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Near-field dynamics of high-speed diesel sprays: Effects of orifice inlet geometry and injection pressure

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HIGHLIGHTS

- We used an X-ray technique to analyze near-field spray dynamics.
- Spray dynamics was analyzed by auto-correlation analysis of multi-exposed images.
- The methodology was applied to analyze dynamics of optically dense diesel sprays.
- Several notable features of diesel spray dynamics in the near-field were discussed.
- The effects of orifice inlet geometry and injection pressure were discussed.

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ABSTRACT

Unveiling the near-field dynamics of high-speed and optically dense liquid fuel jets and sprays, such as velocity and turbulence intensity fields, is of great importance for successful interpretation and modeling of the spraying and combustion process in internal combustion engines. Characterizing the dynamics using conventional laser optical techniques have been difficult in the near-nozzle region where the fuel jet, ligaments, and droplets interact with visible light strongly producing severe multiple scattering and optical opacity. Here, we use a novel technique to characterize the velocity and turbulence intensity fields of the high-speed diesel sprays in the near-field by multi-exposed X-ray phase-contrast images. With the X-ray-imaging data, the effects of the orifice inlet geometry and injection pressure on the near-field dynamics of the diesel sprays are investigated. Notable features of the spray dynamics in the near-nozzle region and beyond are discussed by comparing the measurement results with the predictions of conventional gas jet theories.

1. Introduction

Low-speed liquid jet with emerging pure liquid core have been well characterized by unstable capillary-wave growth on the jet surface by a pioneering study of Rayleigh [1]. However, the near-field development and breakup of the high-speed fuel sprays for combustion applications are far from those for the low-speed jets, since the emerging liquid flows are governed by complicated turbulent and cavitating flow patterns inside the injection nozzle. Especially, for multi-orifice injector nozzles, the complicated inter-orifice flow can greatly affect the velocity and turbulence intensity fields of the fuel sprays in an even more complex way. Information about the near-field velocity and turbulence intensity fields is crucial to interpret the initial liquid flow development and has an important value as a critical input to validate spray modeling [2–4]. However, near-field spray dynamics has been difficult to characterize due to hardness in optical access to this region.

Limitations in current measurement techniques, mostly based on visible-light methods, are mainly responsible for the less satisfactory situation in understanding the spray dynamics in the near-field. For example, laser Doppler velocimetry (LDV) [5] and particle image velocimetry (PIV) [6–8], have been widely employed to measure the velocity fields of fuel sprays, but their applicability has been limited to the region of a few tens of millimeters away from the nozzle exit. With sub-micrometer wavelength, visible light interacts with the fuel jet, ligaments, and droplets through elastic scattering. The interaction is often so strong that multiple scattering dominates the process in the near-nozzle region. Therefore, the near-nozzle region are extremely optically dense

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and often opaque, which hinder the research effort to derive reliable dynamics information of the near-field fuel jet/sprays.

During the last decade, intense X-rays from synchrotron sources have been introduced to fuel spray research to circumvent the strong multiple scattering problem in the near-field. Hard X-rays, which have weak interaction with the liquid fuels, can pass through the optically dense materials without multiple scattering and severe absorption. In addition, the phase variations of the emerging radiations from the liquid/gas interfaces inside the dense fuel jet can be recorded [9–11] to understand the morphology of fuel jet, ligaments, and droplets. Based on the phase difference during the wave propagation, an X-ray phase-contrast imaging (XPCI) technique has been introduced to visualize the features inside the dense fuel sprays in the near-field and substantial valuable information has been derived using this technique. Resolving liquid/gas interfaces with micrometer resolution, XPCI can also provide benefits to analyze the spray dynamics in the near-field [12,13]. Similar to optical PIV method, two or several short X-ray pulses (sub-nanosecond to a few nanoseconds) with a variety of intervals can be used to take the multi-exposed images of the high-speed fuel sprays. The velocity of the high-speed dense structures of the fuel jet can be derived by tracking the movement of the features recorded in the multi-exposed images without the need of seed particles. This approach was employed in a previous study, but its application was limited to the low-pressure gasoline sprays with speeds well below 100 m/s [12]. In this study, we exploit the potential of the X-ray imaging technique to derive the near-field dynamics of the high-speed diesel sprays in the near-field where the fuel flow speed can reach 500 m/s, almost an order of magnitude higher than what was studied before [12].

The current study has three major topics. First, we briefly describe the novel technique to analyze the near-field dynamics of the high-speed diesel sprays using the multi-exposed XPCIs. Second, the effects of orifice inlet geometry and injection pressure on the near-field dynamics of the diesel sprays are investigated based on the dynamics result. Third, several features of the spray dynamics in and beyond the near field are discussed by comparing the measured result with a simple model using conventional gas jet theories [4,14].

2. Methods

2.1. Propagation-based X-ray phase-contrast imaging (XPCI)

The XPCI of fuel sprays originates from the small refractive index increment of liquid in X-ray regime [15,16]. The weak interaction between X-rays and the liquid jet enables the X-ray beam to pass through the optically dense materials without severe scattering and absorption. When the X-ray beam passes through an object, both absorption and phase-shift occur. We here consider a case in which the X-ray passed through a liquid surrounded by a gas. Due to phase-shift, the unperturbed, scattered and transmitted X-rays generate interference patterns with bright and dark fringes along the liquid/gas boundaries. On the other hand, the absorption reduces the transmitted X-ray intensity slightly through the liquid. The XPCI records both the fringe patterns from the phase-shift and the intensity attenuation from the absorption. The XPCI enables to detect not only the isolated ligaments and droplets, but also the larger liquid structures such as membranes and ligaments still connected to the liquid core. The imaging mechanism of the XPCI is quite similar to that of back-illuminated shadowgraph, but the higher transmittance of the X-rays through the optically dense materials and structures allows imaging the liquid-phase features of the liquid fuel jets. The contrast level of the image is dependent on the feature size and the liquid/gas interface shape. In general, for a fuel jet and spray, the larger the feature size, the higher image contrast level of the fringe pattern.

The short X-ray pulses (ca. 100 ps) at the synchrotron sources such as the Advanced Photon Source (APS) provide a high temporal resolution of the XPCI to freeze the motion of the high-speed fuel sprays, benefiting the visualization of the micro-scale features of the high-speed dense fuel sprays in the near-field with high temporal and spatial resolutions.

2.2. Experiments

2.2.1. Setup for XPCI

The experiments were performed using the XPCI setup at XOR 32-ID beamline at the APS, shown in Fig. 1. To protect the system from being damaged by the high-power unfiltered X-ray beam, two mechanical shutters were used: a slow shutter operating at 1 Hz with ca. 10-ms opening duration and a fast chopper operating at 500 Hz with ca. 10-μs opening duration. The synchronized operation of the shutters cuts the beam heat load over 99.99%.

A scintillator crystal (LYSO:Ce) converts an X-ray image into a visible-light (432 nm) one, which was reflected by a 45° mirror and recorded by a gated charge-coupled device (CCD) camera (Sensicam, 1376 × 1040 pixels, PCO-TECH Inc.). A 5 × magnification lens was applied to improve the spatial resolution of the image to 1.32 μm/pixel resulting in a field of view of the camera of 1.82 mm (in the horizontal direction) by 1.37 mm (in the vertical direction). The source to sample distance was about 40 m where the X-ray beam size was just bigger than the camera's field of view and the X-ray intensity was close to uniform in the view. The sample to scintillator distance was set to 250 mm to optimize the image contrast and resolution for velocimetry measurement.

2.2.2. X-ray timing pattern for XPCI

Fig. 2 shows the APS special timing mode used for the present XPCI-based velocimetry study. X-ray pulses in the timing pattern was generated by an insertion device (undulator) in the APS electron storage ring. This timing pattern contains a single electron bunch (117-ps duration full-width-half-maximum, 16-mA current) isolated from the remaining electron bunches containing 8 groups of 7 bunches with 11 mA per group, a periodicity of 68 ns, and a gap of 51 ns between groups. The total length of the bunch train is 472 ns. The singlet is separated with the bunch trains by symmetrical 1.594 μs gaps. The singlet pulse was used to capture the single-exposed X-ray phase-contrast images for visualizing the spray breakup process. For velocimetry measurement and dynamics analysis, the multi-exposed X-ray phase-contrast images were captured using 2 of the 8 X-ray pulse groups of 17 ns in length each and with 68-ns center-to-center interval.

2.2.3. Fuel injection systems

A common-rail diesel injection system was employed to generate and control the fuel pressure. The injection system was composed of a fuel tank, electric motor, high-pressure pump, pressure control valve, common rail and pressure sensor (as shown in Fig. 1). The pressure in the common-rail was controlled by a feedback-loop driven fuel bleeding valve at the common rail to achieve a set pressure. The pressurized fuel was injected into a spray chamber that was fitted with two Kapton® windows that were X-ray transparent in the photon energy range. A gas flow of sulfur hexafluoride (SF_6, density: 6.17 kg/m^3) with a gentle flow rate of 1 liter per minute was supplied to the spray chamber to blow out the injected fuel during the experiment.