Experimental study on the effect of nozzle hole-to-hole angle on the near-field spray of diesel injector using fast X-ray phase-contrast imaging

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ABSTRACT

Fuel atomization and vaporization process play a critical role in determining the engine combustion and emission. The primary near-nozzle breakup is the vital link between the fuel emerging from the nozzle and the fully atomized spray. In this study, the near-nozzle spray characteristics of diesel injectors with different umbrella angle (UA) were investigated using fast X-ray phase-contrast imaging and quantitative image processing. A classic ‘dumbbell’ profile of spray width (SW) composed of three stages: opening stage, semi-steady stage and closing stage. The SW peaks of two-hole injectors were more than twice of that of single-hole

injector at the opening and closing stages, corresponding to the hollow-cone spray. This indicated the vortex flow was formed with the increase of the UA. The higher injection pressure had little influence on the SW while led to earlier breakup closer to the nozzle at lower needle lift. Significant fuel effect on the SW at higher needle lift was found. However, this effect could be neglect at lower needle lift due to the leading role of internal flow and cavitation on the near-field spray characteristics. In addition, the morphology-based breakup process was observed, which highlighted the important effect of internal flow on the spray development. The possibility of using hollow-cone spray in diesel injector was also discussed.

1. Introduction

In order to meet more strict emission regulation and improve the efficiency in diesel engine, the crucial issue is to control and optimize the spray atomization and combustion process[1, 2]. From the view of relationship between spray and combustion, fuel atomization and vaporization process play a critical role in determining the engine combustion and emission due to strong link between the flame liftoff and spray characteristics[3]. Moreover, the spray characteristics are strongly influenced by the flow dynamics inside the injector nozzle, which largely depend on the nozzle geometry due to the effect of cavitation and turbulence[4].

There are many papers focusing on the effect of nozzle geometry on the fuel spray characteristics. The macroscopic spray characteristics have been investigated with the variation of nozzle hole parameters[5, 6]. In the recent 10 years, more attention has been drawn by the geometry effect on the internal flow which has significant impact on the cavitation appearance and turbulence[7-9]. As a result, variation of the discharge coefficient, exit velocity distribution and injection rate were found[10, 11]. Especially, the vortex flow in the sac, observed in the multi-hole injector[12, 13], had significant influence on the spray penetration and spray width, and increased the spray instability[8, 14]. The recent studies on effect of hole position[15] and spray comparison between single-hole and two-hole injectors[16] indicated the vortex flow could be induced by the hole position or angle, which led the flow to rotate in the sac. However, few studies investigated the effect of nozzle hole angle on the spray characteristics. This is important to reveal the effect of hole location on the internal flow and improve the nozzle design.

It is well known that two break-up processes are involved in the diesel spray: primary break-up and secondary break-up. The primary break-up is the vital link between the fuel emerging from the nozzle and the fully developed spray[17]. However, the primary break-up in the diesel spray has always been ignored because of the dense fuel density in the near-nozzle field (region of primary break-up). It is difficult to visualize the dense spray field using conventional optics methods even though some methods have been used to analyze the primary break-up[18-21]. Therefore, the breakup process is not well understood for high-pressure diesel injection. Recently, fast X-ray phase-contrast imaging has been used to capture the spray morphology in the near-nozzle field [15, 22-24], which make it possible to reveal the primary breakup in high-speed diesel spray. Moreover, the experimental data on the primary breakup is crucial for development and validation of the models and simulations[25].

In this study, the near-nozzle spray characteristics were investigated using two-hole diesel injectors and single-hole injector with different hole-to-hole angle by means of a propagation-based X-ray phase-contrast imaging (XPCI) technique. The effects of injection pressure, needle lift and fuel properties on the spray width and morphology were analyzed.

2. Experimental methods

2.1 XPCI set-up

The detailed XPCI set-up has been described in another paper[26], so a simple introduction of the experimental set-up was made here, as shown in Fig.1a. We conducted the XPCI experiments at 7ID and 32ID beamlines at the Advanced Photon Source (APS) of Argonne National Laboratory. The X-ray white beam and hybrid singlet mode were used. The special hybrid beam mode, shown in Fig.1b, composed of a single electron bunch and eight electron train bunches by symmetrical 1.594 μ s gaps. A millisecond shutter (1Hz) and a microsecond shutter (500Hz) were arranged to chop the X-ray in order to reduce the heat power of the beam. A fast-scintillator crystal converted the transmitted X-rays into visible light, which was reflected by a 45°mirror and reached a fast CCD camera (Sensicam HS-SVGA, 1,024×1,280 pixels, 1Hz) equipped with microscope

1 objective lenses. The effective pixel size of the camera was 0.63 or 1.26 μm for a 10 $\times$ or 5 $\times$ objective lenses
 2 respectively. The single bunch and eight bunches were used to record the images of spray and needle lift
 3 respectively.

(a)

(b)

Fig.1. The XPCI setup and hybrid beam mode in APS

2.2 Two-hole diesel injectors

In order to investigate the effect of hole-to-hole angle on the near-nozzle spray, a single hole and three two-hole diesel injectors were used in the present experiment. The definition of umbrella angle (UA) was the angle between two axes of nozzle orifices, as shown in Fig.2. The nozzle UA70 represented two-hole injector with the UA of 70°. Needle and nozzle body are noted in UA70 image. The nozzle internal structure corresponded to the red region of an injector schematic diagram, as shown in Fig. 2b. The energization and deenergization of an electric solenoid (or piezo) opens and closes the outlet restrictor by the upward and downward movement of ball. The open and close of outlet restrictor change the flow through the inlet restrictor and outlet restrictor. The resulted pressure difference between valve-control chamber and needle forces the needle valve upward and downward. The fuel is injected into the combustion chamber during the needle movement. The needle moving speed is determined by the difference in the flow rates through the inlet and outlet restrictors. More details on the operation principle of a diesel injector can be found in the reference[27]. The injectors have the same nominal hole diameter of 0.12mm, sac diameter and similar hydro-grinding level. The two-dimension images of internal structure for these four injectors are shown in Fig.2a. The measured diameters of nozzle orifices were very close to the designed diameter with a deviation of $\pm 2 \mu\text{m}$ based on the X-ray images.

Fig.2. Internal structures of four nozzles with different UAs.

2.3 Experiment conditions

High injection pressure was generated by a commercial common rail injection system which composed of fuel tank, motor, high pressure pump, common rail, pressure control unit and high pressure line. In order to scavenge the fuel vapor and improve the image quality, a gentle flow of the nitrogen gas was continuously supplied into the spray chamber. Two special Kapton windows on the spray chamber were used to effectively reduce attenuation of X-ray intensity. The high-pressure fuels were injected into a quiescent nitrogen gas ambient from diesel injectors with different nozzles. Two fuels were used in the spray experiments: US No.2 diesel (D) and sunflower biodiesel (SFB). Table 1 lists the detailed experiment conditions. The densities (25°C) of D and SFB are 835.2 and 849.9 kg/m³, and kinematic viscosities (25°C) are 3.32 and 5.4 mm²/s.

Table 1. Parameters of experimental conditions

Injection pressure (P_{inj})	30 and 100 MPa
Injection pulse duration (T_{inj})	2.0ms
Injection repeat	More than 10
Ambient pressure	Atmospheric (0.1 MPa)
Ambient temperature	Room condition (302 K)
Ambient density	1.25 kg/m ³ with nitrogen (N ₂)

3. Results and discussions

3.1 Effect of UA on the spray width

The primary breakup is the key link between initial jet and final spray. For diesel injector, spray characteristics in the near-nozzle field have been used to analyze the primary breakup[28] [29]. In general, biodiesel with higher viscosity can delay the breakup of spray and lead to more stable spray morphology, compared with diesel. In the present experiment, the spray width (SW) of SFB was measured in the whole injection process. The definition of SW was the distance between right boundary and left boundary perpendicular to the spray axis at the location of 1.5mm away from the nozzle exit, as shown in Fig. 3a. Figure

3b shows the needle lift measurement based on the image cross-correlation of red matching template with matching resolution of 1 pixel.

Fig. 3. Measurement of SW and quantitative cross-correlation image processing

Figure 4 shows the needle lift profiles of UA130 at the injection pressures of 30 and 100MPa because the needle lifts for the different injectors were similar. Under the present experimental conditions, the needle reached the top mechanical location at the injection pressure of 100MPa and there was a small duration of semi-steady stage. If the injection pressure was lower than 100MPa, the needle kept moving in the whole process without reaching the limit. That is to say, the needle was still in the transient condition. Since the needle opening speed is determined by the difference of flow rate between inlet restrictor and outlet restrictor (Fig.1b)[27], higher injection pressure led to higher needle opening speed due to larger pressure difference caused by larger difference of flow rates between two needle ends. The similar needle closing speed, independence on the injection pressure, can be attributed to the similar flow rate in the inlet restrictor.

Fig. 4. Needle lift profiles of UA130 at two injection pressures

Figure 5 shows the SW of different injectors at two injection pressures. It can be seen that the SW profile in the whole needle lift was like a “dumbbell”. There were three stages in the SW profile: the opening stage (OS) was defined as the first peak region of SW; semi-steady stage (SS) as the middle stable SW range; closing stage (CS) as the second peak region of SW. The relationship between SW and needle lift were similar to the other experimental and simulation results[30, 31]. At the OS and CS, significant SW peaks and fluctuation were observed and nozzles with larger UA had larger SW. However, the SW profile at the OS was different from that at the CS. At 30MPa injection pressure, there is one peak of SW at the needle lift lower than 100μm at the OS. The SW of two-hole injectors was around 0.6mm, twice as much as the SW of UA0. The second SW peak of UA130 and UA160 at the needle lift between 200 and 300μm, the SW even reached more than 0.8mm. At the CS, the SW peak of UA0 was around half of other three nozzles. At 100MPa injection pressure, two SW peaks merged to one at the OS. The two-hole injectors generally led to larger SW peak compared to single-hole injector. Besides the largest SW appeared for the UA130 injector at the OS, the SW at the OS and CS was similar at two injection pressures. This indicated the injection pressure had little influence on the macroscopic SW at the OS and CS, which implied the significant role of internal flow on the spray characteristics. At the SS, similar SW and little fluctuation were found for those four injectors. The existence of stable range of SS indicated that the needle movement could have little effect on the internal flow until the needle moved up to a

1 threshold location. Figure 6 shows the average SW of four injectors at the SS. Larger SW at the SS was found
 2 under the higher pressure condition due to high fuel-air interaction at high flow speed and high turbulence in the
 3 spray.

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Fig. 5. Effect of UA on the SW at two injection pressures.

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Fig. 6. The SW of different injectors at the top needle lift.

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3.2. Spray morphology analysis

1 The spray characteristics and stability can be analyzed not only from the macroscopic parameters, e.g., spray
2 penetration and spray angle or width, but also from the spray morphology. Spray morphology analysis has made
3 significant contribution in revealing two primary breakup mechanisms[32, 33] and formation mechanism of
4 emerging spray[34]. In this section, the spray morphology analysis was used to investigate the effects of UA
5 and needle lift on the near-field spray characteristics.

6 The movement of needle at the OS and CS resulted in the largest variation of SW. The regions of needle lift
7 corresponding to SW peaks were selected to analysis the spray morphology. At the SS, the spray images at the
8 top needle location were selected. Figure 7 shows the spray morphologies under seven conditions: four needle
9 lifts (100 μ m, 200 μ m, 540 μ m and 100 μ m) at 30MPa injection pressure due to two SW peaks in the OS for
10 UA130 and UA160 and three needle lifts (100 μ m, 960 μ m and 100 μ m) at 100MPa. The nozzle location and
11 spray were noted in the Figure 7a.

12 At the lower needle lift, around 100 μ m, the spray breakup was very close to the nozzle exit at 30MPa injection
13 pressure except UA0. The UA0 shows no breakup at the near nozzle field and the SW peak for UA0 was around
14 50 μ m. In general, the flow choke effect at the lower needle lift could induce the cavitation in the nozzle hole.
15 The enough cavitation bubbles in the nozzle hole could improve the spray atomization and result in fast breakup.
16 Therefore, cavitation could dominate the near-nozzle spray at lower needle lift. However, it should be noted that
17 the SW of UA0 is much smaller than that of other three nozzles, only half SW of two-hole injectors. This
18 indicated another flow mechanism inside the nozzle sac was induced by the UA. Theoretically, the UA0 nozzle
19 could not induce the vortex flow due to no sac room for the flow rotation. On the contrary, the flow in the two-
20 hole injectors should reach the sac bottom and then enter the nozzle hole. This flow tendency may form the
21 rotation flow in the sac at enough flow speed. The clear spreading morphology was found for UA70, UA130
22 and UA160. This confirmed that the rotating flow was formed in the sac volume or even in the nozzle hole and
23 led to the influence on the near-nozzle spray. There were more interesting morphologies in Fig.7, corresponding
24 to the 2nd SW peak (around 200 μ m) of UA130 and UA160. Obvious flow rotation was found in the nozzle exit
25 and a hollow cone spray was formed like other findings[8, 31, 35]. No clear cavitation bubbles were found in

1 the liquid flow. The breakup process was strongly based on the liquid sheet breakup. The largest SW at 2nd peak
2 indicated the highest strength of rotating flow in the UA130 nozzle. However, the morphology between the 1st
3 SW peak and 2nd SW peak was totally different. At the 1st SW peak, the breakup of spray was more random
4 though the SW was similar to 2nd SW peak; on the contrary, the breakup of spray tended to follow the edge of
5 the hollow cone at 2nd SW peak. This indicated the cavitation could dominate the 1st SW peak even there was
6 rotation flow in the nozzle. Without cavitation, strong flow rotation in the nozzle led to the 2nd SW peak.

1

(a) 30MPa

(b) 100MPa

Fig. 7. Selected spray images at two injection pressures

At 100MPa injection pressure, only one SW peak was found at the OS. The rotation flow was still found in two-hole injectors. The string-like cavitation inside the spray can be recognized, the white part in the middle of spray at the nozzle exit. Since the higher injection pressure leads to stronger internal rotation flow, the string cavitation can form in the sac flow and even reaches the nozzle exit. The observed hollow cone spray was similar to the spreading spray due to the string cavitation. Moreover, the earlier breakup process, compared to the case at lower injection pressure, could be attributed to the higher flow turbulence due to high injection pressure.

At the SS, minimum SW and slight SW variation were found. At 30MPa injection, little breakup feature in the near-nozzle field can be recognized for two-hole injectors. However, obvious asymmetric spray development was observed, especially on the left side. This phenomena could be explained by the flow stretch in the large UA nozzle [34]. At 100MPa injection pressure, the fast breakup was found on the left side of spray for two-hole injectors due to the higher turbulence. Based on other simulation results[36], higher injection pressure could induce geometry cavitation on the upside of spray (left side in Fig.7b), which may accelerate the breakup process on that side. However, little cavitation was observed in the spray morphology in the present experiments.

At the SW peak of the CS (around 100 μ m), the similar spray morphology induced by nozzle vortex flow was found corresponding to the similar needle lift at the OS. This implied that the formation of vortex flow in the nozzle occurred in a specified range of needle lift, lower than 200 μ m. Earlier spray breakup was observed at higher injection pressure while the pressure effect on the SW seems to be neglected at both injection pressures.

3.3 Effect of fuels on the SW

It is well known that the fuel properties have essential effect on the spray characteristics [37]. The simulation of internal flow showed the cavitation incipient and concentration was suppressed by the biodiesel [38]. In this section, the fuel effect on the SW in the whole needle lift, especially at the OS and CS, was investigated using SFB and D in UA70 nozzle.

Figure 8 shows the SW comparison between SFB and D at 30MPa and 100MPa injection pressures. The whole needle lift was split into two parts at the top needle location: needle up (opening) and needle down (closing). At the 30MPa injection pressure, there was no clear

difference of SW between SB and D when the needle lift lower than 150 μm . Between 150 and 400 μm , SW of D was roughly 1.5 times as larger as SW of SFB. When the needle lift is higher than 450 μm , slightly larger SW was found for D. The SW peak was mainly related to the strength of internal rotation flow from the results of previous section. At 100MPa injection pressure, the SW peak was observed at the needle lift lower than 100 μm . The largest difference of SW between SFB and D was also found at the needle lift lower than 400 μm . However, the SW difference was much smaller than the case at low injection pressure.

Fig.8. Effects of D and SFB on the SW at whole needle lift

Biodiesel, with a high viscosity, usually causes smaller SW due to more difficult breakup than diesel. At lower needle lift, little effect of fuel properties on the SW was found and morphology comparison showed the earlier breakup and more droplets formed in diesel spray. This indicated

that the dynamic of internal flow may dominate the macroscopic near-field spray characteristics and the fuel properties tended to affect the microscopic breakup process. At higher needle lift, the internal flow became more stable without the vortex flow, the fuel properties, e.g. viscosity and density, played an important role in the spray width, as shown in Fig. 9. At the top needle lift, the SW of SFB was around 12% and 16% shorter than that of D at 30 and 100MPa injection pressures respectively. Compared to the SFB, larger deviation of SW for D was observed, which implied the higher turbulence in diesel spray.

Fig. 9. Comparison of SW between D and SFB at the top needle lift of UA70.

Figure 10 shows the spray images of SFB and D at different needle lifts. At lower needle lift around 120μm, vortex-like spray morphology was found due to the rotation flow in the nozzle hole. At 30MPa, the spray ligaments was more obvious for SFB and it was difficult to tell the breakup details from the diesel spray images. The breakup close to the nozzle exit implied the cavitation breakup with possible rotation flow. At middle needle lift (around 400μm), the wave structure was found in SFB spray and flow stretch phenomena (white line in the middle of the spray) can be observed at 30MPa. It should be noted that the D spray showed the earlier breakup

on the left side and the similar flow stretch. This indicated that the breakup process was strongly related to the spray morphology characteristics. The morphology-based breakup can also be found in the spray images at the needle lift of 540 μ m. Because of no cavitation observed at higher needle lift, the conclusion can be made that the spray breakup process highly depended on the spray morphology under the stable flow condition. Due to the close relationship between spray morphology and internal flow[39], the spray breakup should be strongly related to the internal flow, which highlighted the nozzle geometry and needle lift dominated the spray development from the view of nozzle structure.

Fig.10. Comparison of spray morphology between D and SFB

3.4 Discussions

In the present experiments, the UA of nozzle holes has significant influence on the near-nozzle spray characteristics by inducing vortex flow and cavitation in the nozzle hole to change the flow

1 conditions of nozzle exit. The larger SW (hollow cone spray) of two hole injectors corresponded
2 to the certain needle lift where vortex flow tended to occur. Based on the spray morphology and
3 other findings[12, 40], this hollow-cone spray caused by high-speed rotation flow (even string
4 cavitation formed) composes of liquid sheet. The breakup process is highly related to the sheet
5 breakup. When the vortex flow formed in the nozzle, similar SW at both injection pressures
6 implied that the breakup process tended to follow the spray morphology which strongly related
7 to the internal flow. However, the start of breakup was much closer to the nozzle exit at higher
8 injection pressure due to high turbulence and interaction between fuel and air.

9 Different from the gasoline direct injection (GDI), diesel injector can produce the vortex flow in
10 the sac without designing the swirl path to initialize the rotation flow. This hollow cone spray
11 can be formed at low injection pressure and improve the spray atomization. At 30MPa, one SW
12 peak was found at the needle lift around 100 μ m. There were strong signs of complete breakup
13 close to nozzle exit due to the cavitation and rotation flow. However, the flow path between
14 needle and nozzle body is shallow at lower needle lift, which may cause choke effect and
15 decrease the flow rate. So that this range of needle lift may not be suitable for practical
16 application even better atomization can be obtained. Several studies on the mass flow rates of
17 multi-hole injector showed that if the needle lift was higher than 150 μ m, maximum flow rate can
18 be reached[41-43]. Fortunately, hollow-cone spray still can be formed at needle lift lower than
19 200 μ m, which provides the possibility of improving the spray atomization at lower injection
20 pressure without large loss of flow rate. The large SW at lower needle lift for both injection
21 pressures is also indicative of the potential enhancement on the spray atomization of short
22 injection which is very important for the multiple injection strategy. However, it should be noted
23 that a practical diesel injector has more than six nozzle holes. Significantly uneven flow and

variable spray angle among those holes (theoretically symmetric) have been confirmed by experiments and simulations. Moreover, it was very difficult to control the appearance of string cavitation (or vortex flow) due to nozzle geometry and injection pressure[44]. In addition, the hollow-cone spray breakup was very close to the nozzle exit at 100MPa. This may lead to insufficient spray penetration and combustion close to the injector. As a result, the fuel and air may not be fully mixed using the present chamber design and the possibility of carbon deposition on nozzle and consequent nozzle clogging will be increased. Because our results were based on the symmetric two-hole injector, more experiments should be conducted to determine whether the present findings can be applied to a **commercial** injector.

4. Conclusions

The near-nozzle spray characteristics of diesel injectors with different UA were investigated using fast X-ray phase-contrast imaging and quantitative image processing. The conclusions can be summarized as the following:

1) The ‘dumbbell’ profile of SW composed of three stages: opening stage, semi-steady stage and closing stage. The SW peaks and significant SW fluctuation were found at the OS and CS. However, stable SW and little SW fluctuation were found at SS. The large SW fluctuation at the OS and CS indicated that the internal flow was extraordinary unstable, especially the occurrence of vortex flow in the sac.

2) The SW peak of two-hole injectors was more than twice of that of single-hole injector. The larger SW mainly corresponded to the hollow cone spray. This indicated the vortex flow was induced with the increase of the UA. The strongest vortex-like spray was found for UA130.

3) The spray morphology analysis showed cavitation spray, hollow-cone spray, upper side breakup spray at different needle lift. At 30MPa, the OS 1st peak was dominated by the cavitation due to choke effect at lower needle lift while vortex flow may be involved. The 2nd peak was dependent on the vortex flow in the nozzle hole without cavitation observed. The left side breakup of spray at the SS for two-hole injectors could be attributed to the geometry-induced cavitation. Even though the breakup was earlier at higher injection pressure, the similar SW peaks at both two pressures were possibly indicative of the dependence of breakup process on the spray morphology.

4) Little difference of SW profile between SFB and D at lower needle lifts revealed that the dynamics of internal flow and cavitation dominated the near-field macroscopic spray characteristics and the fuel properties tended to affect the microscopic breakup process. Larger SW for D at higher needle lift indicated the fuel properties played a decisive role in the spray characteristics. In addition, the breakup process based on the spray morphology was observed.

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