Effect of the Number and Position of Nozzle Holes on In- and Near-Nozzle Dynamic Characteristics of Diesel Injection

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Abstract

Despite the fact that all modern diesel engines use multi-hole injectors, single-hole injectors are frequently used to understand the fundamental properties of high-pressure diesel injections due to their axisymmetric design of the injector nozzles. A multi-hole injector accommodates many holes around the nozzle axis to deliver adequate amount of fuel with small orifices. The off-axis arrangement of the multi-hole injectors significantly alters the inter- and near-nozzle flow patterns compared to those of the single-hole injectors. This study compares the transient needle motion and near-nozzle flow characteristics of the single- and multi-hole (3-hole and 6-hole) diesel injectors to understand how the difference in hole arrangement and number affects the initial flow development of the diesel injectors. A propagation-based x-ray phase-contrast imaging technique was applied to compare the transient needle motion and near-nozzle flow characteristics of the single- and multi-hole injectors. The comparisons were made by dividing the entire injection process by three sub-stages: opening-transient, quasi-steady and closing-transient.

Keywords: *high-pressure diesel spray, nozzle hole arrangement, nozzle hole number, needle motion, near-nozzle flow, x-ray phase-contrast imaging*

1. INTRODUCTION

Latest diesel injectors use high injection pressure and small holes to improve the fuel atomization, evaporation and mixture homogeneity [1-5] and to reduce engine-out emissions [6-9]. Each injector nozzle often has many holes to ensure a sufficient fuel flow rate from the small holes, leading to the introduction of multi-hole injectors for modern advanced diesel engines. The holes are placed symmetrically around the nozzle axis. The off-axis hole arrangement can induce much more complex internal and external flow patterns than that exhibited from an axisymmetric single-hole injector.

However, in many spray studies, single-hole injectors are employed due to their simplicity to gain fundamental spray characteristics and easiness of applying diagnostics techniques and instrument around the single fuel jet and spray from the hole. In turn, many engine combustion simulations are developed based on the spray models derived from the single-hole injectors. Therefore, understanding how the arrangement and number of the holes in an injector nozzle affects the spray development is crucial to correlate the fuel flow characteristics of the single- and multi-hole injectors.

The discharge flow rate of the multi-hole injectors is larger than that of the single-hole injectors using the same hole diameter under the same injection pressure. As a result, the sac pressure inside the multi-hole injectors can be lower than that of the single-hole injectors in specific transient conditions. Since the pressure balance across the needle is a key factor determining the needle motion inside the nozzle [10, 11], the difference in sac pressure could cause different needle motion of the single- and multi-hole injectors. On the other hand, in a multi-hole injector nozzle, the upstream flow would be more difficult to enter the hole directly than its single-hole counterpart due to its off-axis hole arrangement. More upstream flow rather rushes to the sac, which would result in the formation of a vortex flow in the sac. This vortex flow inside the sac can be stronger at lower needle lifts due to narrower flow passage and smaller sac volume [12-15]. A considerable amount of research has studied the vortex flow and

related cavitation phenomenon inside multi-hole diesel injectors and their effects on emerging flow pattern using the optically accessible large-scale nozzles or by numerical simulation [13-18]. It was found that the vortex flow is formed inside the nozzle at low needle lifts, which induces turbulent emerging flow patterns of the multi-hole diesel injectors with a faster breakup.

Although the difference in number and position of the nozzle holes between the single- and multi-hole injectors would affect the needle motion and emerging flow pattern of the diesel injectors, thorough understanding of these effects has not been made. There is a lack of information on fuel flows associated with real-scale nozzles under practical operating conditions especially inside the holes and in the near-nozzle region. This lack of information is mainly caused by the difficulties in optical access to the near field, where the fuel jets are optically dense. Measurements using conventional laser optical techniques inside the nozzle and in the near field have not been quite successful owing to optical opaqueness in these regions.

In this study, we compare the transient needle motion and near-nozzle flow characteristics of a number of single- and multi-hole diesel injectors. A propagation-based x-ray phase-contrast imaging (XPCI) technique was employed to visualize the in-nozzle needle motion and near-nozzle flow dynamics and structures of the high-speed diesel sprays by analyzing the x-ray images. The high-energy x-ray beam enables imaging the motion of the needle through the nozzle. Short (sub-ns to 10's ns) x-ray pulses are able to image high-speed and optically dense jet in the near field without severe scattering and absorption. As a result, the detailed information of the in-nozzle needle motion and near-nozzle flow dynamics and structures can be obtained.

2. METHODS

2. 1. XPCI for Fuel Injection Analysis

The principle of the XPCI has been described previously [19-22]. Only a brief introduction to the technique will be given here. The potentials of the XPCI for fuel injection studies originate from the combination of weak interaction between x-rays and materials, high-energy and ultra-short x-ray pulses

available at the third-generation synchrotron light sources such as the Advanced Photon Source (APS). The cross-section of x-ray/matter interaction minimizes multiple scattering. High-energy x-rays are highly penetrative so they can pass through millimeter-thick metal such as injector nozzle. When an x-ray beam passes through an object, both absorption and phase-shift occur. In terms of phase-shift, the incident and scattered x-rays can generate an interference pattern with bright and dark fringes along the object boundary. The XPCI contrast is from both the fringes and the intensity attenuation due to the absorption, similar to back-illuminated shadowgraph in the visible light regime. But the high transmittance of the x-ray to the dense materials enables to image the in-nozzle structure and liquid-phase features inside the dense fuel sprays. In addition, the short x-ray pulses provide a high temporal resolution for XPCI that enables to freeze the motion of the high-speed fuel sprays in the near-field. The potentials of the XPCI described above provide benefits to visualize the in-nozzle needle motion and near-exit flow dynamics of the high-speed optically dense fuel jets.

2. 2. X-ray Imaging Setup

We used the experimental setup similar to that described in detail previously [21-24]. **Fig. 1a** shows the imaging setup at 7ID and 32ID beamlines of the APS. The x-ray beam was generated from an insertion device (Undulator A) in the APS electron storage ring. A special beam timing pattern (hybrid-singlet mode), shown in **Fig. 1b**, was used in the experiment. To protect the imaging system from being damaged by the powerful x-ray beam, there were two mechanical x-ray shutters: a slow one operating at 1-Hz frequency with 8-ms opening duration (Shutter 1) and a fast one of 1-kHz frequency with 9- μ s opening duration (Shutter 2). Synchronized operation of the two shutters cuts off more than 99.9% of the beam heat power. A scintillator crystal (LYSO:Ce) converted the x-ray “shadow” images of the sprays into visible-light images at an emission peak around 420 nm, which were then reflected by a 45° mirror and captured by a charge-coupled device (CCD) camera (Sensicam, 1376 × 1040 pixels, from PCO-Tech Inc.). The temporal resolution of the imaging was determined by the x-ray pulse duration and the camera gating. The effective pixel size of the camera was 0.63 or 1.26 μ m when a 10x or 5x objective lenses were used with the CCD camera, respectively.

2. 3. Analysis Methods

One part of the stored electron or x-ray timing pattern contains eight septets with a total electron current of 88 mA and a length of 472 ns (part A in **Fig. 1b**). The pulse train was used for visualizing the in-nozzle needle motion to ensure sufficient high-energy x-ray photons necessary for visualization through the steel nozzle enclosure. The pulse-train duration of 472 ns was short enough to freeze the needle motion of a less than a meter per second during the injection process.

The near-field diesel jets and sprays were visualized using the x-ray pulse with a 16-mA electron current and 150-ps pulse duration (part B in **Fig. 1b**). On the other hand, the near-nozzle flow velocity was derived using the 3 septets with 11-mA current, 17-ns width, and 68 ns period (part C in **Fig. 1b**).

Fig. 2a shows the needle images of the single-hole injector before and during the injection. The needle lift can be obtained by cross-correlation of the two needle images. The details of the cross-correlation analysis for derivation of two-dimensional needle motion are presented in a recent publication [11]. **Fig. 2b** illustrates the method used to derive the local velocity of the diesel sprays from the images taken by XPCI. First, a multi-exposed x-ray image was taken using the 3 septets as shown in **Fig. 1b**. Then, an auto-correlation analysis was performed in a particular region of interest (ROI) of the multi-exposed images. The displacement vector of the imaged features during the 68 ns time interval can be obtained by detecting the relative location of the displacement peak with respect to the center self-correlation peak. The details of the analysis for deriving the local spray velocity were also described in the recent publications [23, 24]. *The interrogation window size of 250 μm for the axial direction and 50 μm for the radial direction was applied for auto-correlation analysis to have a sufficient number of features to trace for reliable velocity results.*

2. 4. Experiments

Diesel fuel was injected into a spray chamber by a common-rail injection system, composed of a fuel tank, motor, high-pressure pump, injector and common-rail. The fluid pressure inside the common rail was controlled by a feedback system that controlled a bleeding valve attached to the rail. The spray

chamber had two Kapton® windows which allowed the x-ray beam to pass through the chamber without attenuating intensity.

Fig. 3 shows the x-ray images of the mini-sac type single-, 3- and 6-hole diesel injector nozzles used in this study. All injectors have the nominal nozzle hole diameter of 0.120 mm. Meanwhile, the 3- and 6-hole injectors have a nominal umbrella angle of 170°. *The measured nozzle hole diameters from the x-ray images were very close to the designed diameter for all test nozzles with a deviation of $\pm 2 \mu\text{m}$. The inlet edge radii of the applied nozzles were also quite close, in the range of $29 \pm 2 \mu\text{m}$.* **Table 1** shows the experimental conditions. The fuel (US No. 2 diesel) was injected at 150 MPa injection pressure into the chamber at an atmospheric pressure (0.1 MPa) and room temperature (302 K). A gentle nitrogen (N_2) or sulfurhexafluoride (SF_6) flow scavenged the fuel fume between the injections. The SF_6 has relatively high ambient density than N_2 . The injection pulse was chosen to be sufficiently long (1 ms) to ensure that all injections have transient opening and closing periods and a quasi-steady one in between, so that the spray characteristics of the injectors can be compared under the transient and steady conditions.

3. RESULTS AND DISCUSSION

In this section, transient needle motion and near-nozzle flow dynamics and structures of the single-, 3-, 6-hole diesel injectors are compared in terms of needle lift and speed, exit velocity distribution, near-exit flow structure and jet/spray velocity distribution at downstream. The comparison is made in the three stages of the needle motion during an injection event: opening-transient, quasi-steady, and closing-transient.

3.1. Transient Needle Motion

In **Fig. 4**, we show the time dependence of needle lift measured by x-ray imaging and calculated needle speed of the single-, 3- and 6-hole diesel injectors through the entire injection process. *The needle lift results in Fig. 4a are obtained by averaging the results of 5 time-lock snapshots. We did not put the*

error bars in the graphs since the needle motion of the injectors were highly reproducible and the shot-to-shot deviation was less than 0.5 % of the peak needle lift regardless of the nozzles ($< 3 \mu\text{m}$) and almost undetectable. For simplicity, the needle motion discussed in this work is limited to its axial direction. A positive speed value indicates its opening motion while a negative one is associated with closing. The time of start of injection (SOI) was chosen to be the instance when the needle just started to move. The injection delay, defined as the time delay between the injection pulse supply and SOI, appeared identical for the applied injectors. *Based on the needle positions, the injection process is divided into three stages: opening-transient (Region A), quasi-steady (Region B) and closing-transient (Region C). The boundaries of the three stages were defined by the unique characteristics of the needle motion for this type of injectors as shown in Fig. 4. There are clearly three regions, excluding the instance when needles change the direction, for all three injectors. Within the first $100 \mu\text{m}$, the needles accelerate and decelerate. Then they move at a near-constant speed till the change of direction. We defined this initial short transient stage as the opening-transient. The quasi-steady stage is characterized by near-constant needle speeds (opening and closing), during which the needles change their directions. During the needle closing, below the $100 \mu\text{m}$ needle lift, the needle accelerates in the downward direction and decelerates to 0, reversing the process in the opening-transient stage. We define this last $100 \mu\text{m}$ range as the closing-transient stage.*

A highly transient needle behavior is observed immediately after the onset of the needle opening. The needle speed abruptly increases from zero, and then decreases after hitting a peak value of between 1 and 1.5 m/s depending on the nozzle hole configuration before dropping to a more constant speed (about 0.7 m/s) (Region A in Fig. 4). In general, needle movement is initiated by actions of actuator such as solenoids and piezoelectric transducers, but what controls the needle motion is the hydraulic pressure applied to the upstream and downstream ends of the needle [10, 11]. Before an injection begins, a downward force exerts to the needle because the pressure at the needle upstream end (pressure control chamber) is equivalent to that in the common-rail while almost no pressure exists at the needle downstream (nozzle sac). Once the actuator is activated, the fuel discharge passage at the upstream pressure control chamber opens, from which the pressure inside the pressure control

chamber decreases. As a result, the needle starts to moves up and the fuel enters to the nozzle sac with a concurrent increase in the sac pressure. The sudden rise and following drop in the needle speed (like an overshoot) during the opening-transient can be caused either by actuator motion itself or by abrupt rise in the sac pressure due to the sudden introduction of the fuel to the sac. The different needle speed traces of the 3 injectors during the opening-transient indicate that the effect of the flow conditions at the sac should be somehow associated with this result. The higher discharge flow rates of the larger hole number nozzles could decrease the degree of sac pressure rise with slower needle motion during this opening-transient.

In **Figs. 5a and 5b**, we highlighted the above discussion with the plots of the peak needle speed and time at the peak needle speed of the 3 injectors during the opening-transient. The result shows that the peak needle speed becomes lower, and the time at the peak needle speed appears later as the hole number increases. This result demonstrates that the needle motion is highly affected by the fuel flow and pressure at the needle downstream during the opening-transient.

The highly transient characteristics of the needle motion happened before the needle reached *around 100 μm* needle lift for all test nozzles. When the needle lift is over *around 100 μm* , the needle speeds of the all test nozzles become relatively steady (region **B** in **Fig. 4**). **Fig. 5c** shows the needle speed of the 3 injectors during the quasi-steady stage for both the opening (positive needle velocity) and closing (negative needle velocity) processes. The results show that the needle speed is slightly lower (within 10%) when the hole number increased from 1 to 3 and 6. Meanwhile, a reverse trend was observed for steady speed during closing. The increase in flow discharge rate and corresponding lower sac pressure are likely to be responsible for these results. The lower sac pressure decreases the needle lifting force during the upward needle motion while the lower sac pressure reduces the resistance force against the downward needle motion.

At the very low needle lifts during the needle closing, the downward needle speed abruptly increases for the applied injectors (**Region C** in **Fig. 4**). This increase in needle speed is related to the sudden decrease of sac pressure due to flow restriction from the needle at the low needle lifts ("throttling effect of the needle"). If the flow rate entering to the sac becomes lower than the discharging flow rate, the

sac pressure decreases. The decreased sac pressure reduces the resistance force against the downward needle motion that abruptly increases the needle speed. **Figs. 5d and 5e** show the time and needle lift in which the needle speed is double of that during the quasi-steady. The time of the double needle speed is significantly advanced as the hole number increases. The higher needle closing speed with an increase in the hole number is responsible for this result, from which the needle reaches the location of flow restriction at earlier times. The needle lift at the double needle speed appears higher at large hole numbers since the flow becomes restricted from the higher needle lifts due to higher discharge flow rate. Due to the higher needle closing speed, the total injection duration becomes shorter with the increase in the hole number under the same injection pulse duration (see **Fig. 4**).

3.2. Near-Nozzle Flow Dynamics and Structures

3.2.1 Exit velocity distribution

With the x-ray imaging based velocimetry measurement, we are able to obtain the near-nozzle fuel jet velocity as the jet just exits the hole. In **Fig. 6a**, we compare the time dependence of the jet center velocity of the single-, 3- and 6-hole injectors at 1mm from the nozzle exit (see **Fig. 6b**), which is denoted by exit velocity. *Each point in time was collected in a phase-lock mode from different injections. In addition, the data were averaged over 10-shots at every instance in time to improve the signal-to-noise ratio.* Corresponding needle speed curves are also presented together in the **Fig. 6a**. At needle opening, a sharp increase in exit velocity was observed due to increased pressure in the sac and the hole. Interestingly, the single-hole injector showed a small but apparent “overshooting” peak in exit velocity curve, similar to the needle speed. This overshoot diminished with the 3- and 6-hole nozzles. The overshoot may be due to a water-hammer effect accompanying the needle lifting and the restricted outlet flow from the single-hole nozzle. The overflow can generate pressure waves in the sac and higher pressure than the common-rail pressure at certain instance. In the case of nozzles with more holes, this transient overflow may not be happened because of the larger outlet flow. This may also be related to the inter-nozzle vortex flow in the multi-hole injectors at the low needle lifts [12-15, 22, 25].

The vortex flow would dissipate the initial flow momentum in the transverse direction that could reduce the flow velocity in the orifice axial direction.

The exit velocity of the single-hole injector becomes steady when the needle lift reaches over *around 100 μm* . On the other hand, the exit velocity of the multi-hole injectors is lower than that of the single-hole injector and only reached the maximum speed slightly after the needle started to close. *At this point*, the exit velocity of the single and multi-hole injectors had the similar values of just above 500 m/s. This gradual velocity increase of the multi-hole injectors with time and the equivalent velocity of the single- and multi-hole injectors at the top needle location can be associated with the reasons below. As the needle lift increases, the upstream flow passage becomes larger and the space in the sac increases. The larger flow passage increases the flow rate entering the sac and holes that attenuates the sac pressure drop at high needle lifts. Also, the larger flow passage and more space in the sac *make the flow in the hole be more directly supplied from the upper supply passage* that attenuates vortex strength of the multi-hole injectors with the increase in the needle lift [26-28]. These bring the exit velocity of the multi-hole injectors gradually close to that of the single-hole injector. The exit velocity of the 6-hole injector is almost equivalent to that of the 3-hole injector through the whole injection process except at the low needle lifts, in which the effects of hole number on the sac pressure is prominent.

To further understand the exit flow characteristics, the velocity distributions of the single- and multi-hole injectors *at different radial locations* are compared in **Fig. 7a** at the instances of 0.11 ms ('a' in **Fig. 6a**), 0.44 ms ('b' in **Fig. 6a**), 1.44 ms ('c' in **Fig. 6a**) and 2.44 ms ('d' in **Fig. 6a**). *The four points for the velocity comparison were chosen based on the needle motion. The point 'a' is the time at the peak needle speed during the opening-transient stage. The points 'b', and 'd' are within the quasi-steady stages but during the needle opening and closing process, respectively. In both cases, the exit flow velocities of the multi-hole nozzles are lower than that of the single-hole injector. The point 'c' is the time for the exit velocity of the three nozzles are almost identical.* At the time of *0.11 ms*, the exit flow of the applied injectors expands to the radial direction due to the sudden introduction of the fuel flow to the sac accompanying *turbulence or vortex flow* during the opening-transient. The multi-hole injectors show

the higher radial velocity but lower axial velocity than the single-hole injector. The lower axial velocity of the multi-hole injectors can be associated with the lower sac pressure and the vortex flow inside the sac and holes at the low needle lifts. On the other hand, the higher radial velocity of the multi-hole injectors can be associated with the vortex flow inside the sac and holes at the low needle lifts. Until the time of 1.44 ms, the radial velocity of the applied injectors attenuates with time. The difference in radial velocity between the single- and multi-hole injectors becomes smaller with an increase in the needle lift. *However, the shot-to-shot velocity fluctuation of the emerging flows from the multi-hole injectors is still larger than that of the single-hole injector even at the high needle lifts, as shown in Fig. 7b.* The difference in axial and radial velocity between the 3- and 6-hole injectors is insignificant except at the low needle lifts, in which the effects of the hole number on the sac pressure is prominent.

3.2.2 Near-exit flow structure

Fig. 8 presents the near-exit flow structure of the single-, 3- and 6-hole injectors during the opening-transient (**Fig. 8a**) and at the time of 1.44 ms (**Fig. 8b**). *In addition, the three representative shot images of the near-exit flow structure of the 3-hole injector at the instances of 0.44 ms and 2.44 ms are presented in Fig. 8c.*

During the opening-transient, the multi-hole injectors show a more turbulent flow *morphology* (see **Fig. 8a**). The flow instabilities of the multi-hole injectors occur from the nozzle inside and at the whole flow region across the hole while those of the single-hole injector starts to occur outside the nozzle. This more turbulent *flow morphology* of the multi-hole injectors during the opening-transient can be associated with the *formation of* inter-nozzle vortex at the low needle lifts.

At the time of 1.44 ms, the spray widths are almost equivalent for the applied injectors (*quasi-steady state*), *demonstrating that the in-nozzle vortex of the multi-hole injectors associated with the radial flow expansion is almost diminished.* Nevertheless, the breakup process seems to *appear* different. The jet flow breakup of the single-hole injector occurs as if the flow is peeled-off from the surrounding gas, while the breakup of the multi-hole injectors occurs as if the flow is perturbed from internal instabilities. The flow instabilities of multi-hole injectors appear faster at the upper side (*positive radial locations in*

1 **Fig. 7b)** supposedly due to formation of film cavitation at the upper side of the hole. Owing to the high
2 umbrella angle (170°) of the multi-hole injectors, the upstream flow is hard to enter the upper side of the
3 hole. As a result, the film cavitation can be formed at the upper side of the hole as a previous
4 computational study demonstrated [26]. *This supposition can be supported from the fact that the upper*
5 *side jet/spray region of the multi-hole injectors shows the higher shot-to-shot velocity fluctuation at the*
6 *time of 1.44 ms, as shown in Fig. 7b.* In addition, the flow instabilities of the multi-hole injectors can be
7 from the flow-to-flow interaction heading to each hole that can be supported from the fact that the 6-
8 hole injector shows a more turbulent flow morphology than the 3-hole injector as shown in **Fig. 8b**.
9 *At the times of 0.44 ms and 2.44 ms, sometimes wide-jet but sometimes shallow-jet appears for the*
10 *multi-hole injectors (intermediate stage), while the single-hole injector only shows the quasi-steady*
11 *shallow jet. The structure of the wide-jet resembles the jet structure during the opening-transient, while*
12 *the structure of the shallow-jet resembles the jet structure at the quasi-steady state. The probability of*
13 *the appearance of the wide-jet decreased with an increase in the needle lift.*
14 **Fig. 9** shows the 10-shot averaged *near-exit* spray width and its shot-to-shot deviation of the single-, 3-
15 and 6-hole injectors. *The spray width was defined as the distance between the right- and left-side*
16 *boundaries of the flow mainstream across the line perpendicular to the hole axis. The droplets isolated*
17 *from the mainstream were ignored because our main focus is to understand the hydrodynamic*
18 *characteristics of emerging flow related to the internal flow. The results of near-exit spray width in Fig. 9*
19 *were measured at 0.7 mm axial location, in which the flow breakup is not yet active so that the*
20 *hydrodynamic characteristics of the emerging flows can be identified.* At the low needle lifts, the spray
21 width increases for the applied injectors, but the multi-hole injectors show the larger spray width and
22 higher shot-to-shot deviation compared to the single-hole injector. The spray width and its shot-to-shot
23 deviation of the single-hole injector sharply decrease and become steady from around 0.20 ms while
24 those of the multi-hole injectors decrease more gently with time. The spray widths of the multi-hole
25 injectors become almost equivalent to that of the single-hole injector around the top needle lift (1.44
26 ms), but the shot-to-shot deviation is still greater (refer to **Fig. 7b**). *These flow features of the multi-hole*

injectors again demonstrate the high vortex strength at the low needle lifts and attenuated vortex strength with an increase in the needle lift.

Fig. 10 presents the histogram of the *near-exit* spray width of the applied injectors at the times from 1.0 ms to 2.0 ms, in which the 10-shot averaged spray widths of the applied injectors are near constant (quasi-steady). Even in this quasi-steady condition, the spray width of the multi-hole injectors shows a far wider distribution than the single-hole injector due to off-axis hole arrangement and flow-to-flow interaction heading to each hole inside the sac. The 6-hole injector shows a slightly wider spray width distribution with higher turbulence than the 3-hole injector that might be related to the reinforced flow-to-flow interaction inside the sac due to larger hole number.

3.2.3 Jet/Spray Velocity Distribution at Downstream

In this section, we discuss how the differences in near-nozzle flow conditions of the single- and multi-hole injectors alter the jet/spray dynamics at downstream under a quasi-steady condition (1.44 ms after SOI). **Fig. 11** illustrates the normalized jet/spray center velocity (V_z / V_{exit}) of the 3 injectors at the axial locations (z) up to 25 mm. Here, the normalized velocity is defined as the ratio of the jet/spray center velocity (V_z) to the exit velocity (V_{exit}) which is an indicator of the jet/spray deceleration and *degree of momentum exchange between the jet/spray and surrounding gas*. The result shows that the multi-hole injectors show a higher degree of jet/spray deceleration than the single-hole injector. It demonstrates that more turbulent near-nozzle flow characteristics of the multi-hole injectors promote the jet breakup and spray/air mixing process at downstream *at quasi-steady state*.

3.3. Discussion

Understanding the inter-nozzle flow pattern is crucial to interpret the near-nozzle flow characteristics of the multi-hole injectors at each stage. A recent study measured the inter-nozzle flow pattern of a mini-sac type multi-hole injector using a real-size transparent nozzle [27]. The previous study and current study applied different geometries of the needle (Ref. [27]: sharp tip, current study: flat tip), nozzle hole

diameter (Ref. [27]: 0.14 mm, current study: 0.12 mm), and injection pressure (Ref. [27]: 50 MPa, current study: 150 MPa). However, integrated speculations on the results of the previous and current study would provide a way to link the inter- and near-nozzle flow pattern of the multi-hole injectors. The previous results show that the strength of the vortex and the location of vortex core vary with the needle lift. At the low needle lifts, a strong vortex is formed, and the vortex core is close to the *hole* axis. As a result, a spiraling flow can emerge through the *hole* at the low needle lifts. This emerging spiraling flow at the low needle lifts can be responsible for the large spray width and turbulent flow characteristics of the multi-hole injectors during the *opening-transient*. As the needle lift increases, the strength of the vortex decreases and the location of the vortex core moves upstream. A previous computational study also presented a similar result [18]. As a result, the vortex flow becomes hard to enter the hole that causes relatively narrower spray width with decreased shot-to-shot deviation at the high needle lifts. *In the intermediate stage of the multi-hole injectors, the unstable nature of the vortex flow seems to make the vortex sometime emerge through the nozzle but sometimes not. This can be the reason why sometimes wide-jet but sometimes shallow-jet appears during this stage.*

The results above indicate that the inter- and near-nozzle flow, and breakup and mixing processes of the multi-hole injectors are quite different with those of the single-hole injector. The exit flow of the multi-hole injectors is rather affected by the inter-nozzle vortex or turbulence during the entire injection process. Although the difference in exit flow conditions between the single- and multi-hole injectors becomes less significant with an increase in the needle lift, the breakup process seems to be different even at the quasi-steady state. The breakup of the multi-hole injectors is likely to be initiated by the internal instabilities of the flow rather than by the aerodynamic effect outside the nozzle. It indicates that the conventional wave breakup models based on the capillary wave growth on the jet surface is infeasible to describe the spray development of the multi-hole injectors. Introduction of the alternative spray models which regard the effect of turbulence and cavitation on the jet breakup is essential to improving the reliability of the engine simulation results.

4. Summary

In this study, a propagation-based x-ray phase-contrast imaging (XPCI) technique was employed to analyze the transient needle motion and near-nozzle flow structure and dynamics of the single- and multi-hole (3- and 6-hole) diesel injectors in terms of needle lift, needle speed, exit velocity and near-nozzle flow morphology and velocity distribution. The transient needle motion and near-nozzle flow characteristics of the single- and multi-hole diesel injectors are compared in various injection stages during the entire injection event.

□ During the transient stage of needle opening (the needle lift below 100 μm), a sharp increase and following drop in the needle speed (like an “overshooting”) were observed. The slower needle motion and lower peak needle speed were observed with an increase in the hole number during this stage. This result can be associated with the sac pressure decrease with an increase in the hole number due to higher discharge flow rate. During the transient stage of needle closing (needle lift below 100 μm), the needle speed abruptly increased due to “throttling effect” of the needle and following drop in the sac pressure. The throttling effect was initiated at larger needle lifts with an increase in the hole number.

□ The multi-hole injectors showed a higher radial velocity with a lower axial velocity at the nozzle exit than the single-hole injector. The lower sac pressure and vortex flow inside the multi-hole injectors can be responsible for this result. The difference in exit velocity distribution between the single- and multi-hole injectors became smaller with an increase in the needle lift probably due to attenuated inter-nozzle vortex and sac pressure drop of the multi-hole injectors at the high needle lifts. The exit velocity distribution of the 3- and 6-hole injectors appeared quite similar except at the low needle lifts, in which the effects of hole number on the sac pressure is prominent.

□ Unstable wide sprays were formed for the applied injectors at the low needle lifts, but the 10-shot averaged spray width of the multi-hole injectors was much larger than that of the single-hole injector with higher shot-to-shot deviation. At the top needle lift, almost equivalent spray width was observed for the applied injectors, but the breakup process seems to be different. The jet flow breakup of the single-hole injector occurred as if the flow is peeled-off from the surrounding gas, while the breakup of the multi-hole injectors occurred as if the flow is perturbed from internal

instabilities with more turbulent flow structure. This more turbulent flow characteristics of the multi-hole injectors caused faster deceleration of the jet/spray at downstream.

5. References

- [1] Nishida K, Zhang W, Manabe T. Effects of Micro-Hole and Ultra-High Injection Pressure on Mixture Properties of D.I. Diesel Spray. SAE Transactions 2008;116:421-29.
- [2] Su TF, Chang CT, Reitz RD, Farrell PV, Pierpont AD, Tow TC. Effects of Injection Pressure and Nozzle Geometry on Spray Smd and D.I. Diesel Emissions. SAE Technical Paper 1995:952360.
- [3] Naber JD, Siebers DL. Effects of Gas Density and Vaporization on Penetration and Dispersion of Diesel Sprays. 1996, SAE Technical Paper 1996:960034.
- [4] Bergstrand P, Forsth M, Denbrant I. The Influence of Hole Diameter on Flame Lift-Off Length. ILASS-Europe 2002, Zaragoza, Spain, September 2002.
- [5] Siebers D, Higgins B. Flame Lift-Off on Direct-Injection Diesel Sprays under Quiescent Conditions. SAE Technical Paper 2001:2001-01-0530.
- [6] Iida N, Wakimoto K, Takahashi S, Nikolic D. Effect of Nozzle Diameter and Egr Ratio on the Flame Temperature and Soot Formation for Various Fuels. 2001, SAE Technical Paper 2001:2001-01-1939.
- [7] Montgomery DT, Chan M, Chang CT, Farrell PV, Reitz RD, Effect of Injector Nozzle Hole Size and Number on Spray Characteristics and the Performance of a Heavy-Duty D.I. Diesel Engine. SAE Technical Paper 1996:962002.
- [8] Kobori S, Kamimoto T, Kosaka H. Ignition, Combustion and Emissions in a DI Diesel Engine Equipped With a Micro-Hole Nozzle. SAE Technical Paper 1996:960321.
- [9] Bergstrand P, Denbrant I. Diesel Combustion with Reduced Nozzle Hole Diameter. SAE Technical Pape 2001:2001-01-2010.
- [10] Seykens XLJ, Somers LMT, Baert RSG. Detailed Modeling of Common Rail Fuel Injection Process. Journal of Middle European Construction and Design of Cars (MECCA) 2005; III: 30-39.
- [11] Moon S, Tsujimura T, Gao Y, Park S, Wang J, Kurimoto N, Nishijima Y, Oguma M, Biodiesel

effects on transient needle motion and near-exit flow characteristics of a high-pressure diesel injector. *International Journal of Engine Research* 2014; 15:504-518.

[12] Miranda R, Chaves H, Obermeier F. Imaging of Cavitation, Hollow Jets and Jet Branching at Low Lift in a Real Size VCO Nozzle. *ILASS-Europe 2002, Zaragoza, Spain, September 2002.*

[13] Gavaises M, Andriotis A, Papoulias D, Mitroglou N, Theodorakakos A. Characterization of String Cavitation in Large-Scale Diesel Nozzles. *Physics of Fluids* 2009;21: 052107.

[14] Andriotis A, Gavaises M, Arcoumanis C. Vortex flow and cavitation in diesel injector nozzles. *Journal of Fluid Mechanics* 2008; 610:195-215.

[15] Andriotis A, Gavaises M. Influence of vortex flow and cavitation on near-nozzle diesel spray dispersion angle. *Atomization and Sprays* 2009;19:247-261.

[16] Lai MC, Zheng Y, Xie XB, Moon S, Liu Z, Gao J, Zhang X, Fezzaa K, Wang J, Shi J. Characterization of the Near-Field Spray and Internal Flow of Single-Hole and Multi-Hole Sac Nozzles using Phase Contrast X-Ray Imaging and CFD. *SAE International Journal of Engines* 2011;4:703-719.

[17] Lee WG, Reitz RD. A Numerical Investigation of Transient Flow and Cavitation within Minisac and Valve-Covered Hole Diesel Injector Nozzles *Journal of Engineering for Gas Turbines and Power* 2010;132:052802.

[18] Masuda R, Fuyuto T, Nagaoka M, Berg EV, Tatschl R. Validation of Diesel Fuel Spray and Mixture Formation from Nozzle Internal Flow Calculation. *SAE Technical Paper* 2005;2005-01-2098.

[19] Davis TJ, Gao D, Gureyev TE, Stevenson AW and Wilkins SW. Phase-contrast imaging of weakly absorbing materials using hard X-rays. *Nature* 1995; 373: 595-598.

[20] Wilkins SW, Gureyev TE, Gao D, Pogany A and Stevenson AW. Phase-contrast imaging using polychromatic hard X-rays. *Letters to Nature* 1996; 384: 335-338.

[21] Liu Z, Im K, Xie X, Wang Y, Fezzaa K, Lai MC and Wang J. Single-shot Ultra-fast Phase-contrast X-ray Imaging of High-Pressure Diesel Fuel Sprays. 11th International Conference on Liquid Atomization and Spray Systems (ICLASS 2009), Vail, Colorado, US, July 2009.

- [22] Moon S, Liu Z, Gao J, Dufresne E, Fezzaa K and Wang J. Ultrafast X-ray Phase-Contrast Imaging of High-Speed Fuel Sprays from a Two-Hole Diesel Nozzle. ILASS-Americas 2010, Cincinnati, Ohio, US, May 2010.
- [23] Moon S, Gao Y, Wang J, Fezzaa K, Tsujimura T. Near-Field Dynamics of High-Speed Diesel Sprays: Effects of Hole Inlet Geometry and Injection Pressure. Fuel 2014 ;133:299-309.
- [24] Moon S, Zhang X, Gao Y, Wang J, Tsujimura T, Kurimoto N and Nishijima Y. Near-Field Dynamics of Diesel and Biodiesel Sprays at 200 MPa Injection Pressure. 12th Triennial International Conference on Liquid Atomization and Spray Systems, Heidelberg, Germany, September 2012.
- [25] Soteriou C, Andrews RJ, Torres N, Smith M, Kunkulagunta R. Through the Diesel Nozzle Hole – A Journey of Discovery, ILASS-Americas 2001, Dearborn, Michigan, US, May 2001.
- [26] Som S, Aggarwal SK, El-Hannouny EM, Longman DE. Investigation of Nozzle Flow and Cavitating Characteristics in a Diesel Injector. Journal of Engineering for Gas Turbines and Power 2010;132: 042802.
- [27] Hayashi T, Suzuki M, Ikemoto M. Visualization of Internal Flow and Spray Formation with Real Size Diesel Nozzle, 12th Triennial International Conference on Liquid Atomization and Spray Systems, Heidelberg, Germany, September 2012.
- [28] Lee WG, Reitz RD. *A Numerical Investigation of Transient Flow and Cavitation Within Minisac and Valve-Covered Orifice Diesel Injector Nozzles. Journal of Engineering for Gas Turbines and Power 2010;132:052802.*

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Table 1 Experimental Conditions

Injection Pressure (P_{inj})	150 MPa
Injection Pulse Duration (T_{inj})	1.0 ms
Ambient Pressure	Atmospheric (0.1 MPa)
Ambient Temperature	Room Condition (302 K)
Ambient Density	1.25 kg/m ³ with nitrogen (N ₂), 6.17 kg/m ³ with sulfurhexaflouride (SF ₆)
Fuel	Diesel (US No. 2)

Fig. 1 Experiment setup for x-ray phase-contrast imaging (a) and x-ray pulse timing pattern used for PCI-based single-pulse or multi-exposure experiments (b)

(a)

(b)

Fig. 2 Illustration of the x-ray imaging method to derive needle motion and local spray velocity: a) cross-correlation of images taken at different times to derive the needle position as a function of time, and b) multi-exposure spray image (2 or 3 exposures) to calculate the projected velocity map using 2D auto correlation functions

Fig. 3 XPCI images of internal structures near the needle tip, sac, and the orifices

Fig. 4 Transient needle motion characteristics of the single-, 3- and 6-hole injectors after the start of injection (SOI) at an injection pressure of 150 MPa and at 300 K ambient temperature with N_2 environment: a) needle left, and b) needle speed calculated by the derivative of the needle lift profile

Fig. 5 Notable characteristics of the needle behavior of the single-, 3- and 6-hole injectors. During opening-transient stage: (a) peak needle speed and b) time at peak needle speed; During quasi-steady stage: c) needle speeds during opening- and closing-steady; During closing-transient stage: d) time and e) needle lift at doubled needle speed: $P_{inj}=150$ MPa, $T_{amb}=300$ K, N_2 environment

Fig. 6 Time evolution of diesel jet axial speed at 1 mm from the hole exit and needle displacement profiles of the single-, 3- and 6-hole injectors (a) and illustration of the measurement location (b):

$P_{inj}=150$ MPa, $T_{amb}=300$ K, N_2 environment

Fig. 7 Radial distribution of velocity vector map and the shot-to-shot variation of the velocity magnitude measured at 1 mm from the orifice exit (top illustration): a) velocity maps at 0.11, 0.44, 1.44 and 2.44 ms after the SOI, b) radial distribution of the variation for the 3 nozzles at 0.44 and 1.44 ms: $P_{inj}=150$ MPa, $T_{amb}=300$ K, N_2 environment

Fig. 8 Near-exit flow structure of the single-, 3- and 6-hole injectors during opening-transient (a) and at quasi-steady condition (b), and three representative shot images of the 3-hole injector at intermediate stage (c) : $P_{inj}=150$ MPa, $T_{amb}=300$ K, N_2 environment

Fig. 9 Ten-shot averaged near-exit spray width and its shot-to-shot deviation of the single-, 3- and 6-hole injectors measured at 0.7mm axial location, $P_{inj}=150$ MPa, $T_{amb}=300$ K, N_2 environment

Fig. 10 Histogram of the near-exit spray width of the single-, 3- and 6-hole injectors at the 0.7 mm axial location under the quasi-steady condition in the time range from 1.0 ms to 2.0 ms (total 50 samples): $P_{inj}=150$ MPa, $T_{amb}=300$ K, N_2 environment

Fig. 11 Normalized velocity of the single-, 3- and 6-hole injectors at different axial locations (z) of the jet/spray center under a quasi-steady condition: $P_{\text{inj}}=150$ MPa, $T_{\text{amb}}=300$ K, N_2 environment, Time=1.44 ms after SOI, 20-shots averaged