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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

Xusheng Zhang [a,*], Seoksu Moon [b], Jian Gao [c], Eric M. Dufresne [d], Kamel Fezzaa [d], Jin Wang [d]

[a] Merchant Marine College, Shanghai Maritime University, Shanghai 201306, China
[b] Research Center for New Fuels and Vehicle Technology, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan
[c] Propulsion Systems Research Lab., General Motors Global Research and Development, Warren, USA
[d] Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439, USA

HIGHLIGHTS

- Fast X-ray phase-contrast imaging was used to study the near-nozzle spray morphology.
- Effect of nozzle hole-to-hole angle on the spray width was investigated.
- Representative spray morphology related to needle lift and injection pressure was found.
- Strong dependence of breakup process on the spray morphology was revealed.

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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

* Corresponding author.
E-mail address: sjtu.zhang@gmail.com (X. Zhang).

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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 μs gaps. A millisecond shutter (1 Hz) and a microsecond shutter (500 Hz) 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, 1024 × 1280 pixels, 1 Hz) equipped with microscope objective lenses. The effective pixel size of the camera was 0.63 or 1.26 μm for a 10× or 5× objective lenses respectively. The single bunch and eight bunches were used to record the images of spray and needle lift respectively.

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 Ref. [27]. The injectors have the same nominal hole diameter of 0.12 mm, 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 ±2 μm based on the X-ray images.

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/m^3, and kinematic viscosities (25 °C) are 3.32 and 5.4 mm^2/s.

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 1.5 mm away from the nozzle exit, as shown in Fig. 3a. Fig. 3b shows the needle lift measurement based on the image cross-correlation of red matching template with matching resolution of 1 pixel.

Fig. 4 shows the needle lift profiles of UA130 at the injection pressures of 30 and 100 MPa 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 100 MPa and there was a small duration of semi-steady stage. If the injection pressure was lower than 100 MPa, 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.