Fuel 181 (2016) 964–972

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Transient needle motion of an outwardly opening GDI injector and its effects on initial spray formation

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HIGHLIGHTS

- Transient needle motion of an outwardly opening GDI injector was analyzed.
- The effect of needle motion on initial spray formation was investigated.
- X-ray imaging technique was used for needle motion and initial flow analysis.
- Needle vibration was observed and its amplitude damped down with time.
- Initial flow dynamics and breakup varied following the needle vibration.

ARTICLE INFO

Article history:
Received 5 March 2016
Received in revised form 17 April 2016
Accepted 4 May 2016
Available online 14 May 2016

Keywords:
Outwardly opening injector
Transient needle motion
Hollow-cone spray
Initial spray formation
X-ray phase-contrast imaging

ABSTRACT

Outwardly opening injectors for gasoline direct-injection engines form thin-sheet hollow-cone sprays. The spray formation of the outwardly opening injectors is governed by the transient needle motion that alters the initial flow conditions such as liquid sheet thickness, emerging flow velocity and turbulence strength. However, the transient needle motion and its effects on the initial spray formation have been difficult to be studied by conventional lasers due to severe absorption and scattering of the laser lights from dense liquid features in the near-field. The current study investigates the transient needle motion of an outwardly opening injector and discusses its effects on initial spray formation using an X-ray phase-contrast imaging technique. An X-ray pulse with 80 ps duration in FWHM was used to visualize the transient needle motion and near-nozzle flow morphology. On the other hand, three X-ray pulses with 165.2 ns period were used to analyze the dynamics of near-nozzle flow by tracking the movement of the liquid features. An obvious needle vibration was observed through the injection process and the amplitude of the vibration damped down with time. This needle vibration accelerated and decelerated the near-nozzle flow in turn that altered the undisturbed liquid length and flow breakup with time. The temporal variation of the initial flow characteristics caused an irregular droplet size distribution with the distance from the nozzle tip other than monotonous decrease.

1. Introduction

Gasoline direct-injection (GDI) engines have brought the benefits of increased engine thermal efficiency and reduced engine-out emissions by implementation of the stratified-charge lean combustion concept that locates the target fuel–air mixture around of the spark plug. These benefits can be realized when the fuel–air mixture can be controlled in a sophisticated way in a very limited time of an engine cycle that requires the high controllability and robustness of the fuel spray as well as the fast atomization. The piezo-actuated outwardly opening injectors have been considered as one of the injectors that satisfy these requirements.

The needle of the outwardly opening injector is exposed to the surroundings and opens toward outside. As a result, a hollow-cone spray is formed from this injector. Substantial previous studies have reported the effect of injection and ambient conditions and fuel property on the macroscopic and microscopic spray structures of the outwardly opening injectors such as spray tip penetration, droplet size distribution and string-like flow structure on the spray surface [1–5]. On the other hand, the structure of in-nozzle cavitation has been investigated using large-scale transparent nozzles that simulated the structure of the practical injectors [6–8]. However, the previous studies have rarely paid attention to the

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http://dx.doi.org/10.1016/j.fuel.2016.05.012
0016-2361/

transient needle motion and its influence on the initial spray formation.

The needle motion is one of the critical spray control factors especially for the outwardly opening injectors. While the cross-section area of the flow discharge passage is constant for the conventional hole-type fuel injectors, it changes with the needle lift for the outwardly opening injectors. As a result, the initial flow conditions such as the liquid sheet thickness, emerging flow velocity from the nozzle (injection velocity) and turbulence strength can vary by the transient needle motion. Nevertheless, the transient needle motion and its influence on the initial spray formation have been difficult to be studied due to lack of measurement method. A previous study measured the transient needle motion of an outwardly opening injector using a microscope in combination with a high-speed camera [9], but the application of this method has been limited to the dry conditions (without fuel injection) because the injected fuel interrupts the light passage. Furthermore, the initial flow dynamics and structures have been also difficult to be studied due to severe scattering of the liquid features against the laser lights in the near-field.

In this study, the transient needle motion of an outwardly opening injector was measured using an X-ray phase-contrast imaging (XPCI) technique in the dry (without fuel injection) and wet (with fuel injection) conditions. Then, the effects of transient needle motion on initial flow characteristics such as injection velocity, undisturbed liquid length, initial flow angle and droplet size distribution were investigated using the X-ray phase-contrast imaging technique.

2. Method and experiments

2.1. X-ray phase-contrast imaging

In this section, the introduction to XPCI will be made briefly because the principle of XPCI has been well documented in considerable previous studies [10–15].

When an object is irradiated with an X-ray beam, the absorption and phase-shift usually appear together. In terms of the phase-shift, the incident and diffracted X-ray beams form an interference pattern with bright and dark fringes along the object boundary (refer to Fig. 1). By recording both the fringe pattern from the phase-shift and the intensity attenuation from the absorption, the XPCI can visualize the all interfaces of the objects having different densities along the beam path such as needle, liquid fuel and surrounding gas. In addition, the ultra-short X-ray pulses (sub to a few nanoseconds) provide a high temporal resolution of the 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 analyze the transient needle motion and initial flow characteristics of the high-speed dense fuel sprays that have been difficult to be studied using conventional laser methods due to severe absorption and scattering of the laser lights from dense liquid features in the near-field.

2.2. Setup for X-ray phase-contrast imaging

The experiments were performed at the BL40XU beamline of the SPring-8 (super photon ring – 8 GeV). Fig. 2 presents the experimental setup of the XPCI built in the SPring-8. The X-ray beam was generated from an insertion device (undulator) in the electron storage ring. The X-ray beam was chopped by mechanical shutters which let the X-ray beam pass through only at the imaging instance to circumvent possible damages of the imaging systems from the X-ray heat load. The phase-contrast image of the fuel spray was formed on a scintillator crystal (Lu–Si–O) after the X-ray transmission, which converts the transmitted X-ray beam into a visible light (420 nm). The image was then reflected by a 45° mirror and captured by a charge-coupled device (CCD) camera (Hamamatsu Photonics, ORCA-II-ER). One image frame was recorded for one injection from the CCD camera (1 frame/shot). The field of view of the camera was 0.67 mm × 0.51 mm and the image resolution was 1 μm/pixel. For the fuel injection into the spray chamber, the fuel was pressurized using a pneumatic driven liquid pump (Haskel, Model M-71). The supply pressure to the fuel injector was controlled using a liquid pressure regulator (Swagelok, KPP series). The spray chamber had two Kapton windows that allowed the X-ray beam to pass through these with a minor decrease in intensity.

2.3. Methods for needle motion and initial flow analysis

Two X-ray beam modes of the SPring-8, H-mode and C-mode, were used to analyze the transient needle motion and the initial flow structure and dynamics. The H-mode contains a single electron bunch with 80 ps length in FWHM (full width at half maximum) and 5.0 mA current isolated from the 11/29 filling pattern with 1.487 μs interval (refer to Fig. 3). The single exposed X-ray images were captured using the single electron bunch for the analysis of flow structure in the near-field as well as the needle motion. The needle lift at certain timing during the injection was analyzed by the cross-correlation of two needle images, one taken without the fuel injection and the other taken at certain timing during the injection. The details of the cross-correlation analysis for

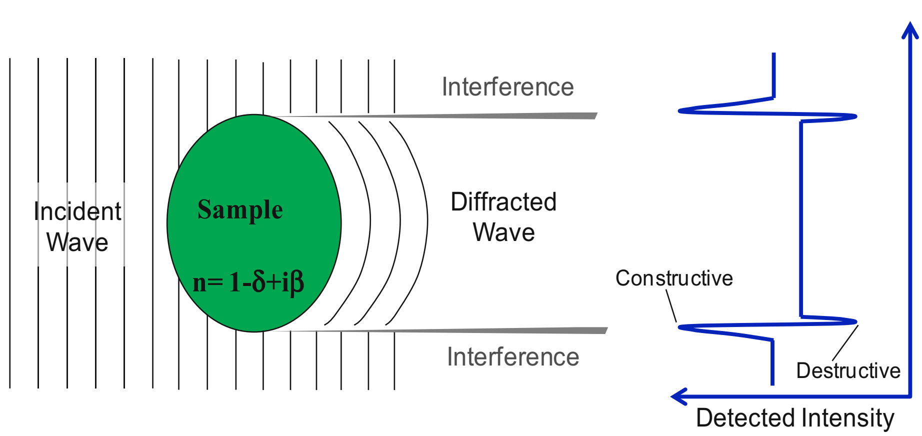

Fig. 1. Principle of X-ray phase-contrast imaging.