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Effect of the number and position of nozzle holes on in- and near-nozzle dynamic characteristics of diesel injection

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HIGHLIGHTS

- We analyze in- and near-nozzle dynamics of single- and multi-hole diesel injectors.
- An X-ray imaging technique was applied for analysis of dynamic characteristics.
- Number of nozzle holes significantly changes the transient needle behavior.
- Near-nozzle flow characteristics are highly affected by the hole arrangement.
- Multi-hole nozzles generate turbulent initial flow with faster mixing at downstream.

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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.

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 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

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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 analyze the in-nozzle needle motion and near-nozzle flow dynamics and structures of the high-speed diesel sprays. 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 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 and structures 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 operating at 1-kHz frequency with 9-μs 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 μm when a 10× or 5× 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 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.