Experimental study on impingement spray and near-field spray characteristics under high-pressure cross-flow conditions

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ABSTRACT

The fuel spray injected into a direct injection (DI) engine is substantially affected by both the in-cylinder air flow and the piston cavity wall impingement. The combined effect of the air flow and the wall impingement plays an important role on the spray development, mixture formation, and subsequent combustion. In this study, the effects of cross-flow and flat wall impingement on the spray development and dispersion were investigated. The spray was injected by a valve covered orifice (VCO) nozzle under various cross-flow velocities and ambient pressures. Impingement spray images in a vertical plane and several horizontal planes were obtained by a high speed video camera and a continuous wave laser sheet. A high speed video camera connected with a long-distance microscope was employed to obtain the near-field spray images. The results show that cross-flow favors spray dispersion while the high ambient pressure tends to compress the spray profile. Additionally, under an approximate liquid-to-air momentum flux ratio q, when the ambient pressure and cross-flow velocity were varied, at 2 ms ASOI the outlines of the spray in the windward side agree well, whereas the spray extended further in the leeward side at a lower ambient pressure. At the plane of y = 25 mm, a complex vortex movement was observed that resulted in a non-uniform distribution of droplets in the upper part of the spray in the leeward side. In addition, at the plane of y = 45 mm, an empty belt area occurred in the vortex core region revealing that the density of the droplets in this region was quite low. The quantitative analysis shows that with increasing cross-flow velocity, the spray tip penetration decreases slightly before impingement while the spray tip penetrates further on the wall surface after impingement. The high cross-flow velocity favors the spray breakup and dispersion leading to a larger wall-jet vortex while the high ambient pressure restrains the spray dispersion leading to a smaller spray tip penetration and vortex height. For near-field spray, the spray image at higher ambient pressure shows fewer ligaments. With increasing cross-flow velocity, the whole spray shifted downstream. The spray outline was wider at the initial stage (0.05 ms ASOI) than that at steady stage (2 ms ASOI) of spray evolution.

1. Introduction

Owing to the advantages of good fuel economy and high thermal efficiency, direct injection (DI) gasoline engines have widely been applied in the automotive field [1]. The DI gasoline engines include two combustion modes: stratified charge combustion and homogeneous combustion. For stratified charge combustion mode, the fuel spray is injected into a cylinder at the compression stroke. For the homogeneous combustion mode, the fuel spray injection usually occurs during the intake stroke [2,3]. In either mode, the air flow movement in the cylinder is strong enough to influence the fuel spray characteristics, such as spray profile, spray breakup, and fuel–air mixing [4]. In a real engine, the study of the effects of air flow on the fuel spray is exceptionally difficult because of the complicated and changeable air flow field [5]. Moreover, the theoretical and fundamental studies under a single condition are insuffi cient. Therefore, it is necessary to introduce a cross-flow to simulate the influence of swirling air flow on the fuel spray in the cylinder. The cross-flow is a particular air flow that is perpendicular to the direction of spray injection.

Recent studies on the spray characteristics in a cross-flow field focused on the interactions between the free spray/jet and cross-flow. Moon et al. [6] used a slit injector to study the effect of a cross-flow on
free spray profiles. It was noted that the variations caused by a cross-flow were different at various parts of the spray. A significant variation was present at the bottom part of the spray, while a slight variation was found near the nozzle exit. With respect to the free spray tip penetration, Guo et al. [7] found that increasing the cross-flow velocity slightly decreased the vertical spray penetration and caused a noticeable increase in the horizontal spray penetration. The breakup of free spray injected into a cross-flow field was reported by some researchers [8–10]. Their works clarified that the cross-flow could promote secondary breakup and have a marked impact on the transport of secondary droplets. These studies have provided an insightful comprehension of the effect of cross-flow on free spray, but did not consider impingement.

In a real DI gasoline engine, owing to the high injection pressure and small cylinder, the fuel spray might impinge on the piston cavity wall before being fully vaporized. Spray impingement usually influences fuel atomization and combustion, resulting in excessive hydrocarbon (HC) and soot emissions [11]. Hence, it is considerably relevant to study the effect of cross-flow on impingement spray than free spray for a real DI gasoline engine. However, only a few investigations reported the impingement spray characteristics under cross-flow conditions. Panão et al. [12,13] reported the application of the mie-scattering method and shadowgraph technique to provide a macroscopic observation of an impingement spray in a cross-flow. They observed that the main spray structure shifted downstream with increasing cross-flow velocity. Based on the results, two stagnation points were also identified in the impingement region and upstream respectively. Arcoumains and Cutter [14] used a phase-Doppler anemometer (PDA) system to investigate the effect of cross-flow on the droplet size and velocity characteristics of an impingement spray. These works clarified that the overall mean droplet size and velocities became larger under cross-flow conditions owing to the smaller droplets entrained by the cross-flow. The formation of a droplet cloud was also observed in the downstream of the spray. Arcoumains et al. [15] have investigated the influence of a preexisting liquid film on an impingement spray under cross-flow velocities of 5 and 15 m/s and atmosphere pressure. They found that the wall film became thicker in a cross-flow that decreases the diameter of the droplets generated from secondary breakup. In these studies, the interaction between the wall-jet vortex structure and the post-impinged droplets was also discussed. However, these studies are still not sufficient to explore the effects of cross-flow on the impingement spray characteristics, especially for the spray structures in different dimensions and rolled-up vortex motion.

As for the near-field spray, the previous work only concentrates on the study in quiescent atmosphere. Roisman et al. [16] evaluated the spray breakup length and effect of ambient pressure on the spray tip region. The breakup process was explained by Bae and Kang [17] using a long-distance microscope. They observed that the ligaments were produced by the disturbed spray surface and small droplets were generated at the end of the ligaments. Tang et al. [18] used an optical long-distance microscope to investigate the spray primary breakup and found that the high injection pressure promoted the spray primary breakup while the high ambient pressure restrained it. However, the near-field spray behaviors in a cross-flow were not completely clarified in the previous works owing to the lack of near-field spray information under cross-flow conditions.

The aim of this study is to examine the effect of cross-flow on the structures of impingement spray and near-field spray in a high pressure wind tunnel. A flat wall was employed as the impingement wall in place of a piston cavity wall. The images of impingement spray were recorded by a high speed video camera using a laser sheet technology and the near-field spray images were captured by applying long-distance microscopy. Spray tip penetration and vortex height were obtained from the impingement spray images for quantitative analysis. The effects of cross-flow velocities and ambient pressures on the spray structures were experimentally studied to provide further physical insight into the impingement spray motion and primary breakup.

2. Experimental setup

The details of the cross-flow wind tunnel system used in the study have been reported previously [19], and a brief description is provided here. Fig. 1 is a schematic of the high pressure wind tunnel that was applied to provide a uniform cross-flow field. It consists of the diffusion section, the rectification section, the contraction section, the observation chamber and two control valves. Guide vanes are used in the diffusion section to diffuse the air flow, and mesh screens are utilized in the rectification section for uniform air flow. The uniform cross-flow is acquired in the observation chamber located downstream of the contraction section. The cross-flows with various velocities and pressures are obtained by adjusting the open areas of valve 1 and valve 2. The timing sequences of valve control, cross-flow velocity evolution, and ambient pressure evolution with a cross-flow velocity of 5 m/s are shown in Fig. 2. In this case, valve 2 was set at a 61° (0° is closed and 90° is fully opened) opening angle and valve 1 was fully opened. The pressure in the chamber increased rapidly to a peak value and then dropped gradually. When the cross-flow velocity and ambient pressure...
would achieve the experimental conditions, the pulse generator would be triggered to operate the spray injector and camera.

The light source used in the experiment was a continuous wave laser sheet (DPGL-2W, Japan Laser Corp.) with wavelength of 532 nm and thickness of 1 mm. A high speed video camera (Photron FASTCAM SA-Z) was applied to record the tomographic images of the impingement spray with a frame rate of 40,000 fps and frame size of 1024 × 512 pixels. After calibration, the field of view is 4880 × 2440 μm².

The window size of the observation chamber is 200 mm in length with a 100 × 100 mm² inner section, as shown in Fig. 5. The window is composed of Pyrex. A valve covered orifice (VCO) type nozzle was fixed on the upper surface of the chamber with a 25° spray angle to maintain the spray direction perpendicular to the direction of the cross-flow. The hole diameter of the single-hole VCO nozzle is 0.15 mm. A hot wire anemometer possessing a short response time was assembled to monitor the cross-flow velocity, and a high sensitivity pressure transducer was employed to measure the ambient pressure in the chamber. The impingement wall was composed of transparent acrylic with 140 × 90 mm² size placed below the injector, and the impingement distance was maintained at 50 mm based on the impingement condition of a 1.5 L displacement DI gasoline engine. The nozzle tip position was defined as the origin O of this coordinate system. The direction of cross-flow is along the positive x-axis, whereas the injection direction is along the positive y-axis. Dry-solvent was utilized as a test fuel in this study, since its physical property is close to that of gasoline. In addition, the dry-solvent possesses a higher ignition point. The density and viscosity of the dry-solvent are 0.77 g/cm³ and 1.3 mm²/s (at 20 °C), respectively. The surface tension is 23.9 mN/m (at 20 °C). In our previous study on free spray [19], the injection duration was 4 ms and cross-flow velocity was 5 m/s. In order to compare free spray and impingement spray in the future, we chose the same condition with free spray experiment. In this experiment, the injection pressure is 10 MPa and the ambient pressure varies between 0.1 and 0.4 MPa. The measurement at every condition was repeated three times. The detailed experimental
conditions are listed in Table 1.

3. Results and discussion

3.1. Cross-flow velocity distribution

The uniformity of the cross-flow velocity distribution was examined using PIV technology that has been described in detail previously [20]. The test section was in the xoy plane and above the impingement wall. Fig. 6(a) represents the velocity vector distribution under a cross-flow of 5 m/s and an ambient pressure of 0.4 MPa. The velocities were approximately 5 m/s and the direction distributions were almost uniform except in the areas behind the nozzle and near the wall. In order to show the detailed velocities, the cross-flow velocities in lines of x = 0 and 40 mm are plotted respectively, as shown in Fig. 6(b). In this study, the velocity curves are the average results obtained by conducting the tests five times. The difference of the maximum and average velocities is the positive error bar, and the negative error bar refers to the difference of the minimum and average velocities. It is noted that from y = 0 to 2 mm, the cross-flow velocity in the line of x = 0 mm is lower than that in the line of x = 40 mm owing to the effect of the nozzle tip, and from y = 48 mm to the wall, the velocity decreases gradually. Within the domain of y = 2–48 mm, the velocity is approximately 5 m/s that offers a uniform condition for the impingement spray.

3.2. Impingement spray

3.2.1. Spray in vertical plane

Fig. 7 shows the image processing method and structure of an impingement spray. The raw image was shown in a false color format based on the image brightness. False color images were used in the study owing to the fact that they are beneficial to observe droplets distribution and the details of the spray structure. The impingement spray structure mainly includes the main jet region, mixing flow region, wall main jet region, stagnation region, and wall-jet vortex [21]. The main jet region refers to the middle section of the incoming spray. After the spray impinged on the wall, the wall main jet appeared with secondary droplets generated owing to splash and rebound. Some secondary droplets were entrained by the wall-jet vortex formed around the wall. The stagnation region was located on the edge of the impingement region, where the droplets with exceedingly low momentum nearly stagnated. The droplets adhering on the wall surface contributed to the formation of the wall film.

Fig. 8 shows the impingement spray profiles versus time under different cross-flow velocities and ambient pressures. For $P_a = 0.1$ MPa and $U_x = 0$ m/s case, after spray impingement on the wall, the spray vertical momentum was converted into radial momentum, and a wall-jet vortex developed along the wall surface, resulting in a lower density for the post impingement spray. Thus, a lean mixture was formed in the post impingement spray. Due to the window size of the observation chamber is not large enough the spray upstream structure was not captured, resulting in the spray is not symmetrical in Fig. 8. For $U_x = 5$ m/s case, numerous tiny droplets in the middle and bottom of the spray were entrained by cross-flow, flowing to the downstream side. The reason is that small droplets at the edge of the middle and bottom spray lose their initial momentum in a short time and follow the cross-flow, while the droplets and ligaments in the near nozzle region tend to follow their initial trajectory owing to a high vertical momentum. In the windward side, the spray edge is smooth, which is different from the quiescent case that showed saw-tooth waves for the edge. We believe that the smooth edge occurred under the cross-flow condition owing to the spray breaking up into tiny droplets at the edge and the droplets being blown downstream. The main spray body was shifted downstream, and the spray trajectory had a large distortion in the windward side. The wall-jet vortex in the downstream side also became larger and penetrated further owing to a large stream wise momentum under cross-flow condition. It can be seen that cross-flow promote spray dispersion, and the droplets distributed non-uniformly at the leeward side. Moreover, the spray became dense and the penetration velocity of the spray tip was decreased because increased density of the ambient gas leads to increased air resistance. It was interesting to note that under the cross-flow condition, a considerable amount of tiny droplets were
observed in the leeward side at higher ambient pressure, owing to the larger momentum flux of cross-flow.

The wall-jet vortex structure is a key feature for the impingement spray that could promote air entrainment and fuel–air mixture formation. Fig. 9 displays the effects of ambient pressure and cross-flow velocity on the vortex structure at 4 ms after start of injection (ASOI). At atmospheric pressure, the rolled-up spray tip spread along the wall in a circular shape and it spread further downstream with increasing cross-flow velocity. In addition, the tip position of wall-jet vortex is indicated by the red line. The tip becomes much sharper at higher cross-flow velocity. This is because cross-flow increases the radial velocity of the wall-jet vortex, leading to an increased shear force from the ambient air. Moreover, the phenomenon of a larger vortex structure and considerably severe breakup under cross-flow conditions suggests that the cross-flow is beneficial for spray dispersion and mixture formation.

Under 0.4 MPa ambient pressure, the vortex shape was more regular than that under 0.1 MPa ambient pressure. At 5 m/s cross-flow condition, the vortex height at 0.4 MPa is about 18% smaller than that of 0.1 MPa. This is primarily because of the larger drag at a higher ambient pressure that leads to decreased penetration velocity and consequently a less severe breakup occurrence. It is noteworthy that though increasing the ambient pressure causes a weak air-entrainment motion, this does not mean that the fuel–air mixture formation would become poor under higher ambient pressure because the air-entrainment has higher density. In order to better analyze the behavior of the wall-jet vortex, the vortex structure was enlarged, as shown in the right image of Fig. 9. It could be seen that the rolled-up structure is formed near the wall surface caused by the interaction between droplets and gas. Droplets were generated by secondary breakup of liquid film on the wall. The rolled-up motion and momentum exchange between the ambient air and fuel spray occurred near the vortex region. It illustrates that the ambient gas could be entrained into the spray jet when the vortex is growing. In this image, the red arrow indicates the global direction of rolled-up motion of the vortex, and the yellow arrows display the velocity direction of single droplet in the vortex edge; the pink arrow represents the direction of air-entrainment near the wall-jet region, and the black arrow indicates the flow direction of wall-jet. It is interesting to notice that the spray concentration is considerably low in the vortex core region, which is indicated by a red circle. The tip of the wall-jet vortex penetrated further compared to the fuel film distribution.
above the wall surface; thus, the fuel film edge is at a position behind the vortex tip.

In Fig. 10, the effect of cross-flow velocity on the spray outline is analyzed at the ambient pressure of 0.4 MPa and time of 4 ms ASOI. In order to clearly distinguish the outline of the spray, a threshold level of 20 out of 255 was used. The red and blue curves represent the spray outlines under the cross-flow velocities of 0 and 5 m/s, respectively, and the difference between them is significant. At no cross-flow condition, the spray outline is distributed almost symmetrically, however, under the cross-flow velocity of 5 m/s, the outline shifted downstream. The area of outline at cross-flow condition was evidently larger than that of without cross-flow, and this reveals that the cross-flow could improve spray dispersion. Two interesting phenomena have been illustrated in this figure. First, under the cross-flow condition, numerous tiny droplets were distributed in the upper region of the spray at the leeward side, and the droplets distribution was non-uniform. This illustrates that the movement of the droplets in this part has exceeded the laser sheet plane. We consider that this phenomenon maybe caused by spray fluctuation and it is further explained in detail in Section 3.2.2. Secondly, in the windward side, without cross-flow, some droplets were distributed near the outline; however, under cross-flow condition there was no droplet.

The liquid-to-air momentum flux ratio \( q \) is an important parameter used to determine the distortion of the spray profile [22]. The definition of \( q \) is given by \( q = (\rho_l U_l^2/\rho_x U_x^2) \), where \( \rho_l \) is the fuel density, \( U_l \) is the injection velocity, \( \rho_x \) and \( U_x \) are the density of ambient air and cross-flow velocity, respectively. In theory, when the values of \( q \) are similar, the distortions in the windward side should agree satisfactorily. Fig. 11 compares the spray outlines under almost the same momentum ratio. The red line refers to the spray outline under ambient pressure of 0.1 MPa and cross-flow velocity of 9.6 m/s. The velocity is set at 4.4 m/s under 0.4 MPa ambient pressure, as shown in the blue line. According to the PIV results in previous experiment [19], the spray velocity at 0.1 MPa and 0.4 MPa were 93.4 m/s and 82.2 m/s, respectively. Under two cases it can obtain the close value \( q \) (56,531 and 52,055). The outlines in the windward side agree satisfactorily, especially at the upper part. However, in the leeward side the spray outline extended further at lower ambient pressure. The reason is that at lower ambient pressure the cross-flow velocity was higher and air resistance decreased thus it is easier for spray to flow downstream. Based on the definition of \( q \), when the ambient pressure or cross-flow velocity increases, the momentum ratio decreases resulting in the downstream shift of the outline in the windward side. One interesting phenomenon is that in the outline of the windward side, almost no droplets were present, but there were numerous droplets near the outline in the leeward side. This is primarily because the spray or ligament disintegrated owing to shear force under cross-flow, especially in the windward side. The cross-flow induced secondary breakup of spray and the droplets were shifted downstream.

### 3.2.2. Spray in horizontal plane

Under cross-flow condition, some phenomena, such as the non-uniform distribution of droplets at the leeward upper region of the spray, are difficult to comprehend merely by analyzing the impingement spray behavior in the vertical plane due to the asymmetric structure of the impingement spray. To clarify the spray structure...
three-dimensional space, spray images in horizontal plane were obtained by the laser sheet and a high speed video camera. Fig. 12 provides spray image in vertical plane of \( z = 0 \) mm and its corresponding images at horizontal planes of \( y = 25 \) and \( 45 \) mm at 0.1 MPa ambient pressure. In the right image, a wave-shaped structure was observed in the horizontal plane of \( y = 25 \) mm marked by a red rectangle. The structure resembled a vortex motion, and the wave shape was almost similar to the Karman vortex street [23]. The arrows in the image are employed to indicate the fluctuation of the Karman vortex-like structure. In this region, although the wall film was not on the laser sheet plane, it still influenced the observation of the Karman vortex-like structure, leading hard to distinguish the boundary of Karman vortex-like structure. The structure of the main spray in the plane of \( y = 45 \) mm was shaped like a fish. The spray upstream region was dense and wide, but downstream, the spray became thin and narrow. This is because the spray in downstream was formed by tiny droplets entrained by cross-flow that flowed downstream. It is noted that almost no droplets were present in the stagnation region in this plane and an empty belt was observed near the vortex core region, which indicates that the droplet density in this region was quite low.

At a higher ambient pressure, as shown in Fig. 13, the phenomenon of the Karman vortex-like structure became considerably evident in the plane of \( y = 25 \) mm. This is because the cross-flow with larger momentum flux caused a considerably severe spray fluctuation. The stagnation region in the plane of \( y = 45 \) mm was smaller than that under atmospheric pressure and the wall-jet vortex was caught up by the droplet cloud entrained by cross-flow. It could be comprehended that the whole vortex structure penetrated more slowly along the wall due to the larger air resistance under high ambient pressure. Moreover, the larger momentum flux induced a considerably severe spray breakup; thus, more droplets were entrained and shifted downstream. In this case, the phenomenon of the empty belt in the vortex core region disappeared. The reason is that the position of the vortex core was below the plane of \( y = 45 \) mm.

### 3.2.3. Spray tip penetration and vortex height

The spray tip penetration \( S \) and the vortex height \( H \) are widely used to analyze the characteristics of the impingement spray [24–25]. Fig. 14 provides the definitions of \( S \) and \( H \) based on the spray profiles. As shown in Fig. 14(a), the vertical distance from nozzle exit to spray tip is...
used to express the spray tip penetration before impingement. After impingement the spray tip penetration is defined as the sum of the impingement distance \( L_w \) and radial length \( L_r \), and the vortex height \( H \) is the highest position of the vortex from the wall surface in the vertical direction (see Fig. 14(b)). The threshold of outline curve is 20 out of 255. The experimental error as shown by the error bars is added in the rest of figure. The error percentages of spray tip penetration and vortex height are below 10% and 28%, respectively.

Fig. 15 illustrates the spray tip penetration under cross-flow velocities of 0, 2 and 5 m/s at different ambient pressures. Under all conditions, the development of spray tip penetration could be divided into two stages. In the first stage, the penetration increased linearly against time before impingement, and in the second stage, the growth of penetration became slow. This phenomenon may be attributed to the fact that in the second stage, the post impingement spray breakup occurs and results in the formation of a considerable amount of droplets. For the impact regimes, researchers used the dimensionless \( K \) number (\( K \)) as the splashing threshold parameter [26].

Mundo et al. [26] found the value of \( K \) (57.7) can be used to separate the deposition and splash. When \( K \) is smaller than 57.7, most droplets deposit on the wall, otherwise most droplets splash off the wall. In this study, at 0.1 MPa ambient pressure, 5 m/s cross-flow velocity and 4 ms ASOI, the droplet diameter was 28 \( \mu \)m and velocity was 29 m/s measured by PIA (Particle Image Analyzer) system in the location of \( x = 2 \) mm, \( y = 48 \) mm, \( z = 0 \) mm. In this case (\( K = 725.4 > 57.7 \)) most droplets splash off the wall after impingement. Moreover, a friction force from the wall could be regarded as another factor that decelerates the spray tip velocity after the spray impinged on the wall. With increase in the cross-flow velocity, the spray tip penetrations markedly increased after impingement, while before impingement the penetrations were nearly constant. At higher ambient pressure, at a given time the spray tip could penetrate shorter distance, and the penetration difference between various cross-flow velocities is smaller than that under low ambient pressure.

To clarify the effect of cross-flow on the spray tip penetration before impingement, the penetration results of the early stage of spray evolution were shown in Fig. 16. Under an ambient pressure of 0.1 MPa, the penetrations were almost the same before 0.35 ms ASOI, but after the 0.35 ms ASOI, the penetrations slightly decreased as cross-flow velocity increased. When ambient pressure is 0.4 MPa, increasing the cross-flow velocity evidently decreased the penetrations, especially after 0.5 ms ASOI. This is because the shear force increased with the increase in cross-flow, causing the breakup of spray tip then the vertical velocity of spray tip decreased. At higher ambient pressure, the increased momentum flux of cross-flow led to considerably severe breakup and larger momentum loss of the spray thus this phenomenon became substantially evident. The evidence based on the slip Weber numbers was provided to justify the statement. The Weber number (\( \text{We} \)) is defined as

\[
\text{We} = \frac{\rho v^2 d}{\sigma}
\]

When ambient pressure is increased, the parameter of air density \( \rho \) increases and the spray column \( d \) increases due to larger spray angle under higher ambient pressure [27]. The parameter of velocity \( v \) and surface tension \( \sigma \) is constant. So the slip Weber number increases with the increase of ambient pressure. Therefore higher ambient pressure led to more severe breakup.

Increases in the cross-flow velocity tended to a larger vortex height in the cases of 0.1 and 0.4 MPa ambient pressures, as shown in Fig. 17. The reason of this phenomenon maybe is that after cross-flow through the upstream side vortex and main spray body, its flow direction maybe produce fluctuation and become non-uniform in horizontal direction. Then the fluctuating cross-flow in the downstream side influence the dispersion of vortex, resulting in the formation of a larger vortex shape. When the cross-flow velocity is fixed, the density of ambient air increases with the increase in ambient pressure, leading to an increased penetration resistance that in turn decreased the momentum of the impingement spray and so reduced the vortex height \( H \). The splashing resistance also increased, and this inhibited the splashing of secondary droplets and thus further decreased the vortex height.

### 3.3. Near-field spray

Because of the high turbulence behavior of spray flow at the exit of the nozzle, observing the spray behavior at near-nozzle region, where spray breakup occurs, is beneficial to understanding the mixing and breakup processes of spray. Moreover, in the above analysis, the effects
of cross-flow and ambient pressure on the macroscopic structure of the impingement spray are evidently, however, the effects on the near-field spray is unknown. Thus, another important work in this study is to investigate the effects of cross-flow and ambient pressure on the near-field spray.

Fig. 18 shows how we process the raw image of near-field spray and the image description. The raw image was inverted thus the gray value of black has a count of 255 and the white of 0 and consequently the gray value is larger at dense spray region. It is not easy to identify the nozzle shape in this image owing to the residual fuel, thus the nozzle shape is indicated by a yellow arc here. To observe the droplets distribution in a substantially intuitive manner, the gray values were extracted in a line of $y = 3.75$ mm which is located at 25 times of nozzle hole diameter downstream from the nozzle exit, as shown by the line marked with green dots.

Fig. 19 shows the effect of cross-flow velocity on the spray profiles at the immediate nozzle downstream ($y < 5$ mm) with ambient pressures of 0.1 and 0.4 MPa. In this figure, two typical images at 0.05 ms and 2 ms were shown, corresponding to the initial stage and the steady stage of spray evolution respectively. The effect of cross-flow on the initial spray seemed weak; however, cross-flow caused droplets distribution in both sides of the spray quite differently at 2 ms ASOI. There are almost no droplets in the windward side but numerous tiny droplets are distributed in the leeward side, as shown in the red rectangle. The droplets in the windward side were entrained by cross-flow and shifted downstream. For initial spray, only a few ligaments and droplets were generated at the spray edge under high ambient pressure of 0.4 MPa, and this is evidently different from that of lower ambient pressure ($P_a = 0.1$ MPa) that show numerous ligaments and droplets formation because of the residual fuel breakup. This phenomenon could be explained based on the fact that at a higher ambient pressure, the residual fuel of the last injection was compressed to 0.4 MPa before the injection occurred. Thus, the denser spray tip is less easy to breakup into ligaments and droplets compared with that at lower ambient pressure.

Fig. 20 compares the gray value distributions in a line of $y = 3.75$ mm. At low cross-flow velocity, the gray value in windward side is larger than that in the case of high cross-flow velocity, which suggests that a considerable amount of droplets were shifted downstream under cross-flow condition. Particularly at a 0.4 MPa ambient pressure, the whole spray evidently shifted downstream because of cross-flow. This phenomenon was considerably evident at higher ambient pressure due to its larger momentum flux at the same cross-flow velocity. Near the axis of the nozzle hole, the gray value distributed.
unevenly at lower ambient pressure compared with that at higher ambient pressure. This is because the spray at higher ambient pressure was compressed thereby the spray became dense and uniform.

The outlines of near-field spray in various cross-flow velocities plotted by colored curves are listed in Fig. 21. The threshold of outline curve is 20 out of 255, and the curve was selected based on the condition whose penetration is almost same with the average penetration. At the time of 0.05 ms ASOI, for a given cross-flow velocity, the spray tip penetration decreased as the ambient pressure increased. This is primarily attributed to the larger aerodynamic drag force under higher environmental gas density. In the case of 0.4 MPa ambient pressure and 0.05 ms ASOI, the spray tip penetration evidently decreased with increasing cross-flow velocity, and this phenomenon is consistent with the quantitative analysis in Fig. 16. From the images at 2 ms ASOI, we could visualize that the whole spray curve shifted downstream with the increase in cross-flow velocity, and this phenomenon is consistent with the quantitative analysis in Fig. 16. From the images at 2 ms ASOI, we could visualize that the whole spray curve shifted downstream with the increase in cross-flow velocity, and this phenomenon is consistent with the quantitative analysis [28].

4. Conclusion

An experimental study was conducted to investigate the effect of cross-flow on the characteristics of impingement spray and near-field spray at different ambient pressures. A high speed video camera and a continuous wave laser sheet were employed to capture the impingement spray profile in a vertical plane and two horizontal planes. The near-field spray behavior was detected by a high speed video camera connected with a long-distance microscope. Spray tip penetration and vortex height were obtained from the captured impingement spray images for quantitative analysis. The main conclusions of this study are listed below:

1. Under the almost same liquid-to-air momentum flux ratio $q$, when the ambient pressure and cross-flow velocity were varied, the impingement spray outlines in the windward side were almost coincident, particularly at the upper part, but in the leeward side, the outline extended further at lower ambient pressure.

2. In the plane of $y = 25$ mm, the movement of the Karman vortex-like structure was observed that resulted in a non-uniform distribution of droplets in the upper part of the spray in the leeward side. In the plane of $y = 45$ mm, in the vortex core region, the droplets density was quite low, showing an empty belt.

3. With increase in the cross-flow velocity before impingement, the spray tip penetration decreased slightly, while it evidently
increased after impingement. The increased cross-flow velocity led to an increase in the vortex height because of the enhanced spray dispersion. The high ambient pressure restrains the spray dispersion and leads to a shorter spray tip penetration and smaller vortex height.

(4) For near-field spray, the image at a higher ambient pressure shows few ligaments and droplets. When the cross-flow velocity is increased, the whole spray profiles were evidently shifted downstream. Moreover, the spray outline was wider at the initial stage (0.05 ms ASOI) than that at steady stage (2 ms ASOI) of spray evolution.

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Reference