speed airflow. It is worth exploring whether a liquid sheet issued from a flat orifice would alter atomisation characteristics such as jet penetration and resulting droplet size. For the same injected liquid volume, a sheet formed from a flat nozzle may be thinner, more prone to breakup, and capable of generating smaller droplets [28-30]. Hence, it is also necessary to investigate the breakup behaviour of LJIC using nozzles with different orifice geometries.

In the present study, the effect of cavitation inside the nozzle on the behaviour of a liquid jet in crossflow (LJIC) is investigated. The OC-OFV technique is employed to quantify the interfacial velocity of the LJIC under different levels of cavitation within the nozzle. The resulting interfacial

velocity features are shown to serve as indicators of both the occurrence and the intensity of cavitation.

In addition, the breakup characteristics of LJIC issued from a nozzle with a flat orifice are examined and compared with those from a round-orifice nozzle. Shadowgraphy is used to capture the jet trajectory and breakup behaviour, while Planar Laser-Induced Fluorescence (PLIF) is applied to measure the near-nozzle droplet size distribution. Section 2 in current manuscript describes the experimental setup and operating conditions for both parts of the study. Section 3 presents the OC-OFV results for LJIC under cavitating conditions. Section 4 discusses the differences in breakup characteristics associated with the two nozzle geometries. Section 5 summarises the conclusions and outlines future work.

2.Experimental arrangement and operating conditions

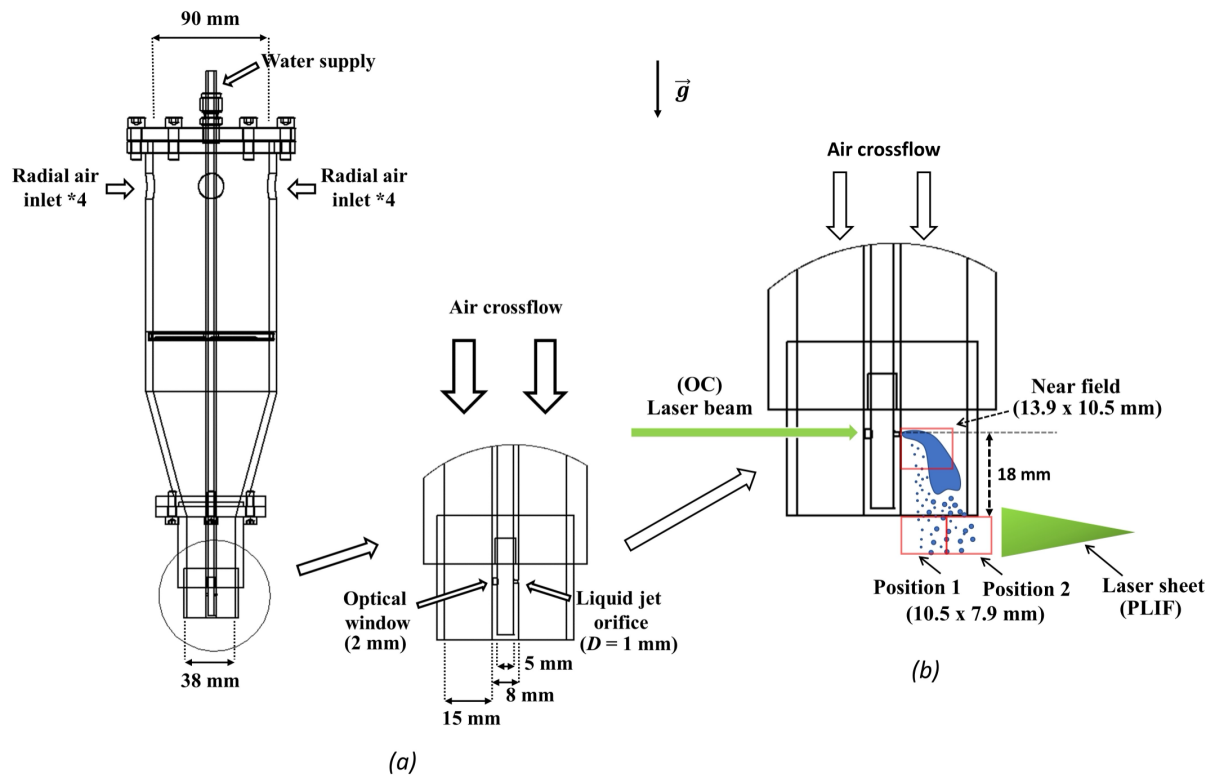


Figure 1: (a) Schematic of the atomiser, showing a liquid jet exposed to a crossflow of air. The detail in the bottom right shows the design of the liquid-jet nozzle exit and the optical window that allows the laser beam to enter the liquid jet. (b) Schematic of the optical experiment. The laser beam is introduced through the optical window for OC.

A laser sheet is used to illuminate the downstream droplet cloud for droplet sizing at positions 1 and 2.

The gas crossflow atomiser which is specifically designed for operating Optical Connectivity (OC) is presented in Figure 1(a), while the atomiser also allows the application of shadowgraphy technique. The main body of the atomiser was set vertically and mounted with four radial inlets

at the far end of a cylindrical plenum chamber to deliver the axial gas flow toward the nozzle after flowing through a mounted straightener which is applied to prevent the generation of turbulence in the gas flow, the detailed description of the atomiser can refer to [3]. The cylindrical chamber was closed at the far end by a plate and, at the other side, was connected to a conical contraction with 38 mm exit diameter to accelerate the gas flow. The contraction ended in a straight nozzle and connected with an extending straight glass tube, which was used to confine the gas flow from the contraction. Moreover, the glass tube allows the light source for both OC and shadowgraphy techniques to illuminate the gas and liquid flow. Within the length of the glass tube, the atomisation of the liquid jet takes place within a surrounding air crossflow with a constant velocity.

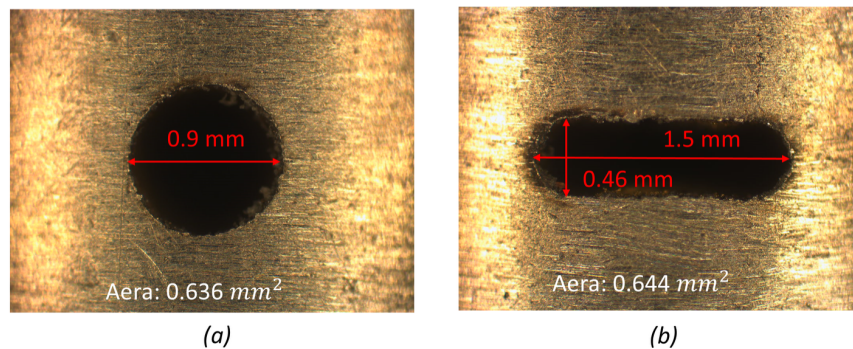


Figure 2: The orifice geometries of the nozzles used to compare the breakup characteristics of liquid jet and sheet in crossflow: (a) a round orifice with a diameter of 0.9 mm; (b) a flat orifice with a length of 1.5 mm and a height of 0.46 mm.

The liquid was supplied through a long straight stainless-steel tube of circular cross-section with 5 mm internal and 8 mm external diameter. In order to apply both OC and PLIF in this study, the Rhodamine B was also mixed in the supplied water with concentration of 5×10^{-7} mol/L. The delivering tube was supported along the centreline of the atomiser main body and was connected to the liquid supply at one end. For the cavitation study, the other end of the delivering tube was closed and a circular hole with diameter of 1 mm was drilled at the side of the tube normal to its centreline at the start of the transparent glass tube (more detail in Figure 1(a)). With this design, a liquid jet can be injected normally to the gas flow within the bounds of the transparent glass tube, which allows the study for LJIC. For the implementation of OC, an optical window with 2 mm diameter was placed on the liquid-delivering tube right opposite of the liquid exit, as shown in the detail at the bottom right of Figure 1. Owing to the transparent glass tube which provided direct optical access to the optical window at the back of the liquid injection orifice, a laser beam can be directed into the liquid jet for applying OC, as shown in Figure 1(b). By applying OC, the

interfacial structures and the breakup length of the liquid jet can be observed within the near-field observation region with size of 13.9×10.5 mm.

To investigate the breakup characteristics of LJIC under different orifice geometries, two nozzles were manufactured. Figure 2(a) and (b) show the microscopic images of the two orifices. Figure 2(a) corresponds to a round orifice with a diameter of 0.9 mm, while Figure 2(b) presents a flat orifice with a length of 1.5 mm and a height of 0.46 mm. The areas of the two orifices are comparable, ensuring that both nozzles eject nearly the same liquid volume over a given time period. PLIF was applied to quantify the downstream droplet sizes near the nozzle. The laser beam was shaped into a sheet with a height of 20 mm and a thickness of 1 mm, and was introduced along the central line of the spray core to excite fluorescence from droplets located at Positions 1 and 2, as shown in Figure 1(b). Position 1 was located 18 mm below the centre of the nozzle orifice and adjacent to the nozzle wall, while Position 2 was positioned next to Position 1 at the same height. The observation region for both positions measured approximately 10.5×7.9 mm. In addition, for both the cavitation and orifice geometry studies, shadowgraphy was employed to observe the jet trajectory and breakup features using a back-illuminated LED light source through the transparent glass tube. The field of view (FOV) of the shadowgraphic images is described in the corresponding section.

A double-pulse nanosecond Nd:YAG laser (Nano PIV) was used as the light source for both OC and PLIF. The laser operated at 532 nm with a pulse duration of 4 ns, a pulse energy of 140 mJ, and a beam diameter of 6 mm. Images of OC, PLIF and shadowgraphic were all captured using a PCO Sensicam QE inter-frame CCD camera (12-bit, 1040×1376 pixels) fitted with a SIGMA 105 mm f/2.8 lens. Since Rhodamine B dissolved in water absorbs 532 nm laser light and emits fluorescence with a peak wavelength of approximately 575 nm at room temperature [32], a Schott OG 550 long-pass filter was mounted in front of the lens to block the green excitation light and other unwanted wavelengths for OC and PLIC measurement.

Several non-dimensional parameters can affect the characteristics of the crossflow atomisation, such as breakup regimes, droplet size distribution and liquid breakup length [10, 33-35]. The considered non-dimensional parameters of the current study include $We_G = \rho_G U_G^2 D / \sigma$, $M = \rho_L U_L^2 / \rho_G V_G^2$, $Re_G = \rho_G V_G D / \mu_G$, $Re_L = \rho_L U_L D / \mu_L$, $Oh = \mu_L / \sqrt{\rho_L D \sigma}$, since these parameters have been reported to affect or determine the breakup features of the LJIC [10, 17, 34, 36-40]. The parameters are defined with the diameter of the injection orifice D , density of crossflow gas ρ_G , density of injected liquid ρ_L , liquid and gas viscosity μ_L and μ_G , and liquid surface tension σ which are constant in the present study. Water and air were used as the supplied liquid and gas, and their relevant properties are listed in Table 1.

Here, we use the liquid breakup regime map suggested by Sallam *et.al* [34]. Six gas flowrates, shown in Table 2, are considered in the current study of cavitation. The air velocity for all six cases is fixed at 92 m/s, which places all cases in the shear breakup regime ($We_G > 110$) [17, 34]. In this regime, the breakup is dominated by shear forces acting around the liquid jet, generating small droplet sizes downstream, which is of particular interest for combustion applications. Moreover, the liquid jet trajectory, maximum penetration length, and, most importantly, the cavitation intensity inside the nozzle is mainly influenced by the liquid jet velocity U_L and the relevant momentum flux ratio M . Hence, from Case 1 to Case 5, the liquid jet velocity U_L is gradually increased to study the breakup characteristics under different cavitation intensities. Additionally, due to the uncertainty and sensitivity of cavitation, different cavitation intensities may occur even under the same liquid velocity. Case 6 and Case 5 have the same liquid and air conditions, but hydraulic flip occurs in Case 6; this case is therefore studied to examine the differences in breakup characteristics when supercavitation occurs. Table 2 lists the non-dimensional parameters of the considered flow conditions.

For the study of different orifice geometries, nozzles with varying orifice shapes but the same cross-sectional area, as shown in Figure 2, were tested under the same flow conditions listed in Table 3. For the nozzle with a flat orifice, the characteristic length D used for calculating non-dimensional numbers is set to 0.9 mm, the same as for the circular orifice. Similar to the study focusing on cavitation within the nozzle, all flow cases fall within the shear breakup regime, with an air velocity of 92 m/s. From flow Case 1 to Case 3, the liquid flow velocity is gradually increased to investigate how the breakup features vary with different momentum ratios M . To minimise the effect of cavitation, the liquid flow rates in this study are lower than those used in the cavitation study, thereby reducing the influence of cavitation on the breakup characteristics.

Table 1: Properties of experimental fluid

$\rho_G(\text{kg/m}^3)$	$\rho_L(\text{kg/m}^3)$	$\mu_L(\text{pa} \cdot \text{s})$	$\mu_G(\text{pa} \cdot \text{s})$	$\sigma(\text{N/m})$
1.225	997	8.90×10^{-4}	1.85×10^{-5}	7.28×10^{-2}

Table 2: Non-dimensional parameters and breakup regime of the considered flow cases for cavitation study.

Flow Case	U_L (m/s)	V_G (m/s)	We_G	M	Re_G	Re_L	Oh	Breakup Regime
1	6.4	92	142.6	3.9	6092	7126	3.3×10^{-3}	Shear
2	8.5	92	142.6	6.9		9522		Shear
3	10.6	92	142.6	10.8		11874		Shear
4	12.7	92	142.6	15.6		14227		Shear
5	14.8	92	142.6	21.2		16648		Shear
6*	14.8	92	142.6	21.2		16648		Shear

Table 3: Non-dimensional parameters and breakup regime of the considered flow cases for orifice geometry study

<i>Flow Case</i>	<i>U_L (m/s)</i>	<i>V_G (m/s)</i>	<i>We_G</i>	<i>M</i>	<i>Re_G</i>	<i>Re_L</i>	<i>Oh</i>	<i>Breakup Regime</i>
1	5.2	92	132.6	2.6	5577	5285	3.5×10^{-3}	Shear
2	7.9	92	132.6	5.8		7928		Shear
3	10.6	92	132.6	10.8		11874		Shear

3.Results

In this section, the results from different studies are presented. Section 3.1 provides the breakup characteristics of the liquid jet associated with different cavitation intensities, including the breakup length and interfacial velocity distribution acquired with OC and OFV. A nozzle with the same geometry, manufactured from Perspex, was also tested at the flow rates listed in Table 2. The different cavitation intensities were visualised due to the transparent surface of the nozzle, which helps to calibrate the results from OC and OFV measurements. Section 3.2 includes shadowgraphy images of the jet geometry during breakup near the nozzle for different orifice shapes under the flow cases presented in Table 3. The droplet characteristics near the nozzle, including size, number, and curvature, were also quantified using PLIF images to demonstrate differences in breakup behaviour between the orifice geometries.

3.1 Study of Cavitation

Figure 3 shows the OC images acquired from the liquid jet ejected through a nozzle with a 1 mm diameter circular orifice under the flow cases presented in Table 2. The corresponding shadowgraphy images are presented in Figure 4 as comparison. For OC, the laser light propagates only within the continuous liquid core, enabling a more reliable measurement of the breakup length, as the fluorescence intensity decreases sharply when the jet disintegrates [13]. In contrast, the breakup point can be obscured by droplet clouds and is therefore difficult to identify, as shown in Figure 4. In Figure 3, the breakup length, which is roughly indicated by the high fluorescence intensity, increases slightly from Case 1 to Case 3, as shown in Figure 3(a)-(b). However, the breakup length does not change when the liquid velocity is further increased from Case 3 to Case 5 (see Figure 3(b) and (c)).

In both Figure 3 and Figure 4, the liquid jets in Case 3 and Case 5 exhibit a wider liquid core immediately after exiting the nozzle compared with Case 1, and the liquid core shows a slight upward deviation while the jet surface appears rougher. Under the same flow conditions as Case 5, the liquid jet can transform into a thin liquid sheet in Case 6, as shown in Figure 3(d) and Figure

4(d). In this case, the jet becomes thinner and forms a liquid sheet with a significantly longer breakup length, while its surface remains smooth right after ejection, as more clearly observed in Figure 4(d). Both OC and shadowgraphy images indicate that supercavitation occurs within the nozzle for Case 6. When hydraulic flip takes place, the liquid no longer attaches to the nozzle wall, producing a smoother jet surface during ejection. Consequently, the jet exhibits a longer breakup length than in Case 5. Also, comparing the jet geometry after the nozzle exit in Case 5 with that in Case 1 and Case 3 suggests that strong cavitation may exist within the nozzle in Case 5. The wider liquid core profile observed in Case 5 may be attributed to disturbances arising from bubble generation and collapse within the nozzle and the jet.

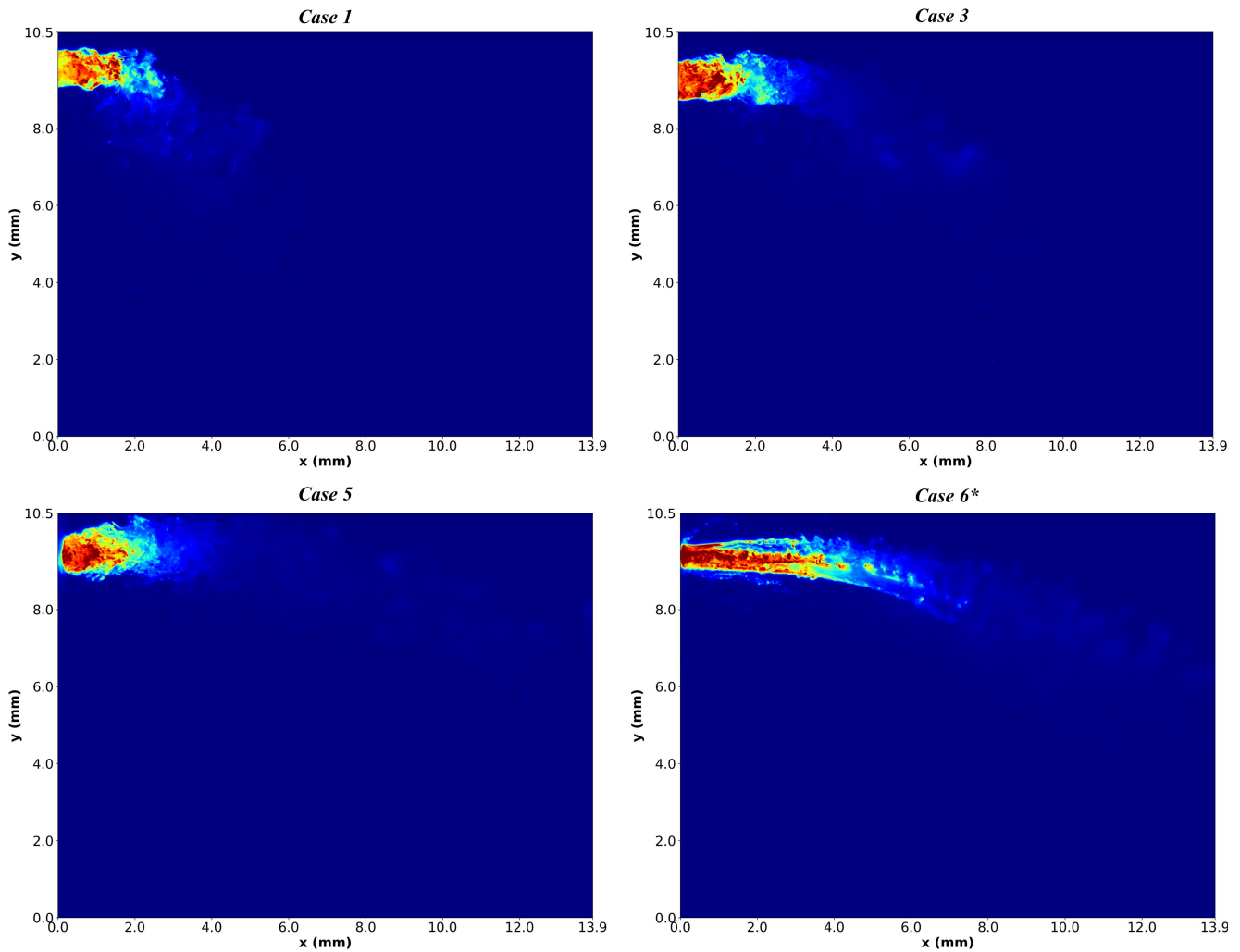


Figure 3. Optical Connectivity images from different flow cases in Table 2. (a) Case 1; (b) Case 3; (c) Case 5; (d) Case

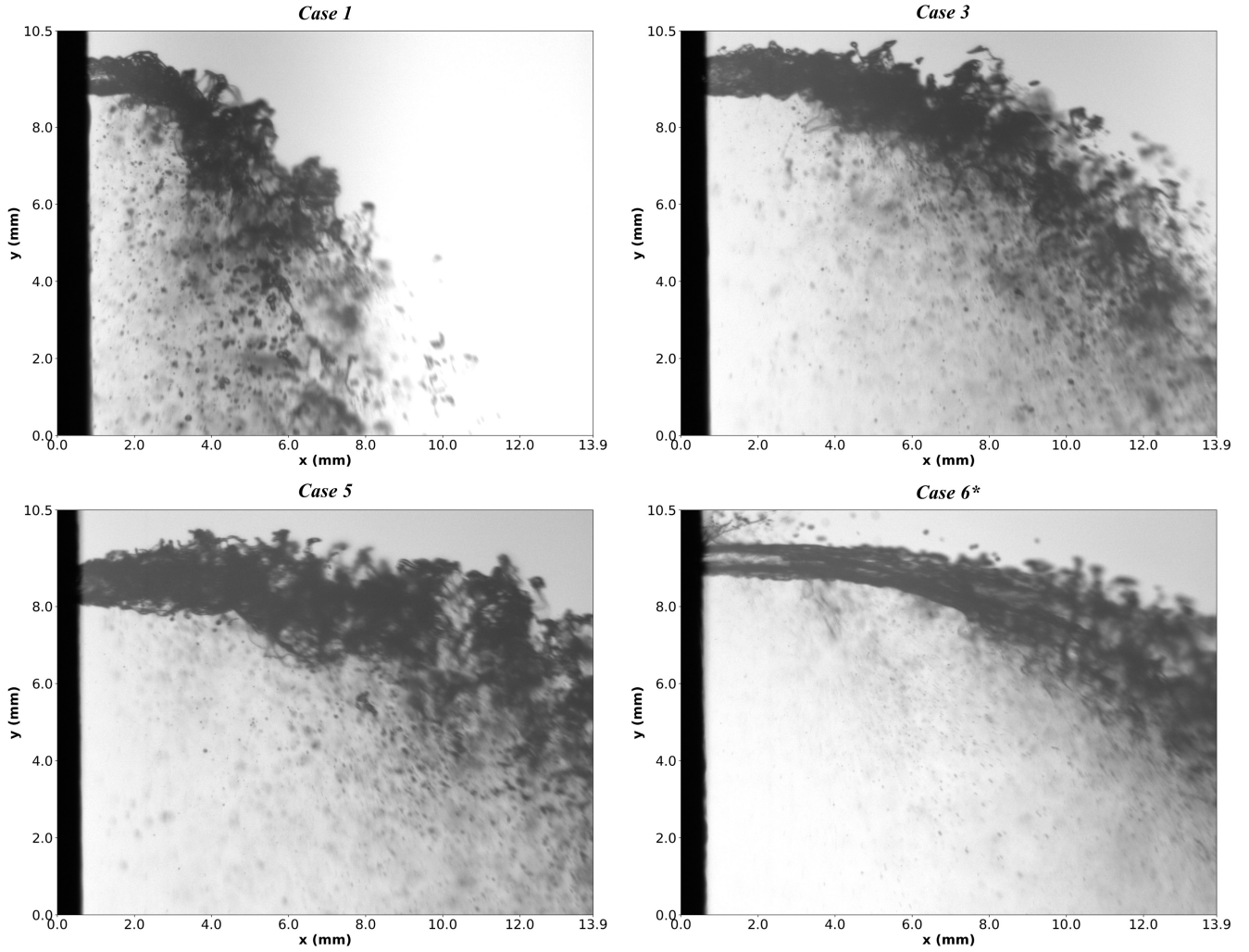


Figure 4. Shadowgraphy images from different flow cases in Table 2. (a) Case 1; (b) Case 3; (c) Case 5; (d) Case 6.

To estimate the breakup length of the ejected liquid jet, the OC images were used. Intensity values lower than 3% of the maximum fluorescence intensity in the images were removed to obtain a clear representation of the continuous jet. In this way, weak fluorescence from droplet clouds downstream of the breakup point, caused by laser light leakage, can be eliminated. As a result, the binary image used to quantify the breakup length, h , is illustrated in Figure 5(a). Figure 5(b) presents the measured breakup length for the flow cases shown in Table 2, labelled with blue dots, together with the breakup lengths from our previous OC study, labelled with red dots. Measurements from other studies based on shadowgraphy [35, 38] are also plotted for comparison. As expected, all breakup lengths measured using OC are shorter than those obtained from shadowgraphy images. It is also noted that, from Case 3 onwards, the breakup length no longer follows the model obtained in our previous study [13] using OC at lower liquid jet velocities U_L , in which the breakup length increases with the square of the momentum ratio M . This may indicate

that mild cavitation has already occurred within the nozzle from Case 3 with $U_L = 10.6$ m/s, and bubble formation inside the nozzle can shorten the breakup length through collapse and the relevant strong disturbance to the liquid jet. In addition, the breakup length increases significantly from Case 5 to Case 6, demonstrating that hydraulic flip within the nozzle markedly delays liquid jet breakup due to the smoother surface of the liquid sheet.

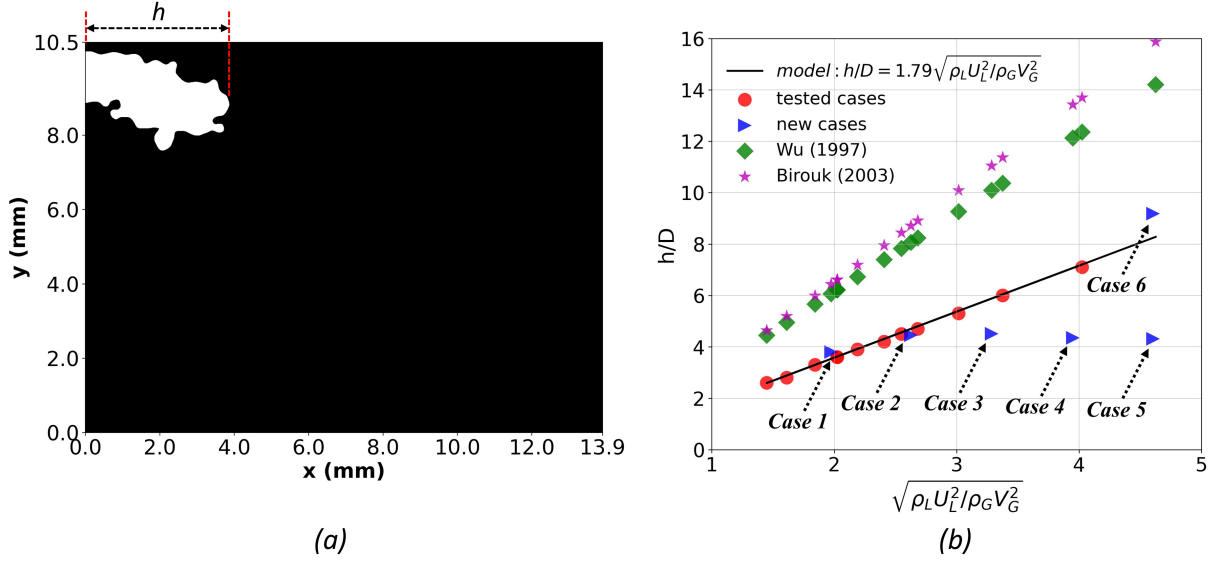


Figure 5 (a) Binary image processed from the OC image to quantify the breakup length, h . (b) Breakup height for different cases listed in Table 2, measured using OC and compared with models from the literature.

Figure 6 presents the averaged interfacial velocity vector field of the liquid jet obtained using OC-OFV, together with contours indicating the magnitude of the velocity components. For the detail of the OC-OFV methodology, the reader can refer to [26]. In brief, a double-pulsed laser is used to capture pairs of OC images, as shown in Figure 3, with a separation of $5 \mu\text{s}$. The fluorescence patterns emitted from the liquid-gas interface are tracked to obtain instantaneous interfacial velocity vector fields. A total of 500 instantaneous fields are then averaged to produce the results shown in Figure 6. The liquid distribution appears slightly broader than the actual jet geometry, as velocities of some detached liquid structures are also captured, including ligaments beneath the liquid core and droplets just stripped off downstream of the breakup point. The centre of the nozzle orifice is indicated by red dots in each case. The coordinate system used in this study is shown on the left-hand side of the figure, where U represents the velocity along the liquid-jet injection direction and V represents the velocity in the crossflow direction. The maximum uncertainty in the measured velocities is below 8%, based on a 95% confidence interval.

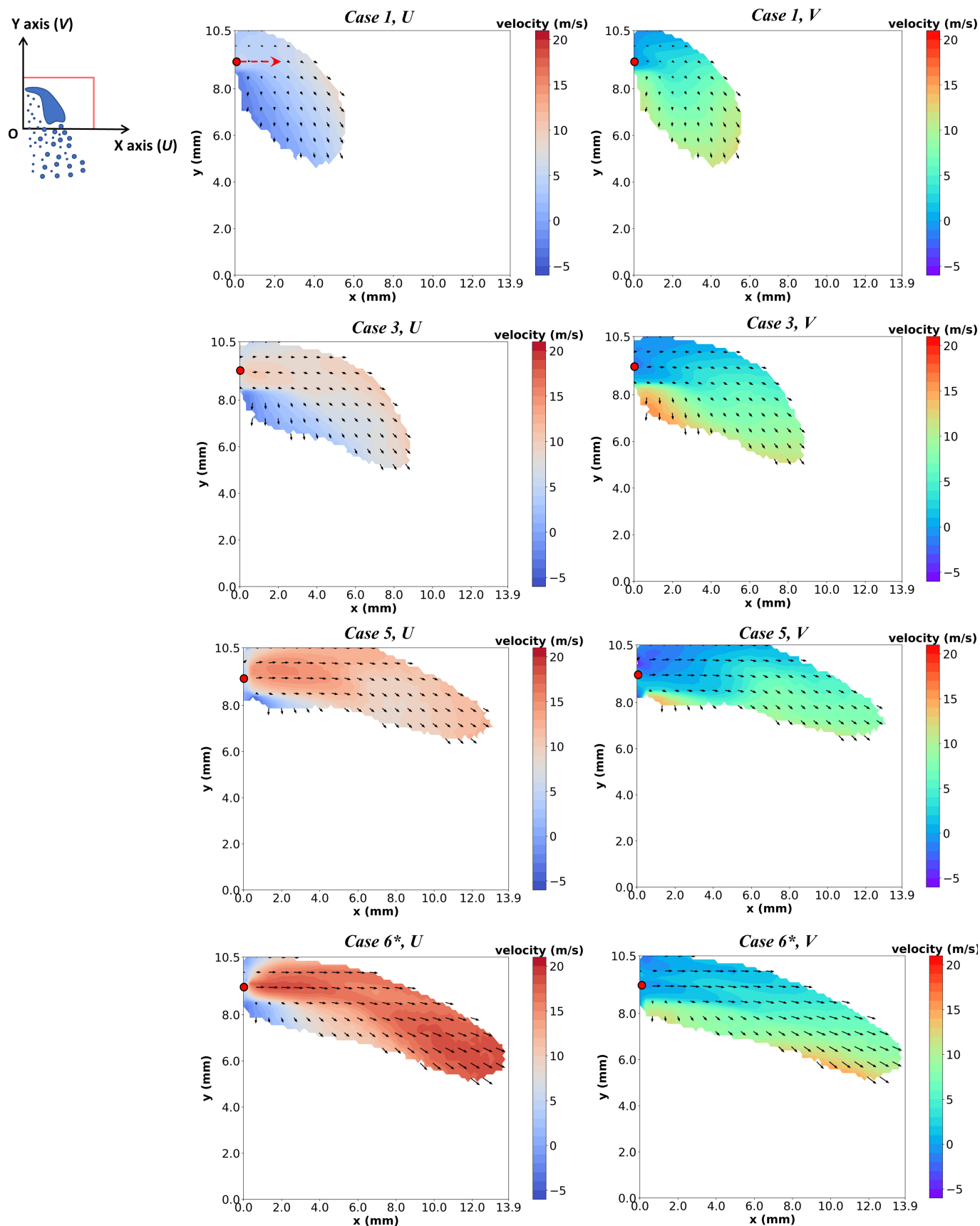


Figure 6. Distribution of interfacial velocity measured by OC-OFV for Case 1, Case 3, Case 5 and Case 6. The contours show the magnitude of the corresponding velocity component.

From all cases shown in Figure 6, the V component increases from zero along the y -axis, aligned with the airflow direction. This is because aerodynamic forces continuously shear the jet surface and accelerate the interfacial structures downward. Consequently, the maximum V is observed near the tip of the jet, where the interfacial structures have experienced acceleration over a longer time. In addition, the maximum V along the surface is comparable across all cases, as the crossflow air velocity, V_G , was kept constant for different cases.

The U component along the side of the liquid jet also accelerates downstream of the nozzle exit (see the velocity along the red arrow in Figure 6, Case 1, U component). As the aerodynamics have a small effect on the U component along the side of the liquid jet near the nozzle exit, this acceleration is mainly due to viscous forces arising from the velocity gradient within the liquid shear layer. In addition, the magnitude of the U component also increases from Case 1 to Case 5 as the average liquid velocity U_L increases. Interestingly, the U component in Case 6 is higher than in Case 5, even though both cases have the same volumetric flow rate. This is because the hydraulic flip occurs within the nozzle reduces the effective cross-sectional area of the orifice, causing the liquid jet to form a thin liquid sheet. As a result, the sheet velocity in Case 6 is higher than the jet velocity in Case 5, leading to a higher U component of the interfacial velocity.

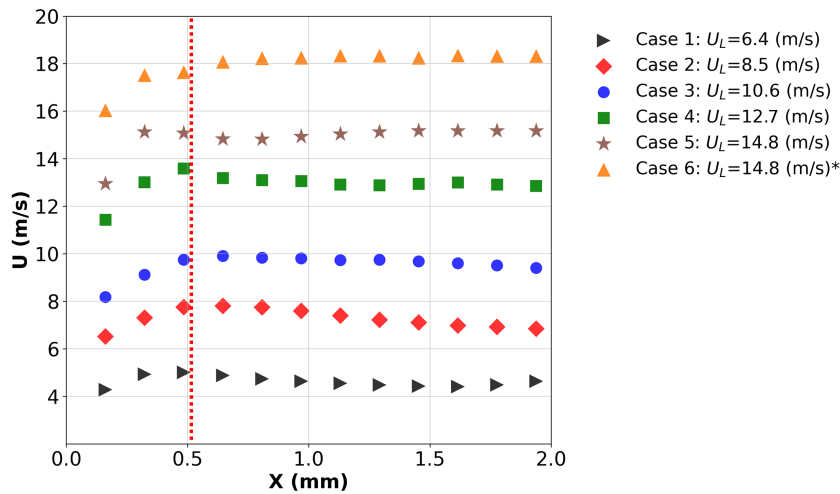


Figure 7. (a) U -component of the interfacial velocity measured horizontally from the centre of the nozzle orifice up to $X = 2$ mm along the red arrow shown in Figure 6. The red line indicates where the interfacial acceleration stops.

The U component of the interfacial velocity along the red arrow shown in Figure 6 is plotted in Figure 7 for all tested cases. The velocity is measured horizontally from the centre of the orifice along the side of the liquid jet, up to $X = 2$ mm. An obvious acceleration of U is observed from the nozzle orifice up to $X = 0.5$ mm, as marked by the red dashed line, due to viscous forces in the shear layer. From $X = 0.5$ mm to 2 mm, the U component remains stable as the relaxation process

of the shear layer ceases and the aerodynamics begin to balance the viscous forces within the shear layer. Importantly, the maximum U component in Case 1 and Case 2 is lower than the corresponding average liquid velocity U_L , which is reasonable because the interfacial velocity is expected to be lower than U_L due to the presence of the shear layer and aerodynamic effects. However, from Case 3 onward, the maximum U component approaches U_L and even exceeds U_L in Cases 4 and 5. This unusual behaviour indicates that, from Case 3, the effective cross-sectional area of the orifice has been reduced by cavitation bubbles, leading to an actual U_L higher than the theoretical U_L . Consequently, the maximum U component of the interfacial velocity can exceed the theoretical U_L .

This effect is even more pronounced in Case 6, where hydraulic flip occurs. The maximum U component reaches approximately 18 m/s, about 25% higher than the theoretical U_L . In Case 5, which has the same theoretical U_L but milder cavitation intensity, the maximum U component is around 15.5 m/s, about 7% higher than the theoretical U_L . Therefore, by tracking the magnitude and variation of the U component of the interfacial velocity of the ejected liquid jet using OC-OFV, the presence and intensity of cavitation within the nozzle can be assessed.

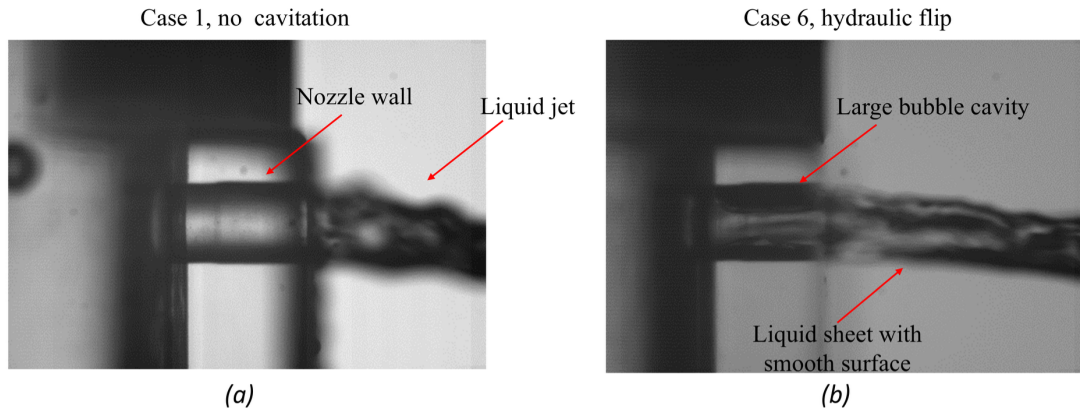


Figure 8. Cavitation conditions observed in the Perspex nozzle under different cases: (a) Case 1; (b) Case 6.

To calibrate the relationship between cavitation and the measured features, including breakup length and interfacial velocity, a Perspex nozzle with a circular orifice of 1 mm diameter was manufactured and used to test the flow conditions listed in Table 2. This enables direct flow visualisation within the nozzle. Figure 8 presents images observed through the wall of the Perspex nozzle. In Figure 8, no bubble flow is observed in Case 1, whereas hydraulic flip is clearly visible in Figure 8(c), corresponding to Case 6, with two large cavitation bubbles on the top and bottom sides of the nozzle wall. These bubbles block part of the orifice cross-section, resulting in a liquid sheet exiting the nozzle with a much higher velocity than the theoretical U_L .

Although not shown here, bubble flow is observed from Case 3 to Case 5 (as seen in the supplementary video), indicating the onset of cavitation within the liquid jet. Although not shown here, bubble flow is observed from Case 3 to Case 5 (as seen in the supplementary video), indicating the onset of cavitation within the liquid jet. Therefore, the results in this section confirm that the interfacial velocity quantified by OC-OFV can be used to indicate the presence of cavitation inside the nozzle, which is otherwise difficult to observe.

3.2 Study of different orifice shape

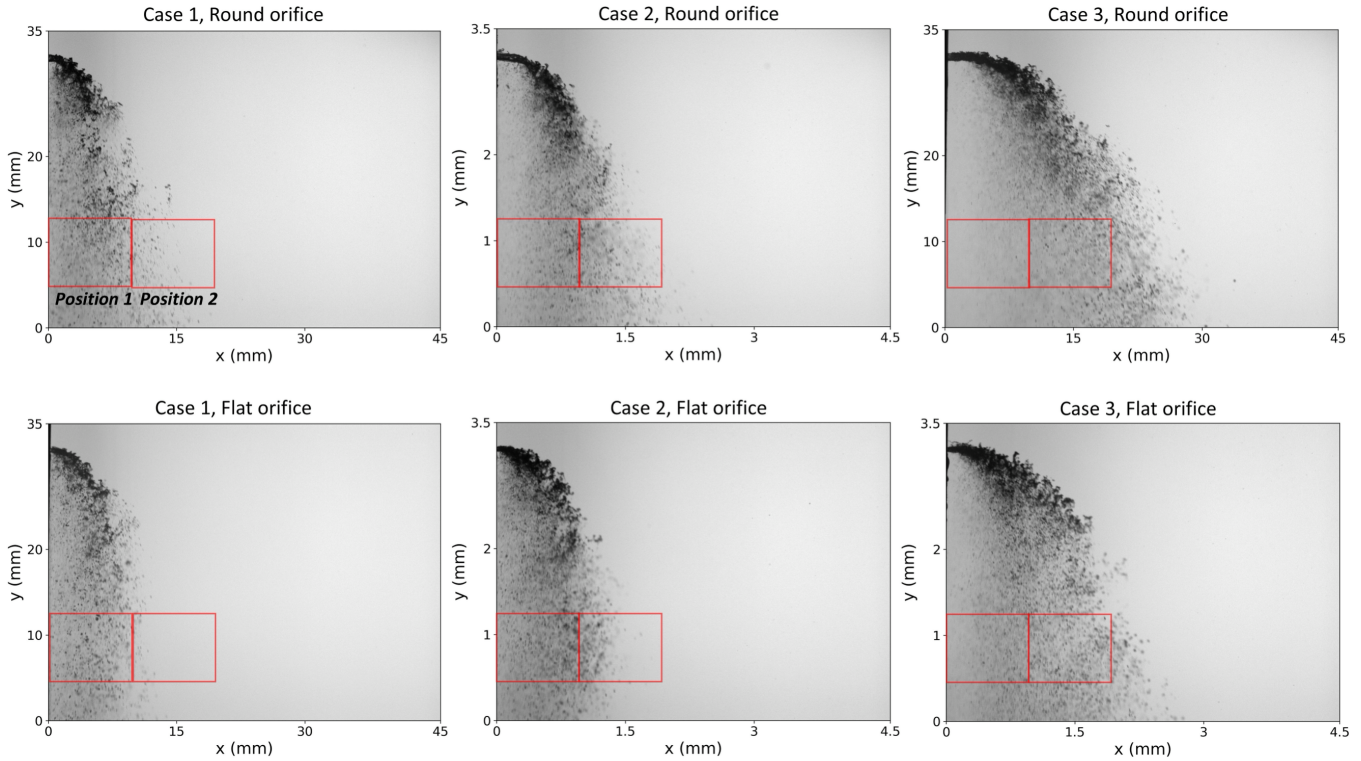


Figure 9. Jet trajectory during breakup from nozzles with different orifice shapes under the flow cases shown in Table 3. The upper row corresponds to the circular orifice, and the lower row corresponds to the flat orifice.

In this section, the characteristics of jets ejected from nozzles with different orifice geometries are investigated using the nozzles shown in Figure 2 under the flow conditions listed in Table 3. The near-nozzle breakup features are observed using shadowgraphy (field of view: 45 mm $\times$ 35 mm), as presented in Figure 9. Liquid jets and sheets ejected from nozzles with round and flat orifices are shown in the top and bottom rows, respectively, for different flow cases. The two positions used for droplet sizing measurements with PLIF, as shown in Figure 1, are also indicated by red frames in the images.

In Figure 9, at the same flow conditions, the liquid sheet ejected from the flat orifice bends further towards the crossflow and exhibits more intense breakup near the nozzle exit. For example, in

Case 2, a denser droplet cloud is observed immediately downstream of the nozzle for the flat orifice compared with the liquid jet from the round orifice, while the trajectories of both the liquid sheet and the droplet cloud shift closer to the nozzle exit. These features may be attributed to the shape of the liquid sheet, which induces higher aerodynamic drag than the round liquid jet, resulting in greater bending. Meanwhile, under the shear breakup regime investigated in this study, droplets from the liquid jet are mainly stripped from the circumferential surface, whereas, for the liquid sheet, the central region may form a thin film due to pressure effects and subsequently break up near the nozzle orifice, leading to a denser droplet cloud close to the nozzle exit.

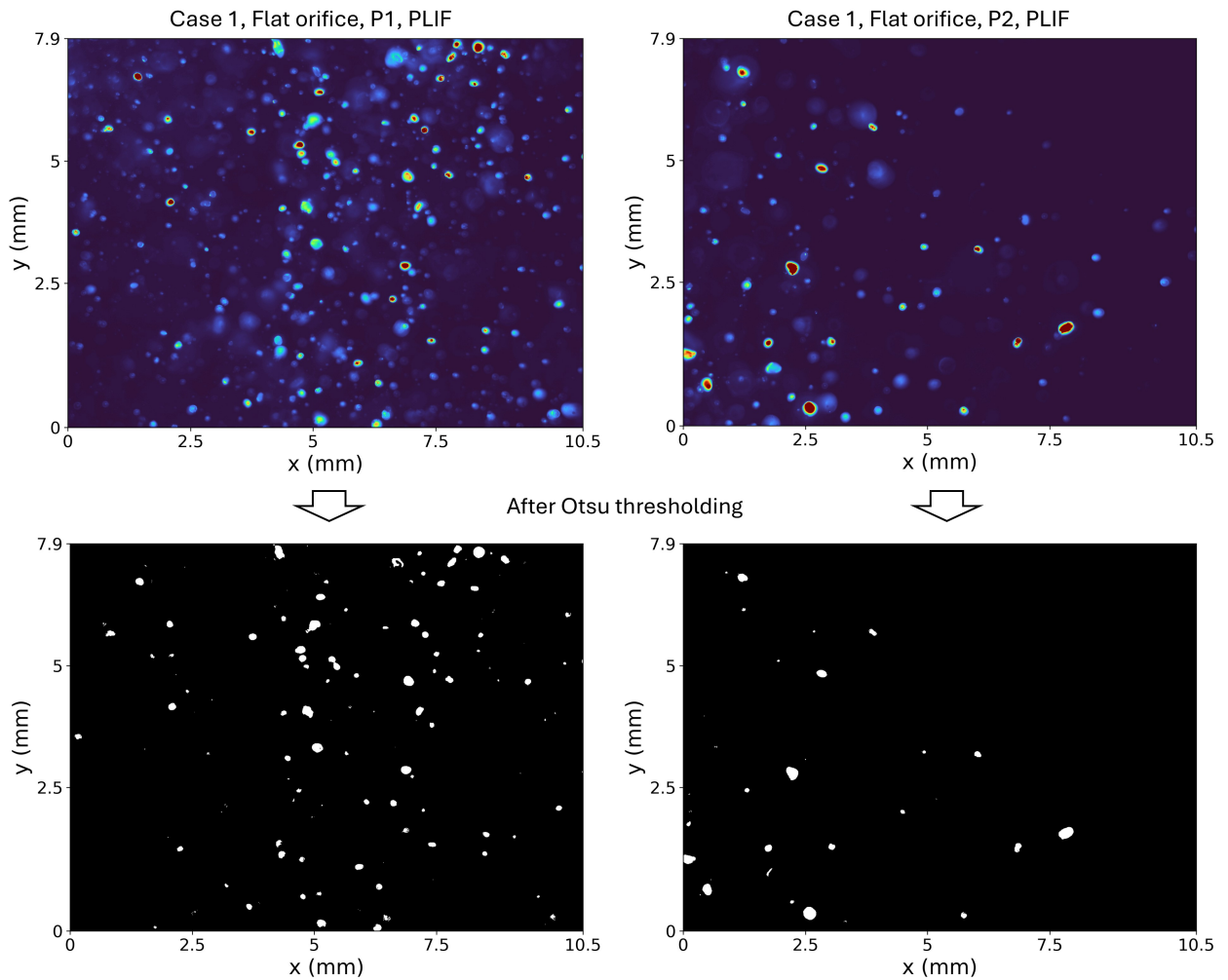


Figure 10. PLIF images acquired at Positions 1 and 2 for Case 1 with the flat-orifice nozzle, along with the corresponding binary images (processed using Otsu's method) used for droplet analysis.

For droplet size computation, the irregular droplet shapes in the binary images are characterised by their long axis, a , and short axis, b . The droplet diameter is then quantified using the volume-equivalent diameter, calculated as $D = \sqrt[3]{a^2 b}$ with a spatial resolution of $7.6 \mu\text{m}/\text{pixel}$ for all the acquired PLIF images.

The characteristics of the droplets generated from the jet and sheet issued by different orifice geometries are analysed using 250 PLIF images acquired at Positions 1 and 2, as shown in Figure 9. These two locations are selected to provide a broader view of droplet characteristics both immediately downstream of the nozzle exit (Position 1) and further along the liquid flow direction (Position 2). The detailed morphology of droplets at both positions for the liquid jet and liquid sheet captured by PLIF is illustrated in Figure 10, which presents representative images obtained at the two measurement locations for the liquid sheet from flat orifice under Case 1 in Table 3.

. In this study, the PLIF laser sheet is aligned with the centre of the nozzle orifice, and the acquired images are processed into binary form using Otsu's method. In this way, only droplets with high fluorescence intensity located within the laser sheet are retained, while out-of-plane droplets illuminated by scattered laser light, which appear blurred in the images, are removed [41].

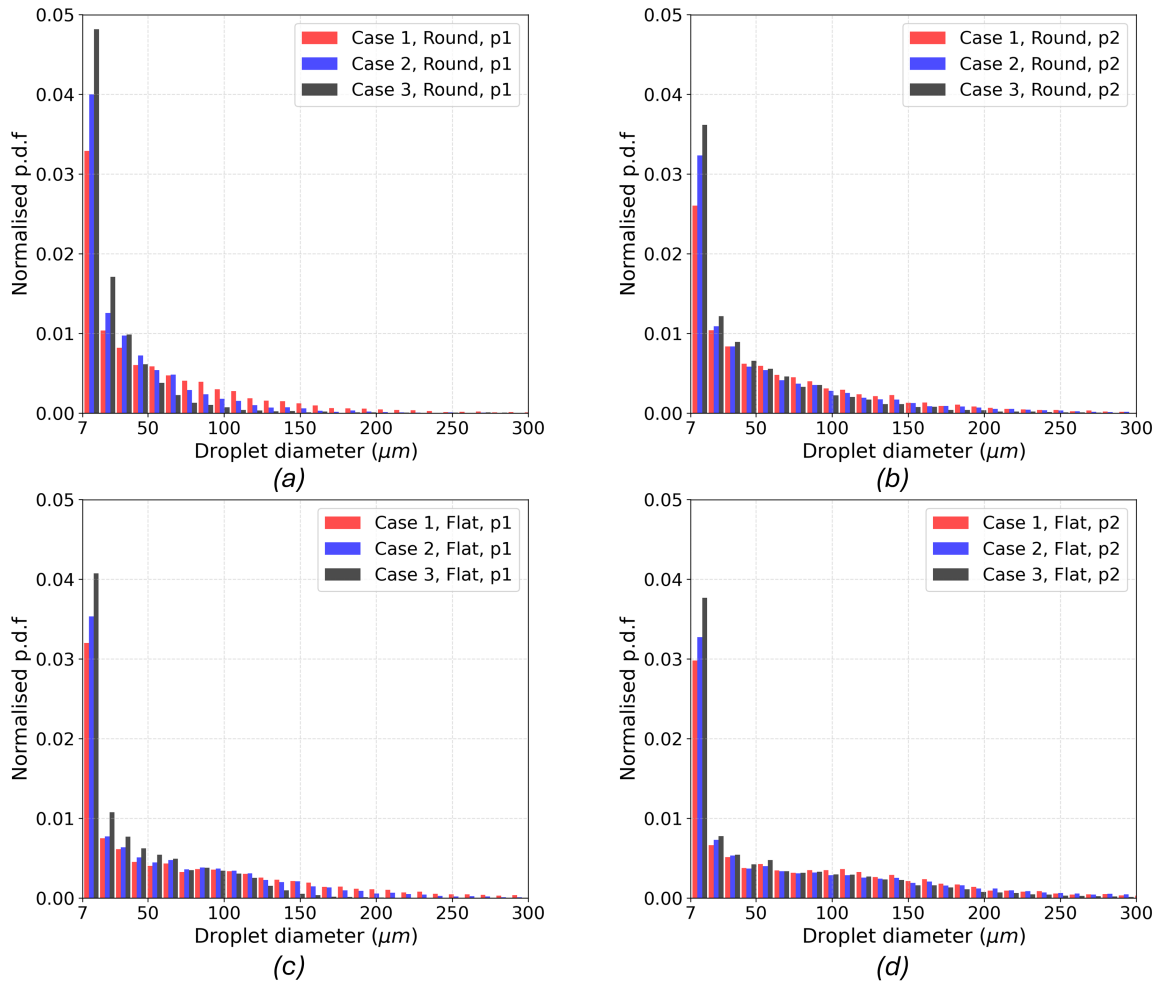


Figure 11. Probability density of droplet sizes at Position 1 (a) and Position 2 (b) for the nozzle with a round orifice.

Probability density of droplet sizes at Position 1 (c) and Position 2 (d) for the nozzle with a flat orifice.

The probability density of droplet sizes at different positions for the various cases is shown in Figure 11. For both nozzles across all tested cases, Position 1 contains more droplets with diameters

smaller than $100\ \mu\text{m}$, while more droplets with diameters larger than $100\ \mu\text{m}$ appear at Position 2. This trend is reasonable, as surface breakup, which produces smaller droplets, occurs closer to the nozzle exit along the entire liquid core, whereas column breakup occurs farther downstream at the liquid breakup point, generating larger droplets that are more likely to be captured at Position 2. However, the difference in the probability density between Positions 1 and 2 is smaller for the flat-orifice cases than for the corresponding round-orifice cases. This indicates that the droplet size distribution along the liquid flow direction is more uniform for the liquid sheet cases.

Additionally, at both Positions 1 and 2, a greater probability of smaller droplets ($< 50\ \mu\text{m}$) appears as the liquid velocity increases (from Case 1 to Case 3). A higher liquid-jet or liquid-sheet velocity results in a longer penetration distance; therefore, the surface breakup process dominates over a longer portion of the penetration trajectory. Meanwhile, larger droplets generated mainly from column breakup tend to remain in the far field of the spray core due to the longer penetration distance and may fall outside the observation region, as illustrated in Figure 9 for Case 3. Hence, the probability of smaller droplets is higher in the images for cases with higher liquid flow velocity, as the droplets contained within these two positions are mainly produced by surface breakup.

Comparing the probability density of droplet size from both the liquid jet and liquid sheet cases, it is notable that the droplet distribution of the liquid sheet is more extreme. As shown in Figure 11(a) and (c), the liquid sheet produces a high probability of extremely small droplets (below $20\ \mu\text{m}$), similar to the liquid jet case, while also exhibiting a higher and more uniform probability of larger droplets compared with the liquid jet distribution. This trend is observed in all cases and at both measurement positions, which may be explained by the different breakup mechanisms and jet trajectories illustrated in Figure 9.

During ejection, the liquid sheet may expand into a thin film near the nozzle exit, from which small droplets can be stripped from the film edge through surface breakup, as well as formed within the film through film breakup. These two processes may generate more small droplets than in the liquid jet case near the nozzle, where droplets are produced only through surface breakup at the jet edge. In addition, film breakup in the liquid sheet may generate more larger droplets than in the liquid jet case at Position 1, as the film rim can produce larger droplets. Meanwhile, the liquid sheet experiences more pronounced bending (see Figure 9), leading to a shorter penetration distance. Consequently, more large droplets which generated near the tip of the spray core may be observed at both measurement positions. These factors collectively explain the more extreme droplet probability density observed for the liquid sheet in crossflow.

To justify the proposed different breakup mechanism in the liquid sheet, Figure 12 presents the number-based droplet size distributions at the two observation positions across all flow cases. The

liquid sheet cases exhibit a higher number of droplets across all droplet sizes compared with the corresponding liquid jet cases at both positions. This indicates that the liquid sheet undergoes more intense breakup than the liquid jet at the near field and therefore produces more droplets at both measurement positions, which is consistent with Figure 9. This behaviour is likely promoted by the suggested film breakup occurring immediately downstream of the nozzle exit, which generates both more small and large droplets at both positions. Furthermore, compared with Case 1, more droplets are observed at Position 2 for Cases 2 and 3 for both nozzles, due to delayed bending induced by the higher momentum ratio M , which allows more droplets to travel further downstream from the nozzle exit.

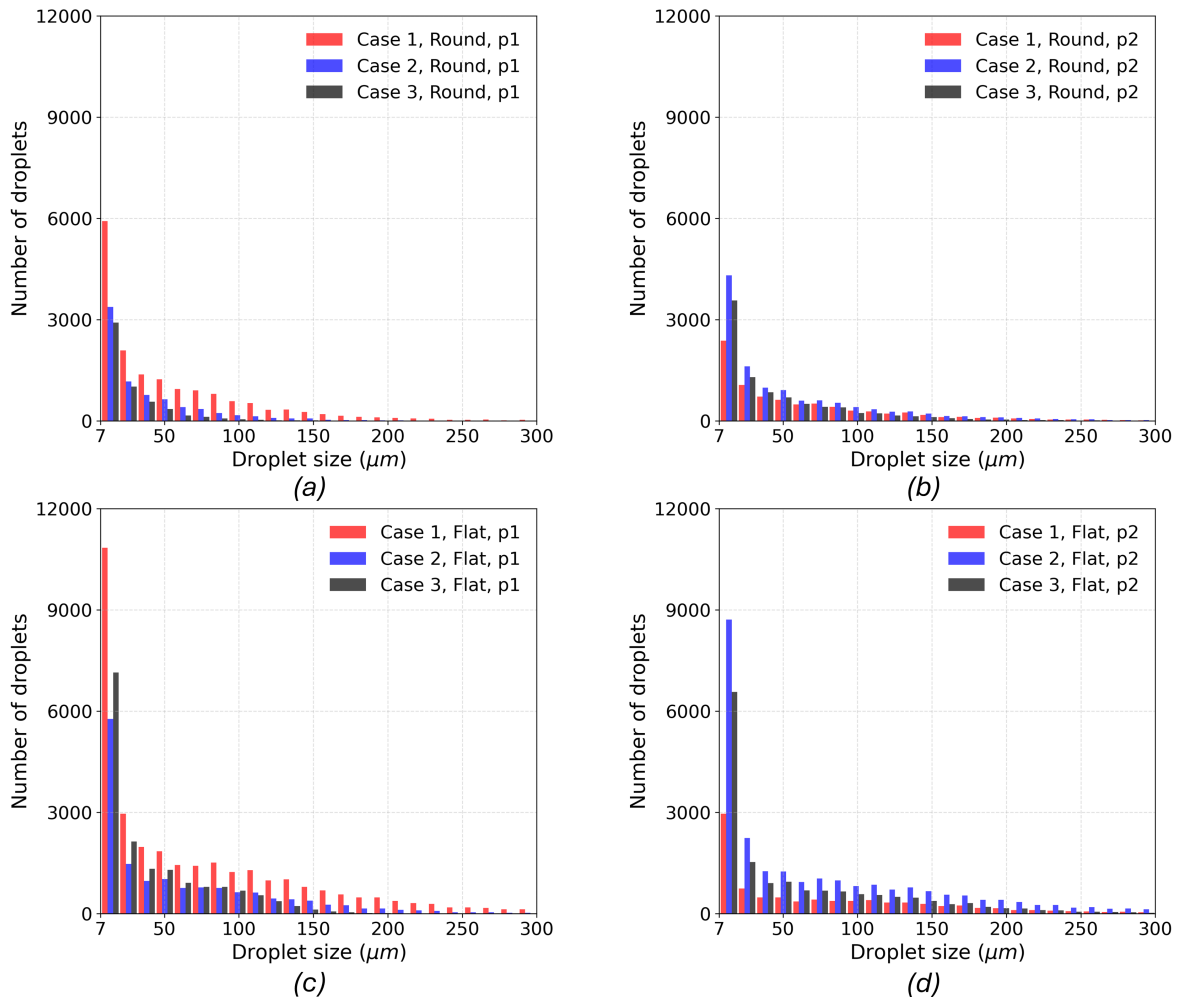


Figure 12. Number-based droplet size distribution at Position 1 (a) and Position 2 (b) for the nozzle with a round orifice, and at Position 1 (c) and Position 2 (d) for the nozzle with a flat orifice.

In general, in the shear breakup regime investigated in the current study, the liquid sheet exhibits more complex breakup behaviour and forms more droplets, both small and large, in the region close to the nozzle, compared with a liquid jet ejected from a round orifice. This is because film breakup in the liquid sheet adds an additional breakup mechanism and produces more intense

atomisation in the near field. The liquid sheet also shows shorter penetration and earlier bending towards the crossflow. In addition, compared with the liquid jet case, the droplet size probability distribution for the liquid sheet may be more uniform along the liquid ejection direction.

4. Conclusions

This study investigates the breakup characteristics of liquid jets in crossflow (LJIC) under varying cavitation intensities and orifice geometries. OC-OFV, shadowgraphy, and PLIF are employed to examine breakup length, interfacial velocity, and droplet size distribution. In addition, a curvature-based method is applied to characterise droplet morphology from PLIF images. The main findings are summarised as follows.

First, cavitation within the nozzle reduces the breakup length. However, when hydraulic flip occurs under supercavitation conditions, the breakup length increases due to the smoother liquid jet surface.

Second, the bubble flow generated during cavitation reduces the effective cross-sectional area at the nozzle exit and increases the actual injection velocity. This leads to a higher interfacial velocity, which can be measured using OC-OFV. If a reference interfacial velocity is known for a given injection velocity under non-cavitating conditions, any measured increase beyond this reference can serve as an indicator of cavitation intensity, without requiring direct observation of the internal nozzle flow. This provides a potential approach for monitoring cavitation within the nozzle.

Finally, the liquid sheet produced by a flat orifice exhibits earlier and more intense surface breakup near the nozzle exit, likely due to its expansion into a thin liquid film. This film may break from its centre shortly after ejection, generating a denser droplet cloud in the near-field region compared with a round-orifice jet. In addition, the liquid sheet experiences higher aerodynamic drag on the windward side, causing it to bend towards the crossflow earlier. As a result, both small and large droplets are more concentrated near the nozzle, leading to a greater liquid presence in the near field. Therefore, for applications requiring enhanced atomisation close to the nozzle exit and a more uniform droplet distribution downstream, leading to improved combustion performance, liquid sheet injection is more suitable than a round jet.

Future work will focus on investigating how downstream droplet size is affected by cavitation of different intensities within the nozzle. This will improve the understanding of how cavitation influences the overall performance of LJIC. By monitoring cavitation intensity through interfacial velocity using OC-OFV, it may be possible to control the downstream performance of LJIC by changing the cavitation intensity.

Acknowledgments

(Yannis, I'm not sure which grant I should include, could you please advise)

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