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Initial dynamic development of fuel spray analyzed by ultra high speed imaging

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HIGHLIGHTS

- Ultra-high speed imaging was used to study near nozzle spray.
- Spray structures using four different fuels were examined.
- The formation and development of mushroom shape were discussed.
- Micro cone angle during the quasi-steady stage was investigated.

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ABSTRACT

Effects of injection pressure and fuel thermodynamic properties on near nozzle spay patterns at the start of the fuel spray were investigated with an ultra-high speed imaging technique. Ethanol (ETH), winter fuel (WIN), diesel (REF), and Rape Methyl Ester (RME) were injected from a single-hole injector at 60 MPa, 90 MPa and 120 MPa. A long distance microscope coupled with an ultra-high speed camera (Shimadzu HPV-2) was also used. The spray structure at the start of the spray included a mushroom and a trail zone. The initial mushroom was generated by the residual fuel in the SAC volume which was responsible for the variation between the different injections. The ultra-high speed imaging revealed that delays from the start of triggering (SOT) to the emergence of liquid from the nozzle were not the same under various injection pressures for different fuels, because of their thermodynamic properties. Mushroom lengths and viscosity were closely related. RME had the longest mushroom zone while ETH had the shortest mushroom zone with no stem. At higher pressures, no ligaments were observed and the leading mushrooms were integrated into the trail zone, which can be referred to as the fully atomized region. At fully atomized regions, the increase of injection pressure did not affect spray patterns. Development of the micro cone angle during this quasi-steady stage experienced a sudden increase followed by a relatively steady stage. Injection pressure and fuel viscosity were shown to have effect on the development of spray cone angle at the opening stage.

1. Introduction

Study of spray break-ups near the nozzle tip is essential for the fundamental understanding of spray formation, since characteristics of this region determine the degree of atomization achieved further downstream. The near nozzle jet atomization region is defined as the place where the coherent liquid core breaks up into droplets and ligaments followed by the secondary break up [1]. Prediction of spray characteristics is difficult because of the complicated processes such as the internal nozzle flow, cavitation, hydrodynamic instabilities, effects of turbulence, initial formation of ligaments and droplets and their secondary breakup, evaporation and the entrainment of air within the spray [2,3].

It is difficult to experimentally characterize near nozzle atomization at engine operating conditions because of its microscopic scale, high liquid to gas volume ratio, high velocities, and high pressure and temperature. However, many studies have visualized sprays injected into atmospheric or to relatively low ambient pressures [4–8]. Microscopic imaging information of diesel spray is non-existent in the literature for conditions relevant to the actual engine operating conditions (gas temperature exceeding 800 K), except for a preliminary attempt for measuring droplet

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sizes at high-pressure (6 MPa) and high-temperature (approx. 850 K) by Crua et al. [9]. Crua et al. [10] also experimentally investigated the near nozzle break-up region of a common rail diesel injector using a long range microscope. They observed an oblate spherical cap leading to the spray formation for a wide range of injection conditions and it was concluded that the cap originated from the residual fuel which remained in the injector from the previous injection. The residual fuel can also result in the formation of deposits inside the injector passage.

A high level of turbulence and the action of aerodynamic forces result in instabilities of the liquid–gas interface at the exit and quickly initiate the breakup process. Thus, fluid properties such as density, viscosity and surface tension play important roles in the spray breakup processes [11,12]. Hattori and Narumiya [13] analyzed the initial breakup mechanism of diesel sprays into high-pressure ambient conditions and they found that the initial liquid jet emerging from the nozzle hole was divided into two zones: the intact liquid pillar zone and the umbrella-like thin liquid protrusion zone at the tip of the jet. They noted that the breakup happened mainly in the periphery of the thin liquid umbrella ahead of the intact liquid pillar tip.

Desantes and Payri et al. [14,15] investigated the cavitation effects on near-nozzle spray characteristics and they found that the jet cone angle increased as the injection pressure conditions for the test made the flow more prone to cavitation. Esmailet [16] used both direct microscopic imaging and Laser Induced Fluorescence (LIF) to investigate the near-nozzle fuel-spray atomization process of a practical Port Fuel Injection (PFI) injector. Comparison between experimental results of direct microscopic images and LIF images demonstrated the accuracy of the direct microscopic imaging technique. Heimgärtner and Leipertz [17] investigated the spray cone angle close to the nozzle and showed by comparison that the near-nozzle microscopic angle was always larger than the measured spray angle of the macroscopic spray. Yi [18] used a long distance microscope to take images at different near nozzle zones and they found that in the near nozzle area, the fuel structure contains a lot of ligaments.

Shoba et al. [19] used the microscopic imaging of diesel, RME and kerosene sprays to identify the effects of viscosity and surface tension on the spray by observing the morphology of the initial jet emerging from the injector. RME due to its high viscosity and surface tension was more resistant to the formation of surface waves, ligaments and droplets.

Due to the limitations of the diagnostic equipment, very few of the previous research studies provided a complete near nozzle spray morphology while tracking the spray development at the same time. This paper provided the near nozzle spray morphology for the start of the fuel spray at different injection pressures for different fuels. The objectives were to gain more fundamental understanding of initial stage of diesel spray formation. The information deduced from the visualized images was supposed to be used to improve and validate CFD models of fuel spray.

2. Experimental setup

Fig. 1 showed the layout of the test rig. The test rig consisted of three major subsystems: the fuel injection system, optical system, and the injector control system. The technical specifications of each subsystem were briefly described in the following sections.

2.1. Injection system and fuels

A commercial high pressure diesel fuel pump driven by a 5.5 kW three phase AC motor provided a controllable fuel pressure of up to 150 MPa to the common rail. There was a long tube connected to the injector, which provided a sufficient reservoir to stabilize the injection pressure during the opening stage.

Four different fuels were used in experiments: normal diesel (referred to as REF), winter diesel (WIN), ethanol (ETH), and RME. The fuel properties were presented in Table 1. The WIN was made by removing part of the high Carbon components of the normal diesel and by replacing them with some fuel additives.

2.2. Optical set up

The optical set up was comprised of a 500 W Xenon lamp as the light source and an 80 mm diameter lens to converge the light into a small area near the injector tip, as shown in Fig. 1. This backlighting technique provides sufficient illumination for the spray to achieve good imaging quality. A long distance microscopic camera lens, QM 100, was used to capture near injector tip images.

The camera used was a Shimadzu HPV-2 with 1,000,000 fps (max), a fixed resolution of 312 × 260 and a fixed number of frames of 102 for all camera speeds. The long distance microscope lens coupled with the ultra-high speed camera was aligned at 180 degree relative to the light source. The working distance of the microscope lens was 17 cm. A Place Macro Calibration Grid was used to calibrate the image dimensions.

2.3. Fuel injector and its control system

The fuel injector used was a solenoid-driven single-hole injector with 0.18 mm diameter. Its L/D ratio was 4.4. A custom made multichannel injector control system was used to synchronize the control of injector and camera with an accuracy of 1 μs, which provided the capability to determine the exact time of fuel emergence out of the nozzle. The injection duration chosen for the tests was 800 μs.

2.4. Test conditions

The test conditions were listed in Table 2. All fuels were tested with 3 different injection pressures, 60 MPa, 90 MPa, and 120 MPa, except for ETH, for which only 60 MPa and 90 MPa were used in order to protect the pump, due to its low viscosity. 1,000,000 fps and a 250 ns exposure time were selected to reduce the motion blur for the start of spray imaging. For the start point of each spray test, 40–50 injections were imaged and time delays were also recorded. Among them 10–12 were used for image processing basing on a selection criteria described in the following section.

3. Results and discussion

The initial liquid emerging from the nozzle hole often had several distinctive zones which are referred to as the mushroom shape zone, the trail zone, and the intact liquid column, as shown in Fig. 2. The mushroom length was the distance between the tip of the mushroom and the trail region. It was commonly accepted that the initial mushroom was generated from the residual fuel in the injector SAC volume prior to the start of injection [10,19,20]. The pressurized fuel acted as a piston, pushing the residual fuel out of the SAC volume, and due to the initial interaction with the ambient air it formed a mushroom structure which propagated and broke up into ligaments and droplets ahead of the trailing zone. The trail zone, however, was the freshly injected fuel corresponding to the present injection. Depending on the injection condition and fuel thermodynamic properties, these two zones were not clearly separated in some test conditions. According to Badock [20], when the injector needle lifted, bubbles in the spray hole will partly be sucked into the SAC zone. When the main injection event