Energy 115 (2016) 615–625

Contents lists available at ScienceDirect

Energy

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

Novel insights into the dynamic structure of biodiesel and conventional fuel sprays from high-pressure diesel injectors

Seoksu Moon

Research Institute for Energy Conservation, National Institute of Advanced Industrial Science and Technology, 1-2-1 Namiki, Tsukuba, Ibaraki, 305-8564 Japan

ARTICLE INFO

Article history:
Received 11 May 2016
Received in revised form
12 August 2016
Accepted 9 September 2016

Keywords:
Biodiesel
Fuel property
Spray dynamics
Diesel injector
Synchrotron X-ray velocimetry

ABSTRACT

The spray dynamics of biodiesel has not been thoroughly investigated in previous studies. Understanding the dynamic structure is important for successful modeling of biodiesel sprays and the proper use of biodiesel in modern engines. This study compares the dynamic structure of biodiesel and conventional fuel sprays from single- and multi-hole diesel injectors using a synchrotron X-ray velocimetry technique. Three fuels, biodiesel, diesel and Viscor16br, were used in this study. The results showed that the high viscosity and density of biodiesel decreased the injection velocity compared to conventional fuels. The biodiesel effect on injection velocity was less significant for the multi-hole injector. For the single-hole injector, the biodiesel slowed down the flow breakup and increased the intact core length that caused the lower velocity decay rate and turbulence intensity along the spray center. Meanwhile, in the case of the multi-hole injector, the flow breakup, and the velocity decay rate and turbulence intensity along the spray center appeared equivalent regardless of the fuel. The fuel viscosity did not play a dominant role in the spray dynamics of the multi-hole injector and the dynamic structure of the biodiesel and conventional fuel sprays can be scaled based on the momentum conserving gas jet theory.

1. Introduction

The introduction of bio-derived fuels to automotive engines has drawn great attention as a measure to depletion of fossil fuels and global warming. The physical properties of the bio-derived fuels vary dramatically from those of the conventional fossil fuels [1–4]. These differences in fuel properties can significantly alter the dynamic structure of fuel sprays in an unpredictable way that prevents the application of the bio-derived fuels in modern engines. Considerable previous studies have investigated the effect of bio-derived fuels on the fuel flow and macroscopic spray characteristics of fuel injectors [5–11]. Particularly, great attention has been paid to the biodiesel, which is one of the most widely used bio-derived fuels for automotive engines. Biodiesel has been considered as a diesel substitute and already introduced in the market in some countries. Biodiesel has a similar fuel density, but substantially higher fuel viscosity and surface tension than conventional fuels that could cause extraordinary fuel spray characteristics [1–4].

Regarding the biodiesel effects on initial flow characteristics, Moon et al. compared the in-nozzle needle behavior and emerging flow characteristics of the biodiesel and diesel injected from a single-hole diesel injector [11]. They observed that the high viscosity of the biodiesel slows down the needle motion, and decreases the nozzle outlet flow velocity and the level of initial flow turbulence. Som et al. performed a three-dimensional computational fluid dynamics (CFD) to analyze the nozzle internal and emerging fuel flow of a multi-hole diesel injector fueled with biodiesel and diesel [6]. Their results showed that the in-nozzle turbulence strength and flow performance decrease in the case of the biodiesel due to its higher viscosity. Regarding the biodiesel effects on downstream spray characteristics, Kuti et al. compared the droplet size distribution, entrained air mass and macroscopic spray structure of the biodiesel and diesel sprays injected from single-hole diesel injectors [9]. They observed that the biodiesel sprays have the larger droplet size, less air entrainment, narrower spray angle and longer spray tip penetration than the diesel sprays. It was discussed that the high viscosity and surface tension of the biodiesel could be responsible for this results trend. Similar results have also been reported from substantial previous studies.

E-mail address: ss.moon@aist.go.jp.

http://dx.doi.org/10.1016/j.energy.2016.09.062
0360-5442/

Although a certain level of understanding has been achieved through the previous studies, there are still a couple of critical subjects that need to be further understood. First, we are blind to the internal dynamic structure of the biodiesel sprays compared to that of the conventional fuel sprays. This information is of great importance not only to derive the better understanding of the spray formation process but also for successful modeling of the sprays from various bio-derived fuels. Second, we have little knowledge on the biodiesel spray characteristics issued from the practical multi-hole diesel injectors for modern engines. The current understandings have been built mostly using the axisymmetric single-hole injectors that generate far less turbulent flow characteristics than practical multi-hole injectors. The practical multi-hole injectors generate highly turbulent and dispersive fuel flow induced by the in-nozzle vortex and turbulence owing to their off-axis hole arrangement [12–16]. Thus, the biodiesel effects could show different aspects for the practical multi-hole injectors that have not been thoroughly investigated so far.

The current study investigates the effects of biodiesel and conventional fuel properties on the internal dynamic structure of fuel sprays injected from single- and multi-hole diesel injectors. The velocity and turbulent intensity distributions of fuel sprays from nozzle exit to 25 mm downstream were analyzed using a synchrotron X-ray velocimetry technique which derives the local flow velocity from the autocorrelation analysis of the triple-exposed X-ray phase-contrast images. The fuel property effects on the spray dynamic structure were investigated in different injection pressure and ambient density conditions with the corresponding Reynolds numbers from 9543 to 64986, in the normal operation regime of high-pressure diesel injection.

2. Method and experiment

2.1. X-ray phase-contrast imaging

The current study uses an X-ray phase-contrast imaging technique to analyze the structure and dynamics of the dense liquid sprays in the near-field (from nozzle exit to 25 mm downstream). The potentials of the X-ray phase-contrast imaging for near-field spray analysis originate from the combination of weak interaction between X-rays and liquid fuels and ultra-short X-ray pulses (sub-to a few nanoseconds) available at the third-generation synchrotron light sources. The high transmittance of the X-ray to the liquid fuels enables to image the flow structures inside the dense liquid sprays based on the phase-contrast mechanism. Both absorption and phase-shift occur when an X-ray beam passes through a fuel spray. Regarding the phase-shift, the incident and diffracted X-rays can generate an interference pattern with bright and dark fringes along the liquid/gas interfaces [17,18]. 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. On the other hand, the ultra-short X-ray pulses from the third-generation synchrotron light sources provide a high temporal resolution of X-ray phase-contrast images that enables to freeze the motion of the high-speed liquid fuel sprays in the near-field with a high spatial resolution.

2.2. Experimental setup

The X-ray phase-contrast imaging setup at 7-ID beamline of the Advanced Photon Source (APS) was used in this study (see Fig. 1) [11–13,19,20]. To protect the imaging system from being damaged by the powerful X-ray beam, two mechanical X-ray shutters were used: a slow one operating at 1-Hz frequency with 8-ms opening duration (Shutter 1) and a fast one operating at 1-kHz frequency with 9-μs opening duration (Shutter 2). The synchronized operation of the two shutters cuts off more than 99.9% of the beam heat power. A scintillator crystal (LYSO:Ce) converted the X-ray "shadow" images of the sprays into visible-light images at an emission peak around 420 nm, which were then reflected by a 45° mirror and captured by a charge-coupled device (CCD) camera (Sensicam, 1376 × 1040 pixels, from PCO-Tech Inc.). The temporal resolution of the imaging was determined by the X-ray pulse duration and the camera gating. The effective pixel size of the camera was 0.63 or 1.26 μm when a 10× or 5× objective lens was used with the CCD camera, respectively.

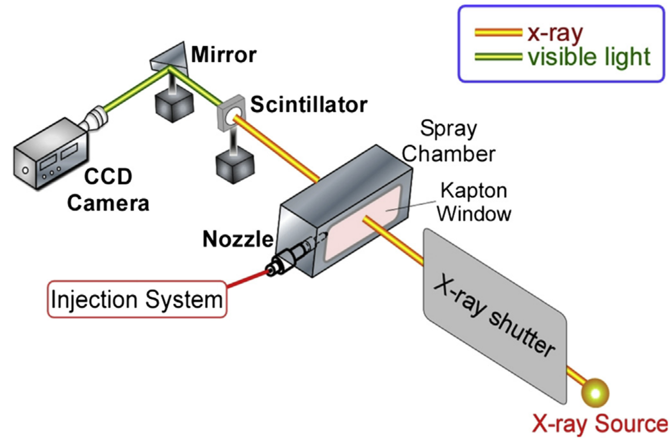

Fig. 1. Experimental setup of X-ray phase-contrast imaging.

2.3. Methodology for spray dynamics analysis

A special beam timing pattern (hybrid-singlet mode) presented in Fig. 2a was used in the experiment. The near-field spray dynamics was analyzed using triple-exposed X-ray phase-contrast images taken using three septets with 11-mA current, 17-ns width, and 68-ns period (see Fig. 2a–b). An autocorrelation analysis was performed in a particular region of interest (ROI) in the triple-exposed images. Then, the velocity of the imaged features was derived by detecting the relative location of the displacement peak against the center self-correlation peak (see Fig. 2c) [11,19]. The turbulence intensity was derived by dividing the shot-to-shot deviation of the 20-shot velocity results by the shot-averaged velocity. The interrogation window sizes of 250 μm for the axial flowing direction and 50 μm for the radial direction were applied for the autocorrelation analysis to have a sufficient number of features to trace for the derivation of reliable velocity results.

The local flow velocity distribution of the spray cross-section perpendicular to the beam path and containing the injector axis was extracted from the line-of-sight X-ray images by introducing two critical assumptions addressed below.

- The liquid sprays have the feature sizes and the velocity distribution of general solid cone sprays in which the feature sizes and the velocity gradually decrease with radial distance from the spray center.
- The autocorrelation analysis detects the velocity of the largest features in the beam path based on the consideration that the larger features usually provide the higher correlation factor.