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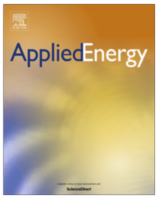

Ultra-high speed imaging study of the diesel spray close to the injector tip at the initial opening stage with single injection

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HIGHLIGHTS

- Ultra-high speed micro imaging and fuel injection mass rating was developed.
- Near field primary breakup characteristics of diesel spray were investigated.
- The formation regime of the mushroom shaped spray tip was examined.
- The quality of the dispersion in the near field was quantified.

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ABSTRACT

This study focused on the primary breakup of spray at the initial injector opening stage at injection to atmospheric conditions. A real-time mass flow rate instrument was first used to study the injection characteristics at the injector opening stage. A long distance microscope together with an ultrahigh speed CCD camera was then employed to study the primary breakup of diesel spray by photography technique with the help of backlighting. The mechanism of the formation of the mushroom shaped spray head was discussed and the laminar flow regime was expected to be the main reason for the resultant shape. During the initial spray stage, the mushroom spray head penetrated almost linearly with respect to time. The quantification of the fuel mass/spray area ratio suggested that the dispersion of the spray is greatly improved within a very short time, which is assumed to be caused by the further opening of injector.

1. Introduction

The initial breakup of the spray jet plays a pivotal role in engine combustion performance (including ignition delay, heat release rate and combustion phase) and emissions [1]. The liquid fuel generally begins its breakup at the outlet of the injector tip and the primary breakup determines the spray initiation and evolution, for instance the spray morphology and macroscopic characteristics [1,2]. The spray morphology dominates momentum transfer between liquid and gas, thus the fuel distribution, mixture preparation and the resultant combustion performance and emissions [1,3]. Better primary breakup is thought to provide better dispersion quality and secondary dispersion, thus smaller droplets [2]. The smaller droplets are expected to evaporate and diffuse more quickly, thus forming combustible air/fuel mixture more quickly. The closely following combustion event tends to be different when the amount of combustible air/fuel mixture varies [1]. Larger cone angle and better radial fuel expansion can also be achieved if spray is well dispersed. The availability of sufficient oxygen because of the good dispersion enables the soot and particles to oxidize more quickly [3]. It is therefore thought to be very helpful to investigate the involved physical regimes and breakup characteristics for primary breakup to get a better understanding of combustion and emissions. The significance of the primary breakup arouses great interests and great efforts have been made to reveal the complex regimes and mechanisms involved.

For primary breakup study, the near field downstream of the injector is generally the interested field. It should be noted that for a whole injection event, at least 3 stages (injector opening stage, steady stage and injector closing stage) exist. For various stages, the characteristics are expected to be quite different due to different flow mechanisms and breakup regimes. The studies of primary breakup mechanism through the observation of the spray morphology in the injector opening stage show that the

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radial expansion of liquid jet and the air drag force are important factors for the mushroom-shaped jet formation [4,5]. Some fuel of the previous injection is left in the sac and this residue fuel is reported to influence the mushroom shaped head for the next injection [5]. For the quasi-stationary phase, the primary breakup highly depends on the flow regimes in the injector, namely, the injection conditions. Akira et al. [6] reported that the strong turbulence and cavitation considerably affect the initial breakup of the spray jet. Desantes [7] investigated the impact of cavitation on the primary breakup by injecting fuel into a liquid of the same type, allowing the visualization of air bubbles induced by cavitation. The results showed that higher pressure drop led to stronger cavitation and more air bubbles, resulting in great increase of the microscopic cone angle.

The initial disintegration of spray is significantly affected by the nozzle geometry [8–12]. Schugger [3] studied the effects of injector geometry by employing PIV and High-Speed Cinematography. It was reported that for nozzles with sharp inlet edge, stronger turbulence and cavitation significantly boost the primary breakup. This is because the redirection of fuel at the hole inlet is more obvious for sharp inlet edge injector than for that with round edge. Heimgartner et al. [13] also investigated the impact of nozzle geometry by employing the Mie scattering technique and long distance microscope. It was shown that the rise of injection pressure caused an increased microscopic spray cone angle for valve covered orifice (VCO) nozzles but the reduced cone angle for mini sac nozzles.

The aforementioned studies revealed some important mechanisms for initial breakup. However, the relationship between the flow regime in the injector hole and the mushroom-shaped spray jet has not been deeply studied although the development of the mushroom head has been fully described in [4,5]. The fuel dispersion quality in the near field has not been quantified either. With the aim to address these unknown questions, a long tube real-time mass flow rate measuring instrument was first adopted to calibrate the injection characteristics, allowing the mass flow rate (MFR) measurement at the initial injector opening stage. A long distance microscope together with an ultra-high speed CCD camera was then employed to study the spray primary breakup. One novelty of the present paper is the theoretical and experimental study of the fundamental forming regime of the mushroom head by the combination of photography and mass flow rate measurement. Another novelty is that the flow regimes during the early stage are studied by calculating the boundary thickness in the nozzle to stress the importance of flow regimes for the formation of 'mushroom'. In addition, the quantification of dispersion quality in the near field by the application of imaging and fuel flow rate measurement is quite original.

2. Experimental setup and test conditions

A single in-axis hole solenoid injector with the hole diameter of 0.18 mm was used for the study. The hole of the injector is cylindrical with sharp edged inlet. The length/diameter of the nozzle is 4. The setup of the backlighting photography is shown in Fig. 1. A highly resolved long distance microscope which enables the CCD camera to focus on the view field of 2.3 mm downstream of injector was employed to visualize the spray morphology development. The ultrahigh speed camera involved is a Shimadzu HPV2 CCD digital camera with maximum frame speed of 1,000,000 fps, meaning that the time interval between two consecutive images is 1 μs. This maximum frame speed was employed in the present study and the constant resolution is 312×260 pixel^2. Due to the employed ultrahigh frame speed, a xenon lamp with power rate of 500 W was used as light source and a convex lens was employed to focus the light to sufficiently illuminate the spray. It should be noted that the employment of the convex lens leads to uneven illumination at the tip of the injector which can be observed in the images. However, this study was focused on the breakup within a very small area (2–3 mm) and the illumination within this small area is thought to be evenly distributed after careful focusing. The 250 ns exposure time was employed. For each testing case, 15 sets of images were taken and processed with Matlab code. The variation of results from shot to shot of the images is approximately 10% ((the lowest or highest value of penetration or spray area)/average value < 10%) due to the occasional existence of the mushroom-shaped spray head (shown in result section). The averaged results are employed to represent the characteristics of the spray in this study.

The tests were carried out under room temperature (25 °C) with atmospheric back pressure. The injection pressure varied from 45 to 120 MPa and the injection duration was 0.8 ms. The investigated area is 2.3 mm long downstream of the injector tip. The fuel used is winter grade pump-grade diesel with density of 806 kg/m^3, viscosity of 2.23 cSt and surface tension of 24.56 mN/m @ 40 °C.

An in-house built long tube real-time mass flow rate measuring instrument based on Bosch method was used to measure the MFR. The structure of the instrument is presented in Fig. 2. The injector holder (3) is used to fix injector (2) and connect the long tube (5). The pressure signals can be detected by the two strain-gauges (4) located at the tip of injector. The instrument can be protected from being over pressurized by the relief valve (7). The discharging pressure in the tube (5) can be regulated through the needle valve (9). The pressure gauge (8) is employed to monitor the discharging pressure. The volume and weight of the injected fuel can be measured through the cylinder (10) and scale (11) respectively. The inaccuracy (less than 6% for this instrument) can be minimized with careful calibration. More details can be found in [14,15].

3. Results and discussion

3.1. Mass flow rate

The initial injector opening stage is very important for the spray characteristics. As shown in Fig. 3, the varying trends of MFR under various injection pressures are quite different. To provide consistent information for imaging tests presented below, the back pressure for MFR test was set to atmospheric although it can be easily regulated. Higher injection pressure apparently results in higher fuel mass flow rate. The MFR is believed to determine the heat release rate, pressure rise rate, temperature and the emissions [14]. The delivered fuel MFR at different injection stages varies the combustion characteristics in different ways. High MFR under high injection pressure for pilot injection leads to short ignition delay, while lower MFR with increased number of injections near TDC may be favorable for emissions [14]. It also can been seen that higher injection pressure causes earlier start of injection. The different start of injections suggest obvious different spray characteristics at the early injection stage. This study therefore mainly focused on the initial injector opening stage, as marked in Fig. 3.

3.2. Morphology development under various injection pressures

One example of the morphology of spray (under 60 MPa) is shown in Fig. 4. The spray generally can be divided into three parts, namely, main spray, "neck" and mushroom shaped head. These parts present various characteristics under different conditions, as shown in the following section.

As presented in Fig. 5, with 45 MPa injection pressure, the mushroom-shaped tip appears and shows little sign of breakup