Fuel 180 (2016) 292–300

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Near-nozzle dynamics of diesel spray under varied needle lifts and its prediction using analytical model

Weidi Huang [a], Seoksu Moon [a,*], Katsuyuki Ohsawa [b]

[a] Research Institute for Energy Conservation, National Institute of Advanced Industrial Science and Technology, 1-2-1 Namiki, Tsukuba, Ibaraki 305-8564, Japan
[b] Department of Mechanical Engineering, Tottori University, 4-101 Koyama-cho Minami, Tottori 680-8550, Japan

HIGHLIGHTS

- Needle lifts in diesel nozzle under varied injection pulse durations were studied.
- Needle-lift dependence of near-nozzle diesel spray dynamics was revealed.
- Critical needle lift to ensure sufficient spray momentum was discussed.
- Analytical model to correlate the needle lift to spray velocity has been proposed.

ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form 4 April 2016
Accepted 8 April 2016
Available online 16 April 2016

Keywords:
Diesel injector
Injection pulse duration
Needle lift
Jet axial velocity
Analytical model

ABSTRACT

Due to the lack of sufficient measurement methods, great difficulties are still present in clarifying the relationship between the nozzle internal flow and liquid-jet dynamics, especially when considering the needle motion effect. In this study, by utilizing the X-ray phase-contrast imaging (XPCI) technique, the in-nozzle needle motion characteristics and the liquid-jet dynamics in the near-nozzle field have been measured within a wide range of injection-pulse durations, based on which the needle-lift dependence of liquid-jet dynamics has been discussed in detail. The study is important for the nozzle related investigations, especially in view of the increasingly widely adopted multiple-injection strategies in the injection systems. The results indicate that, ruled by the mass flow equilibrium inside the nozzle sac, the liquid-jet flow dynamics in the near-nozzle field is closely related to the needle lift and injection pressure. Insufficient needle lift under short injection-pulse duration hurts the liquid-jet momentum that should be highly considered in the multiple-injection strategies. An analytical model has also been proposed to predict the jet axial velocity in the near-nozzle field. The model was found to have good agreement with the experimental results at different conditions.

1. Introduction

The precise control of injection event contributes greatly to the optimization of engine performances and the reduction in pollutant emissions. In the last few decades, substantial efforts have been made to unveil the fundamental nature of fuel sprays and associated phenomena, such as spray behaviors under different injection pressures [1,2], different environment conditions [3,4], and different fuel properties [5,6]. These investigations proved that the high-speed relative motion between the liquid jet and environment gas is one of the key factors causing the jet disintegration and atomization. Nevertheless, because of the highly transient and multiphase process of fuel injection, the inherent mechanism of spray atomization and evaporation has not been conclusively determined [7,8] yet.

Lately, increasing attentions have been drawn to the flow characteristics inside the diesel nozzle due to their profound influences on the near-field spray behaviors. The investigations showed that the in-nozzle flow is strongly affected by the nozzle internal geometrical factors and the needle motion. From one aspect, the influences of the nozzle geometry on the internal flow [9,10], spray macroscopic structure [11–14] and mass flow rate [15,16] have been widely discussed. Many solid conclusions have been gained and thereby some numerical models have also been established [17,18]. For instance, by utilizing a recently developed primary breakup model (KH-ACT), Som et al. conducted the simulation study to reveal the effect of the orifice structures on the in-nozzle flow, spray, and combustion process [18]. Different from the previous studies, in Som et al.'s simulation the effects of

* Corresponding author.
E-mail address: ss.moon@aist.go.jp (S. Moon).

http://dx.doi.org/10.1016/j.fuel.2016.04.042

cavitation and turbulence inside the diesel nozzle were coupled with the effect of aero dynamics to decide the spray breakup and atomization processes. Their results showed that the conicity and hydro-grinding reduce the cavitation and turbulence inside the nozzle, and then slow down primary breakup, increase spray penetration, reduce the vaporization rate and air-fuel mixing, and ultimately cause the ignition occurring further downstream.

From another aspect, the needle motion inside diesel nozzle has also been proved to play a decisive role for the spray dynamics [19–21]. However, by utilizing the conventional measuring methods, the needle lift is either calculated from other indirectly measuring parameters, or measured with the displacement sensor that is mounted centimeters away from the needle tip on the injector body. These measurements unavoidably bare the defects of insufficient accuracy. While experimental researches were exposed to great difficulties, the numerical investigation has become another important method [21–23]. For instance, Margot et al. [21] conducted the simulation investigation with the three dimensional moving-mesh method. Their results showed that the turbulence kinetic energy of internal flow is mostly created by the needle motion. At the low needle lifts, during opening and closing, the turbulence kinetic energy is more intense compared to that at the high needle lifts.

In recent years, a promising technique based on X-ray phase-contrast imaging (XPCI) was employed to analyze the diesel spray. The high-energy and short-pulse (sub-ns to 10's ns) X-ray beam enables the direct imaging of the needle motion through the steel nozzle tip and high-speed jet in the near field without severe scattering and absorption. Based on this technique, several investigations have been conducted to analyze the needle motion under the actual operating conditions [24,25], near-nozzle jet dynamics [26,27], and structures of diesel jets [28,29]. However, a thorough investigation to understand the needle-lift dependence of near-nozzle liquid-jet dynamics is still missing especially in the wide-range injection-pulse durations. This study is actually very important accounting for the increasingly widely adopted multi-injection strategies in injection systems. Within the multi-injection strategies, the conventional main injection event is split into two or more shorter pilot-injection events, which can effectively improve engine performance compared to the single-injection strategy [30,31]. Nevertheless, further shorten the pilot-injection event may cause the needle lift apparently lower than its normal situation, which on the contrary potentially results in the injection being unstable, decreasing the liquid-jet velocity, slowing the breakups, and then further humbling the combustion. Therefore, it is highly significant to define the correlation between the needle motion and the jet dynamics, especially at the short injection-pulse durations.

In this study, by taking advantage of the XPCI technique, we firstly measured the in-nozzle needle motion and the near-field liquid-jet dynamics, including the jet axial velocity and lateral width, within a wide range of injection-pulse durations. Then the needle-lift dependence of near-field jet dynamics was discussed in detail. The critical needle-lift to ensure the sufficient jet momentum was defined. Furthermore, an analytical model was proposed to predict the near-field jet axial velocity, which will not only promote the understanding of the correlation between the needle lift and the jet dynamics, but also benefit for pilot-injection control in the multi-injection strategies.

2. Description of experiments

2.1. Experimental setup

We used the similar experimental setup for XPCI that was described in previous investigations [26,27]. Fig. 1a shows the sketch of XPCI setup at 7ID and 32ID beamlines of the Advanced Photon Source (APS), a third generation synchrotron X-ray source. In the Hybrid-Singlet beam mode of APS, an irregular pulse pattern is generated for each cycle with 3.682 μs period as presented in Fig. 1a and b. 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. The X-ray pulses needed for each analysis item can be received for imaging by proper phase and time control of the camera exposure. For specific, the X-ray timing pattern A includes eight septets with a total electron current of 88 mA and a length of 472 ns (part A in Fig. 1b). This pulse train has sufficient high-energy X-ray photons, which can be used for visualizing the in-nozzle needle motion through the steel nozzle enclosure. The total pulse duration of 472 ns was short enough to freeze the needle motion during the injection process, which have the speed of around a meter per second.

The near-nozzle field liquid-jet structures were visualized using the X-ray timing pattern B with an electron current of 16-mA and a length of 150-ps (part B in Fig. 1b). This pulse provides an extremely high time resolution for imaging, which makes it possible to capture the liquid-jet structure in the near-nozzle field that is so dense and turbulent to access by the conventional optical methods. The liquid-jet velocity was derived using the 2 septets with 11-mA current, 17-ns width, and 68 ns period (part C in Fig. 1b). Compared to other light sources, the synchrotron X-ray source contains the pulses with a very short time interval, suitable to capture the double exposed X-ray images for velocity measurements.

2.2. Data analysis

Fig. 2a and b shows the measurement method of the needle motion. Once the time-sequential images of needle motion are obtained, the needle lift profile can be calculated by cross-correlation of the needle images at the original location and measuring location. In this study, the jet axial velocity was introduced to describe the jet dynamics in the near-nozzle field due to its profound influence on jet evolution and atomization. To obtain the jet axial velocity, an auto-correlation analysis is performed in a particular region of interest (ROI) of the double-exposure images, as shown in Fig. 2d–e. In this study, a square region is introduced as ROI, which was 1 mm away from the nozzle tip. Based on data of a previous study (Ref. 27), the jet velocity decays to axial and radial direction as penetrating downstream. Different locations of region of interest may slightly affect the calculating results indeed. However, the focus of this study is the needle motion effect on the near-field jet dynamics and as the first step only the orifice exit velocity was considered. 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 detailed measurement method of the local spray velocity can be found in the recent publication [27].

Besides the jet axial velocity (U_{axial}), liquid-jet expansion angle (θ) was also considered in the analysis of jet dynamics in the near-nozzle field. The θ is defined as the top angle of the trapezoid formed by the orifice outlet diameter and the liquid-jet width at 1 mm from nozzle exit, as seen in Fig. 2c. A larger θ will promote jet breakup and spray–air interaction.

2.3. Experimental conditions

A commercial piezo injector with single-hole nozzle was used for the investigation. The injection pressures of 100 MPa and 200 MPa were selected. For each tested injection pressure, the environment gas density and temperature in spray chamber were fixed to atmospheric and room condition. Detailed information of the nozzle internal geometrical factors and injection conditions