PIV STUDY ON WATER SPRAY MIXING IN A CONFINED AIR CROSSFLOW

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The mixing uniformity of a hollow-cone water spray in an air crossflow is investigated in a rectangular duct by using a particle image velocimetry system. Experiments are carried out with three water/air momentum flux ratios and three nozzle injection angles in the case of a single nozzle. The droplet distributions in both the longitudinal and transverse directions and the velocity vector fields in the transverse direction are obtained. The mixing flow structure along the longitudinal direction has three sequential regions, i.e., vortex controlling, horizontal movement controlling, and impingement controlling regions. The counter-rotating vortex pair (CVP), leading vortex, shear layer vortex, and multiple vortices are observed. The CVP leads to droplet dispersion within a wide range but results in a droplet preferential distribution. A lower water/air momentum flux ratio contributes to a small-scale CVP, while inclined nozzles with an injection angle against the upstream crossflow allow the CVP to occur prematurely. An improved mixing can be achieved with a lower water/air momentum flux ratio and an inclined nozzle with an incidence angle against the upstream crossflow.

KEY WORDS: spray droplets, crossflow, mixing, counter-rotating vortex pair (CVP), particle image velocimetry (PIV)

1. INTRODUCTION

The mixing of spray jets in the crossflow is extensively encountered in the manufacturing and chemical industries and in energy and power engineering. In a water ramjet engine, a good mixing uniformity of spray droplets in the crossflow plays a dominant role in the enhanced propulsion of the ramjet. Much effort has been made in studying liquid jets in crossflow, whereas the fundamental understanding of the spray jet in crossflow has not been substantially revealed. The major distinction between the injection of liquid and spray jets into the crossflow lies in the different development of the initial flow field in the vicinity of the injection zone. In the case of a liquid jet, a liquid column forms at the exit of the nozzle, undergoes successive developments of surface and column breakups, and then disintegrates into ligaments and droplets in the near-injection region, as demonstrated by Wu et al. (1997). However, a hollow-cone liquid film emerges at the exit of the nozzle in the case of the spray jet, and the liquid sheet gradually experiences the processes of sheet breakup and atomization. The atomized droplets may undergo secondary breakup in the near-injection region. The vortices that appear in different types of jets in crossflow can be quite different.

Previous studies on the mixing of liquid jets in crossflow have focused on the breakup of the liquid jet (Wu et al., 1997; Sallam et al., 2004; 2006; Ng et al., 2008), the jet penetration length (Lin et al., 2000; Stenzler et al., 2006; Bunce et al., 2006), and the jet structure (Inamura and Nagai, 1997; Wu et al., 1998; Costa et al., 2006; Elshamy et al., 2007). In Elshamy et al. (2007), the leading and trailing vortices, the wake behind the jet, and the unsteady vortices in the vicinity of the nozzle exit were observed in the mixing of the liquid jet in the crossflow. In the mixing of the gaseous jet in the crossflow, four flow structures were identified as horseshoe, jet shear layer, and wake vortices, and a counter-rotating vortex pair (CVP) (Ibrahim and Gutmark, 2006). The CVP was found to be a prominent structure in the jets mixed with the crossflow, including the gaseous jet (Cortelezzi and Karagozian, 2001), liquid jet (Salewski and Fuchs, 2006), and spray jet (Bai et al., 2009).
With all the relevant works on the mixing of spray jets in crossflow in the past several decades, further studies are still needed due to the wide application and great complexity of spray/crossflow two-phase flows. Ghosh and Hunt (1998) analyzed the dynamics of spray jets in weak, moderate, and strong crosswinds. The ratio of crosswind speed to jet speed was concluded to be a dominant factor in the dynamic flow behaviors of spray/crossflow two-phase flows. By examining the size–velocity characteristics in the presence of a non-uniform crosswind, Farooq et al. (2001) found that different behavioral tendencies switched when the diameter of a droplet was 100 \( \mu m \). Eletribi (1999) found that the air crossflow was a decisive factor in controlling spray dispersion. Phillips and Miller (1999) and Phillips et al. (2000) reported that the initial droplet dispersion was dependent on the entrained air field. Choi et al. (2004) stated that the vortex entrained air to the fuel spray cloud, resulting in an enhanced mixing of air and fuel. The study by Panao and Moreira (2005) revealed that the three-dimensional (3D) vortex in the vicinity of the wall surface was the major factor affecting the impingement of a spray onto the wall surface under the influence of crossflow. The interactions between spray and gas flows played an equally important role in the processes, including droplet vaporization (Trichet et al., 1994), droplet breakup (Lee and Tankin, 1984), and spray trajectory (Sturgess et al., 1985).

Most of the previous experimental investigations primarily focused on the spray characteristics in the vicinity of the spray injection zone. The momentum flux ratio of the spray jet to the crossflow is considered to significantly affect the spray characteristics. The mixing of the spray jet with the crossflow far from the spray injection zone is still not fully understood. It is even challenging to profoundly apprehend the vortex structures that appear in the mixing of a hollow-cone spray in the crossflow in a constrained space. The experimental and numerical investigations by Bai et al. (2009; 2011) dealt with the transverse droplet distributions at different cross sections along the crossflow. In the present work, a particle image velocimetry (PIV) system is used to capture the droplet distributions on both the transverse and the longitudinal sections that occur in the mixing of the hollow-cone spray in the crossflow. The evolution of the CVP near and far from the spray injection zone is also investigated. The influences of the water/air momentum flux ratio and the spray injection angle on the mixing are analyzed. This study provides further visual evidence for more insightful knowledge of the underlying mixing mechanism of the hollow-cone spray in the crossflow.

2. EXPERIMENT

Figure 1 shows the experimental setup used in this study. The air crossflow generated from air blowers (C40-1.5 and C80-1.5, Shaanxi Blower Company, Ltd., Xi’an, China) flows through the rectifying section and then enters the measurement section of the duct. The initial conditions of the air stream and the water spray are given in Table 1. The measurement section is a 1-m-long rectangular duct made of transparent polymethyl methacrylate and a cross-sectional area of \( 0.095 \times 0.095 \, m^2 \). A pressure-swirl nozzle (1/4MK B80100S303-RW, H. Ikeuchi & Company,
FIG. 1: Schematic of the experimental setup.

Ltd., Osaka, Japan) is used to generate the hollow-cone spray. The volume flux of water that flows into the nozzle, the spray angle (see Fig. 2), and the Sauter mean diameter of the droplets are 0.0226 m$^3$/h at 0.70 MPa, 80° and 80 µm, respectively. One nozzle is mounted on the upper wall center of the duct in the single-nozzle experiments (see Fig. 1). As is shown in Fig. 1, a PIV (Flowmaster, LaVision Company, Goettingen, Germany) measurement unit is used to obtain the instantaneous velocities of the spray droplets. Figures 2 and 3 show the longitudinal and transverse measurement sections, respectively. The 3D Euclidean coordinate system used for the measurements is also included in Figs. 2 and 3. The nozzle position is taken as the origin of the 3D coordinate system. One 2-mm-wide slit on the upper wall of the duct, as is shown in Fig. 2, allows an approximate 1-mm-wide laser sheet to illuminate the spray droplets in the longitudinal measurement direction. As shown in Fig. 3, 2-mm-wide slits on the side wall allow the laser sheets to light the spray droplets in the transverse measurement direction. When one transverse section is being measured, the others are sealed. The laser sheets are derived from the second harmonic of a Nd-YAG pulsed laser unit (200 mJ, 8 ns pulse, and 532 nm). A charge-coupled device (CCD) camera (Nikon ImagerPro4M, Nikon Corporation, Tokyo, Japan, 15 Hz, 2048 × 2048 pixels, and cross correlation) positioned perpendicular to the illuminated measurement section is used to capture the digital images. Forty pairs of instantaneous images are taken at each cross section at 5 frames/s in order to obtain the mean of the transient measurements. The camera intermittently moves along the side wall of the duct to shoot the images of the longitudinal measurement sections at different positions when processing the longitudinal measurements. The camera is positioned against the rear of the

FIG. 2: Schematics of the longitudinal measurement sections, nozzle injection angle, and spray angle.
rectangular duct when the transverse measurements are made. To prevent the CCD lens from being contaminated, an air line connected to the blowers shown in Fig. 1 is used to blow the vent. More details about the experimental setup and measurements are available in our previous work (Bai et al., 2009).

Figure 2 also illustrates the definition of the nozzle’s injection angle, denoted by $\alpha$. The effects of three injection angles (i.e., 60°, 90°, and 120°) and three crossflow velocities (i.e., 4.0, 7.0, and 10.0 m/s) on the flow field are investigated in the experiments. The momentum flux ratios of the spray jet to the crossflow can be calculated by

$$q = \frac{\rho_d V_{d,0}^2}{\rho_c U_c^2}$$

where $q$ is the momentum flux ratio; $\rho_d$ is the liquid density of droplet; $V_d$ is the droplet vertical velocity (Fig. 2); $V_{d,0}$ is the droplet velocity at the nozzle exit; $\rho_c$ is the crossflow density; and $U_c$ is the crossflow velocity.

As given in Table 1, the mean droplet vertical velocity at the nozzle exit is measured to be 20.0 m/s by the PIV system. Then, the momentum flux ratios are calculated to be 20,710, 6762, and 3314 for the three respective crossflow velocities, with the droplet vertical velocity at the nozzle exit being 20.0 m/s ($\rho_c = 1.205$ kg/m$^3$ and $\rho_d = 998.200$ kg/m$^3$ at a temperature of 293.15 K and atmospheric pressure). The experiments were carried out at a temperature of 293.15 K and atmospheric pressure. Table 2 lists the experimental scenarios covered in this study.

**TABLE 1: Initial conditions of the experiments**

<table>
<thead>
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<th>Inlet air crossflow</th>
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<tr>
<td>Mass flow rate (kg/s)</td>
<td>0.0342, 0.0598, 0.0854</td>
</tr>
<tr>
<td>$x$ velocity (m/s)</td>
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<tr>
<td>$y$ velocity (m/s)</td>
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</tr>
<tr>
<td>$z$ velocity (m/s)</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (K)</td>
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<tr>
<td>Pressure (MPa)</td>
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<table>
<thead>
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<th>Inlet water spray</th>
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</tr>
<tr>
<td>Mass flow rate (kg/s)</td>
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</tr>
<tr>
<td>Temperature (K)</td>
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<tr>
<td>Spray angle (°)</td>
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<tr>
<td>Sauter diameter ($\mu$m)</td>
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</tr>
<tr>
<td>Average $x$ velocity (m/s)</td>
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</tr>
<tr>
<td>Average $y$ velocity (m/s)</td>
<td>20</td>
</tr>
<tr>
<td>Average $z$ velocity (m/s)</td>
<td>$-5/5$</td>
</tr>
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</table>
TABLE 2: Experimental scenarios

<table>
<thead>
<tr>
<th>Number of nozzles</th>
<th>Nozzle injection angle (°)</th>
<th>Momentum flux ratio</th>
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<tr>
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<td>3314</td>
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<td>1</td>
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<tr>
<td>1</td>
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<td>3314</td>
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<td>90</td>
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<td>120</td>
<td>20,710</td>
</tr>
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3. RESULTS AND DISCUSSION

3.1 Development of the Flow Structure of Spray Droplets in Crossflow

The droplet distribution and velocity vector fields shown in Figs. 4 and 5 were obtained based on the mean of the transient measurements captured using the PIV system with a momentum flux ratio of 20,710 and a nozzle injection angle of 90°. The vortex was the main feature in the flow field of the spray droplets in the crossflow.

The hollow-cone liquid film originally formed when the water was atomized through the pressure swirl nozzle. Subsequently, the film broke into many small droplets due to the pneumatic shear force. Therefore, the concentration of the atomized droplets increased sharply near the spray. The hollow-cone liquid film and the high-concentration droplets impeded the flow of crossflow, and thus a low-pressure area appeared behind the hollow-cone film (leeward side). The crossflow around the hollow cone flowed toward the low-pressure area after bypassing the hollow cone as a result of the pressure gradient. Consequently, the CVP occurred in the upper part of the duct. Due to the first impingement of the air crossflow on the spray jet, a small leading vortex pair occurred around the periphery of the spray cone near the injection location, which was also observed in the mixing of the liquid jet in the crossflow (Elshamy et al., 2007). Then, a rudiment of the first CVP formed in the upper part of the duct because of the aforementioned block, i.e., the hollow cone (at l/d = 0.21 in Fig. 5). With more droplets carried by the vortices, the CVP expanded and occupied a larger area but with decaying intensity (Fig. 6). The two vortices of the CVP were roughly the same size but opposite each other in terms of the rotating direction. Droplets with high momentum will impinge on the side wall when they move to the lower section because the mixing proceeds in a confined space. The droplets may experience adhesion, breakup, rebound, and coalescence according to their momentum. The crossflow will change its direction and rotate under the influences of these complex behaviors. Therefore, another vortex pair emerged due to the constraint of the wall and the performance of the droplets. Then, the pair expanded gradually when more droplets were entrained. With the attenuation of the CVP in the upper section, the scale of vortices in the lower part began to pick up, and therefore these vortices pushed the higher CVP counterpart upward.

The spray cone and droplets caused the vortex to occur, and simultaneously the flow structure of the crossflow influenced the movement of the droplets. Figure 7 shows the development of the horizontal velocity (i.e., $U_d$ in the $X$ direction) and vertical velocity (i.e., $V_d$ in the $Y$ direction) profiles of the droplets along the crossflow under the influence of the flow structure. The velocity profiles were measured at the $XOY$ section, which is shown in Fig. 2. It can be seen that the droplet velocity profiles are asymmetrical in shape. Moreover, the following general development of the droplet $U$ velocity along the $Y$ direction can be observed: beginning with a low value near the top wall, the $U$ velocity increases considerably and then decreases sharply when the droplets go through the upper CVPs; afterward, the $U$ velocity increases gradually to a peak value in the mainstream region due to being carried by the crossflow and then decreases near the bottom wall. The droplet $V$ velocity along the $Y$ direction has a different development: starting with a low value near the top wall, $V$ velocity increases to a peak value (along the negative $Y$ direction) in the upper CVP region due to the entrainment of the CVP; afterward, it decreases gradually when the droplets go through the mainstream. The $V$ velocity reaches its peak value at the lower part of the cross section near the nozzle ($l/d = 0.63$)
FIG. 4: Droplet distributions at different cross sections with a momentum flux ratio of 20,710 (a nozzle injection angle of 90° is used).

because of the great initial $V$ velocity of the droplets. The peak $V$ velocity at the lower section disappears far from the nozzle due to the drag of the crossflow.

Among the vortices, the CVP is the key structure that determines mixing uniformity. The rest of the vortices, such as the unsteady leading vortex, shear layer vortex, and multiple vortices, also play a part in promoting the droplet dispersion. These unsteady vortices will be introduced in the following section. These vortices do not endure and they disappear quickly, whereas the CVP experiences formation, growth, attenuation, and even disappearance under different injection conditions. For instance, take the case of $q = 20,710$ and $\alpha = 90^\circ$ (Fig. 5). The CVP forms first in the upper section immediately after the nozzle location ($l/d = 0.0$), then it begins to grow in the location of $l/d = 0.21$, and later it expands and remains stable at $l/d = 0.63$. The other CVP first occurs in the lower section at $l/d = 0.63$, 

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FIG. 5: Velocity vector fields at different cross sections with a momentum flux ratio of 20,710 (a nozzle injection angle of 90° is used).

while it can be clearly observed at $l/d = 1.26$ with its development. Moreover, the intensity of both CVPs tends to attenuate with their growth because the momentum of the initial droplet is the largest and it decreases gradually due to the interaction between the two phases. However, the intensity of the CVP in the lower section is much weaker than that in the upper section because the momentum of the droplet decreases when the droplet moves to the lower section.

In addition, the disappearance of both the CVPs is not detected in the present mixing length, although it may be observed under different conditions, which will be discussed subsequently. It should be pointed out that the CVP’s evolution, which occurs when mixing the spray jet in the crossflow, is different from that of the liquid jet in the
FIG. 6: Vorticities of the CVP cores on both the top and lower part of different cross sections (a nozzle injection angle of 90° is used and the momentum flux ratio is 20,710).

FIG. 7: Droplet velocity profiles at different locations along the crossflow with a momentum flux ratio of 20,710 (a nozzle injection angle of 90° is used).

crossflow. Unlike in the liquid jet (Salewski and Fuchs, 2006), the CVP forms and grows near the spray nozzle immediately when the spray is introduced into the crossflow.

3.2 Effects of the Momentum Flux Ratio

The experiments on the effects of the momentum flux ratios were carried out with a nozzle injection angle of 90°. Figure 8 shows the droplet distribution at the XOY longitudinal section. Figure 9 shows the droplet distribution at different cross sections. Figure 10 illustrates the development of the transverse velocity vector fields when the momentum flux ratios are 20,710, 6762, and 3314, respectively.

According to the droplet distribution in the longitudinal section and the droplet velocity profiles, the longitudinal flow field qualitatively falls into three regions, namely, the vortex controlling region in the upper section, the horizontal
FIG. 8: Droplet distributions at the $XOY$ longitudinal section with momentum flux ratios of 20,710, 6762, and 3314, respectively (a nozzle injection angle of 90° is used).

FIG. 9: Droplet distribution at different cross sections with momentum flux ratios of 20,710, 6762, and 3314, respectively (a nozzle injection angle of 90° is used).
movement controlling region in the middle section, and the impingement controlling region in the lower section. The vortex controlling and impingement controlling regions are actually dominated by the CVP in the upper and lower sections, respectively. The droplets move and are dispersed via the entrainment of the two CVPs. The horizontal movement controlling region is between the two CVPs, where the crossflow does not change its direction and the droplets move downstream as a result of the crossflow. The CVP in the upper section influences the droplet distribution significantly in the vortex controlling region. It can be seen from Fig. 4 that the droplets in the upper section tend to aggregate ($l/d = 0.84$) or be sparse ($l/d = 1.47$). When the mixing develops, the uneven distribution of the droplets is diminished ($l/d = 2.1$). The centrifugal force of the CVP exerted on the droplets can account for this preferential distribution of the droplets. The droplets tend to move to the periphery of the vortex rather than the vortex center. The distribution is much more uneven when the intensity of the CVP is greater. Therefore, the droplets are distributed unevenly in the vortex controlling region; however, they are distributed uniformly in the impingement controlling region where the intensity of the CVP is much lower (Fig. 4). The droplet aggregation in the vicinity of the lower wall (Fig. 8) is mainly caused by the impingement of the droplets with the bottom wall of the duct. In addition, there is a distinct boundary between the upper and middle sections, which is formed by the periphery of the spray cone under the influence of the crossflow (see the solid line in Fig. 8). The droplets above the boundary move in a random manner and later aggregate due to the presence of the vortices, which can be observed in Fig. 9. In addition to the CVP, the unsteady shear layer vortices in Fig. 8 emerge along the boundary in the longitudinal direction. The difference in the velocities of the spray jet and the crossflow results in the unstable disturbance on the jet surface; consequently, the disturbance induces the shear layer vortex. To some extent, the shear layer vortex promotes the droplet dispersion in the vortex controlling region. When the momentum flux ratio decreases, the horizontal movement controlling region expands, whereas the vortex controlling and impingement controlling regions contract. The boundary is observed to shift upward in Fig. 8. This is also clearly seen in Fig. 11 from the change of the position of the CVP core.

**FIG. 10:** Development of velocity vector fields with momentum flux ratios of 20,710, 6762, and 3314, respectively (a nozzle injection angle of 90° is used).
This allows a large number of droplets to move downstream and avoid the droplet aggregation near the wall and the preferential distribution due to the large-scale CVP. The crossflow exerts a stronger influence on the spray droplets with a decrease of the momentum flux ratio, and as a result the CVP is unstable and easy to break down into small unstable vortices, as shown in Fig. 10. Compared with the large-scale CVP, the small-scale vortices are preferable in promoting droplet dispersion because they can restrain the droplet preferential distribution in terms of eliminating the centrifugal force of the large vortex. More droplets are swept by the crossflow and move downstream; hence, fewer droplets accumulate near the lower wall. For instance, the droplets distribute more evenly in the case of $q = 3314$ than in the other two cases, according to Fig. 9. Therefore, in order to achieve improved mixing uniformity of the spray droplets in the crossflow a lower momentum flux ratio is beneficial because a large-scale CVP is not easily maintained.

3.3 Effects of the Nozzle Injection Angle

A momentum flux ratio of 20,710 was used to study the effects of the nozzle injection angle in the mixing. Figure 12 shows the droplet distribution at the $XOY$ longitudinal section; Fig. 13 shows the droplet distribution at different cross sections; and Fig. 14 presents the development of transverse velocity vector fields with injection angles of $60\degree$, $90\degree$, and $120\degree$. When the spray is injected against the crossflow (e.g., in the case of $\alpha = 60\degree$), the crossflow and the spray begin to interact in advance of the injection, resulting in faster evolution of the CVPs. The CVPs appear prematurely and actually lengthen the mixing. For instance, in Fig. 14 an apparent CVP appears on the very top section at the location of $l/d = 0.21$, and then another CVP emerges at the very bottom at the location of $l/d = 0.84$. Moreover, both CVPs at the injection angle of $60\degree$ fail to grow; instead, the CVP in the upper section quickly disappears. The droplets do not aggregate as significantly in the upper section as they do in the case of $\alpha = 90\degree$ (Fig. 13). Figures 13 and 14 compare the mixing with the injection angles of $60$ and $90\degree$, indicating once again that the smaller CVP leads to better mixing uniformity. It can be preliminarily deduced that an injection angle against the crossflow contributes to improved mixing uniformity.

With a nozzle injection angle of $120\degree$, a larger number of droplets accumulate near the lower wall. Due to the constraint of the wall surfaces, large asymmetric CVPs form and account for the extremely preferential distribution of the droplets, as shown in Fig. 14. In addition, it is interesting to discover that small-scale vortices emerge inside the large CVP at the location of $l/d = 1.47$, i.e., a typical multiple vortex is observed.

Although it helps to transfer the spray droplets from dense to sparse regions, the CVP—particularly a large-scale CVP—brings about a preferential distribution of the droplets. The scale and strength of the vortices that appear in the
FIG. 12: Droplet distributions at the XOY longitudinal section with nozzle injection angles of 60°, 90°, and 120° respectively (the momentum flux ratio is 2710).

3.4 Assessment of Mixing Uniformity

A quantitative assessment of the mixing of the spray droplets in the crossflow can provide an intuitive view of the mixing uniformity. According to Bai et al. (2011), the degree of mixedness is proposed as follows:

$$\xi = 1 - \frac{(1/n - 1) \sum_{i=1}^{n} (X_i - \bar{X})^2}{\bar{X}^2}$$  \hspace{1cm} (2)

where $\xi$ denotes the degree of mixedness; the cross section is divided into small regions, numbered $n$ (Bai et al., 2009); $X_i$ is the flux density of the droplets in region $i$, that is, the number of the droplets per unit area; and $\bar{X}$ is the mean flux density of the droplets in the cross section.

Figures 15 and 16 show the degrees of mixedness with the nozzle injection angles of 60° and 90°, respectively. Figures 15 and 16 also show that the degree of mixedness increases with the decrease of the momentum flux ratio. Moreover, in the three cases of momentum flux ratios, the degree of mixedness with the nozzle injection angle of 60° was greater than that of 90°. This demonstrates again that a small momentum flux ratio and a nozzle injection angle against the upstream crossflow provide a beneficial condition for better mixing uniformity.
FIG. 13: Droplet distribution at different cross sections with nozzle injection angles of 60°, 90°, and 120° respectively (the momentum flux ratio is 20,710).

FIG. 14: Development of velocity vector fields with nozzle injection angles of 60°, 90°, and 120° respectively (the momentum flux ratio is 20,710).

4. CONCLUSIONS

Along the longitudinal direction, mixing falls into three regions, namely, the vortex controlling region in the upper section, the horizontal movement controlling region in the middle section, and the impingement controlling region
FIG. 15: Degrees of mixedness with momentum flux ratios of 20,710, 6762, and 3314, respectively (a nozzle injection angle of 60° is used).

FIG. 16: Degrees of mixedness with momentum flux ratios of 20,710, 6762, and 3314, respectively (a nozzle injection angle of 90° is used).

in the lower section. The vortex is the main feature in the flow field of the cone spray droplets in the crossflow. The CVP immediately forms near the nozzle when the spray jet is introduced into the crossflow and it plays a decisive role in the mixing. In addition to the CVP, the shear layer vortices that appear in the flow field also play a part in the droplet dispersion and distribution. Also, other vortices are detected, such as the leading vortex and multiple vortices.

The CVP experiences four successive phases of development under different conditions, i.e., formation, growth, attenuation, and disappearance. The CVP helps transfer the spray droplets from droplet-rich to droplet-sparse regions, and also contributes to a preferential distribution of the droplets. The small-scale CVP appears to be more favorable for achieving better mixing uniformity in comparison with the large-scale CVP.
The experimental results demonstrate that a smaller water/air momentum flux ratio contributes to a small-scale CVP, while an inclined nozzle with an injection angle against the upstream crossflow allows the CVP to occur prematurely and suppresses the growth of the CVP. Both tendencies are beneficial for mixing uniformity.

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