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Eccentric needle motion effect on near-nozzle dynamics of diesel spray

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HIGHLIGHTS

- Eccentric needle motions in varied conditions were studied.
- Oscillation in spray axial velocity was correlated to the eccentric needle motion.
- Mechanism of the needle eccentricity effect on spray dynamics was discussed.

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ABSTRACT

The eccentric needle motion has been regarded as an important cause of in-nozzle flow disturbances and hole-to-hole spray variations of modern fuel injectors. However, the experimental investigations on this subject have rarely been reported due to great difficulties in the direct measurements of eccentric needle motion and the flow characteristics of individual holes in an injection nozzle. In this study, the axial and eccentric needle motion and the near-nozzle spray dynamics of 3-hole, 5-hole and 8-hole diesel injection nozzles were investigated in varied injection pressure conditions using an X-ray phase-contrast imaging technique. The eccentric needle motion and near-nozzle spray axial velocity showed temporal oscillations during the injection with different oscillation frequencies. The frequencies of these two oscillations were independent to the nozzle hole number and injection pressure. To discuss the mutual dependency of these two oscillations, the time traces of the spray axial velocity were measured for individual holes. The results showed that the oscillation phase, frequency and amplitude of the spray axial velocity were almost identical for all holes, which indicated that the sac pressure variation rather than hole-to-hole flow variation can be the primary cause of the spray axial velocity oscillation by the eccentric needle motion. The adequacy of this consideration was thoroughly discussed using a mass balance model in the nozzle sac that predicted the sac pressure variation during an injection event.

1. Introduction

Spray dynamics have the strong influence on engine performance and emissions [1–3]. Favorable spray dynamics enhance the momentum transfer between the liquid fuel and gas, which promotes the mixture preparation and combustion in engines. Recent advances in investigations have found that the near-nozzle spray dynamics are governed by in-nozzle flow characteristics [4,5]. To create appropriate spray patterns, the parameters that affect the in-nozzle flow characteristics need to be carefully considered in the nozzle design.

On one hand, great attentions have been paid to the geometrical parameters of the nozzle such as the sac shape and volume [6], the diameter, length and number of orifices [7], the convergence and divergence level of orifices [8], and the hydro-grinding level of the orifice inlet [9]. On the other hand, the transient needle motion has been regarded as another important influencing factor of the in-nozzle flow characteristics. There are two aspects when considering the needle motion effect. One is the on-axis needle lift, which can be measured with the displacement sensor or optical sensor [10,11]. Extensive investigations have been conducted on the effect of on-axis needle lift on spray characteristics by experiments [12,13] and numerical simulations [14–16]. Another effect of the needle motion arises from the needle eccentricity, yet the direct measurements in practical nozzles are extremely difficult. The conventional displacement sensor and optical sensor, which are normally mounted centimeters away from the needle tip on the injector body, are incompetent to detect the eccentric motion of the needle tip. Hence, experimental investigations were mostly

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conducted using the enlarged transparent nozzle. For instance, Oda et al. [17] performed the experiment with a 10 times large-scaled valve-covered-orifice (VCO) nozzle. Their results showed that when the needle was positioned at different locations perpendicular to the observed orifice, the cavitation structure in the observed orifice altered as the change in perpendicular positions, which cause a complicated spray dynamic trend during the injection. However, some researchers pointed out that the results acquired from the enlarged nozzles might not be exactly the same as in the practical size nozzles [18]. While the experimental research faces great difficulties, the Computational Fluid Dynamics (CFD) has become another important approach to investigate the effect of eccentric needle motion. Spathopoulou et al. [19] conducted the nozzle internal flow simulations by hypothesizing an eccentric needle motion profile for a multi-hole VCO nozzle. Their results showed that the eccentric needle motion can induce significant hole-to-hole flow variations. However, their research was based on a presumed eccentric needle motion that might be different with the practical cases.

To acquire the actual needle motion in practical nozzles, a promising measurement technique based on the X-ray phase-contrast imaging (XPCI) has been introduced in recent years [20–23]. These measurement data have been used as the input data for CFD simulations. Xue et al. [24,25] modeled the nozzle internal flow of the mini-sac type diesel nozzles using real needle motion data and found that the fuel flow in the nozzle orifice was insensitive to the needle eccentricity in the case of axisymmetric single-hole nozzle. On the other hand, hole-to-hole flow variations and mass unbalances were identified for the multi-hole nozzles which orifices were aligned off-axis with certain inclination angles (umbrella angles). Based on the Xue's investigation, Battistoni et al. [26] conducted further simulations to capture the nozzle internal flow development in the presence of the needle eccentricity. They reported that a local tumbling vortex was formed in the nozzle sac at partial needle lifts (0 mm–0.15 mm) due to uneven flow conditions into the sac, which is the main cause of hole-to-hole flow variations. At high needle lifts (0.15–0.35 mm), the flow structure of each hole became almost identical as in the case without any needle eccentricity, which indicated that the eccentric needle motion has insignificant effects on nozzle internal flow characteristics at sufficiently high needle lifts. These simulation results have provided novel insights into the effect of the needle eccentricity on initial fuel flow characteristics. However, the conclusions drawn from these simulations are still not entirely convinced because the reliability of the simulation results has rarely been validated due to lack of measurement data with regard to the initial flow characteristics of individual holes. This lack of validation data is caused by the difficulties in the optical access to the near-nozzle fuel flow due to the severe scattering and absorption of the conventional light sources against the dense liquid features in the near-nozzle region.

In this study, the experimental observations were performed to reveal the effects of eccentric needle motion on near-nozzle spray dynamics of practical diesel nozzles using the XPCI. First, the on-axis needle lift and eccentric needle motion of three practical diesel nozzles were analyzed using the X-ray phase-contrast images of the needle tip (high energy mode, to be introduced in the following section). The 3-hole, 5-hole and 8-hole nozzles were used and three different injection pressures were applied to each nozzle to clarify the effects of nozzle hole number and injection pressure on the eccentric needle motion. Then, the near-nozzle spray dynamics of the three nozzles were analyzed using the X-ray phase-contrast images of the near-nozzle spray structure (high time resolution mode, to be introduced in the following section) in varied injection pressure conditions. In the final section, the influencing mechanism of the needle eccentricity on near-nozzle spray dynamics was discussed thoroughly based on the measurement results. The results of this study would provide valuable information for the validation of previous simulations as well as a better understanding of the parameters affecting the initial fuel flow characteristics of modern fuel injectors.

2. Experimental method

2.1. X-ray phase-contrast imaging for near-nozzle fuel spray analysis

Conventional light sources have been incompetent for the investigations of the optically dense fuel sprays in the near-nozzle region because they suffer from severe absorption and scattering from the liquid features. To resolve the difficulties, the XPCI has been introduced for near-nozzle spray analysis since the last decade [27]. Compared to the conventional light sources, the high-energy and ultra-bright X-ray beams available at the third generation synchrotron sources have the weak interaction with liquid fuels and possess ultra-short pulses (sub-to a few nanoseconds). These advantages enable the imaging of the dense and high-speed fuel sprays in the near-nozzle region on the basis of the phase-contrast mechanism. When an X-ray beam passes through a dense fuel spray, both absorption and phase-shift occur. The diffracted x-rays can generate an interference pattern with bright and dark fringes along the interfaces having different densities. The X-ray phase-contrast images record both the interference fringe pattern and the intensity attenuation from absorption, similar to back-illuminated shadowgraph in the visible light regime.

2.2. Experimental setup

The experimental setup for the XPCI has been described extensively in previous investigations [7,8]. In the Hybrid-Singlet beam mode of Advanced Photon Source (APS), an irregular pulse pattern is generated for each cycle with 3.682 µs period. This pulse pattern contains a single-bunch with a 150 ps duration and a 16 mA current isolated from the remaining 8 group of 7 consecutive bunches (8 septets) with 11 mA current per group and a periodicity of 68 ns as presented in Fig. 1. To protect the imaging system from the heat-load of the X-ray beam, a mechanical X-ray shutter (the slow chopper in Fig. 1a) is used to allow the beam to pass through the shutter only at the imaging instant (8 ms opening duration). A scintillator crystal (LuAg:Ce) converts the X-ray "shadow" images of the sprays into visible-light images, which are then reflected by a 45° mirror and captured by a high speed camera (Model SA-Z, Photron Inc.). The temporal resolution of the images is determined by the X-ray pulse duration and the camera gating. In this investigation, the camera frame rate of 67,889 Hz (one-fourth of synchrotron revolution frequency) was adopted to record the transient needle motion and near-nozzle spray structure during an injection event. The needle motion and near-nozzle spray structure were recorded separately in different injections because different X-ray pulse patterns were required for their imaging. The phase and opening duration of the camera gate was controlled to receive the desired X-ray pulses for each measurement item.

More specifically, the 8 septets (part A in Fig. 1b) were received by the camera for the visualization of needle motion, which have a total electron current of 88 mA and a length of 472 ns. This pulse train has sufficient X-ray photons to visualize the needle motion through the steel nozzle enclosure. The total pulse duration of 472 ns is short enough to freeze the needle motion during the injection process, which has the speed of around a meter per second. To visualize the near-nozzle spray structure, the single-bunch was received by the camera (part B in Fig. 1b) because it provides a sufficiently high time resolution (150 ps) for the imaging of high-