Fuel 235 (2019) 715–722

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Microscopic study on the mechanisms for formation of the initial spray morphology

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ARTICLE INFO

Keywords:
Spray morphology
Air bubble
Pressure shock wave
Primary breakup
Spray

ABSTRACT

The initial spray morphology reflects the initial nozzle condition (quantity and distribution of residual fuel) derived from the previous injection, which will considerably affect the spray primary breakup. High-speed microscopic imaging technique and a single-hole diesel injector with a transparent Plexiglas nozzle were employed to investigate the mechanisms for the formation of initial spray tip morphologies and the corresponding breakup characteristics under various conditions. It was found that the interaction between liquid fuel and air bubbles, fuel properties and pressure shock-wave strength determined the spray tip morphology. Depending on the initial conditions, several types of morphologies were observed, namely, compact mushroom spray induced by surface tension under initial air-free condition, thin mushroom spray due to the acceleration effect of compressed air under low common rail pressure, drum spray tip (single or double drums) caused by the catastrophic breakup of air bubbles under common rail pressure, and mushroom-drum and central jet under fuel-free condition. Low common rail pressure allowed more time for the air bubbles to be compressed and more energy reserved in the compressed air, resulting in a higher possibility of mushroom spray formation through the accelerating effect. However, strong shock-wave under high pressure caused a high tendency for the catastrophic breakup of the air bubble and thereby production of the dispersed drum. In addition, less residual fuel left by the previous injection under high common rail pressure significantly suppressed the formation of mushroom tip.

1. Introduction

Injection and fuels exert a profound influence on the combustible mixture formation, combustion and emissions of internal combustion engines [1,2]. The internal flow of an injector nozzle significantly affects the spray morphology, primary breakup and secondary breakup. The plume morphology determines spatial fuel distribution, fuel mixing and the overall mixture preparation. The study on the internal nozzle flow and the plume morphology, therefore, becomes a key for further study on spray characteristics and modelling. Plume morphology depends not only on the injection conditions and ambient conditions, also the initial conditions formed by the previous injection [3,4]. Therefore, the plume morphology during the initial stage reflects the initial nozzle condition left by the previous injection. The quantity and distribution of the residual fuel can be estimated, and the contribution of residual fuel on emissions also can be quantified.

In [5,6], the ellipse-shaped spray was observed during the very early stage of diesel spray. The radial fuel expansion due to surface tension is the root reason for the ellipse. It was also pointed out that the residual fuel of the previous injection was responsible for its formation [6]. Wang et al. [7,8] employed a long-distance microscope and an ultra-high-speed camera to investigate the spray primary breakup and reported the existence of mushroom spray during the initial stage of spray development. This special shape was frequently observed under a low common rail pressure, and the formation mechanism was explained. The existence of air bubbles and laminar flow in the nozzle were believed to be the root reasons. By using a transparent nozzle, He et al. [9] studied the internal nozzle flow and found that some air bubbles were sucked back into the nozzle during the end stage of injection. Liquid fuel moved out of the nozzle with a high velocity, and a vacuum condition was generated. Air was consequently sucked into the nozzle, and a mushroom-shaped spray head can be observed. By employing a similar technique, Wei et al. and Gao et al. [10,11] also observed the mushroom-shaped spray under low common rail pressure. The effect of the nozzle geometry on spray morphology was also obvious because cavitation appeared quickly during the initial stage of injection [12,13].

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https://doi.org/10.1016/j.fuel.2018.08.069
Received 26 February 2018; Received in revised form 9 July 2018; Accepted 14 August 2018
0016-2361/

Generally, a sharp nozzle inlet caused strong cavitation, and the spray morphology can be significantly changed, especially under high-injection pressures [14].

Guo et al. [15] employed the large eddy simulation (LES) and volume of fluid (VOF) to investigate the effects of air bubbles in the nozzle on the spray primary breakup. It was found that air bubble causes the formation of two mushroom-shaped sprays and that cavitation considerably boosts the spray instability. Yu et al. [16] also used LES and VOF to study the effect of nozzle internal flow on spray fragmentation in OpenFOAM. The results showed that wall shear and flow detachment are main reasons for the introduction of instability. Shinjo [17] used direct numerical simulation (DNS) to probe the main factors for producing large ligaments. It was reported that the vortexes for the spray tip and periphery surface lead to the formation of large ligaments.

Although many studies on the formation of mushroom spray head were available, many questions remain unanswered. A few of those questions are: (1) why the mushroom spray head is rarely observed under high common rail pressure and what is the corresponding initial in-nozzle condition; (2) the reasons and mechanisms for the formation of several types of spray morphologies; (3) how is the interaction between liquid phase and gas phase with the presence of pressure shock wave when injector needle opens and how this interaction affects the spray morphology; (4) more importantly, how the mechanisms for the formation of plume morphologies affect the primary breakup. To answer these questions, the high-speed microscopic imaging technique was used in the present study to investigate the mechanisms of spray tip formation in a transparent nozzle. This study is believed to be useful for the understanding of internal nozzle flow, primary breakup study and related modelling. In the rest of this paper, the experimental setup, fuel property and test conditions will be introduced in Section 2 and 3. In Section 4, results and discussions from this study will be provided. In the end, main conclusions from this study will be presented.

2. Experimental setup

Fig. 1 shows the experimental setup, including the microscopic imaging system and the high-pressure injection system. The imaging system is equipped with a 500 Watt LED light source, a long distance microscope (QM100) and a high-speed camera (PHANTOM V7.3). The frame rate and exposure time of the camera are set to 30,075 fps and 1 µs. The employment of high-resolution microscopy gives a spatial resolution of 9 µm/pixel. The view-depth and working distance of the microscope are 32 µm and 800 mm, respectively. Backlighting is adopted for the direct microscopic imaging system. The camera is focused at the very tip of the injector to capture the development of nozzle internal flow and plume development. All parts are set inline so that the nozzle can be sufficiently illuminated due to the employment of short exposure time. The injector and the camera are synchronized through a controller. The triggering signal from the controller is sent to the camera when the injector is energized. The testing rate is set to less than 0.1 Hz so that the common rail pressure is stable. The high speed camera subsequently records the spray morphology and nozzle internal flow according to focusing area. The recorded videos which can be transferred into images are then saved in a Computer.

A modern common rail diesel injection system is used to provide pressurised fuel to a Bosch diesel injector. The original nozzle is modified and replaced with a transparent single-hole nozzle. The metal tip (the metal part below the valve seat) is cut, and the metal needle is exposed. Then a transparent Plexiglas nozzle is fixed on the tip of the injector by an external force, providing a good sealing. The diameter and length of the cylindrical nozzle are 0.4 mm and 4 mm, respectively. The good transparency of the Plexiglas nozzle enables the evolution of nozzle internal flow to be clearly visualized. The transparent Plexiglas nozzle is in-house made through a conventional driller. The high strength of the Plexiglas material enables the high injection pressure of 100 MPa to be used in the present study.

3. Test fuel and conditions

The 0# diesel was used in the present study. Fuel density, viscosity and surface tension @ 20 °C are 840 kg/m^3, 3.6 mm^2/s and 25.6 kg/s^2, respectively. Both fuel temperature and ambient temperature were set to 20 °C for all tests. The common rail pressure varied from 30 MPa to 100 MPa while the ambient pressure was set to atmospheric. Single injection strategy with a duration of 2 ms was employed for all tests. 20 repetitions were carried out for each test.

4. Results and discussions

Under real injection conditions, the spray injection is dynamic and random. The internal nozzle conditions left by the previous injection are therefore quite different from injection-to-injection. The number and quantity of air bubbles vary significantly, and the interaction between the two phases considerably varies. A large number of tests under various common rail pressures were carried out in the present study. According to the results, the in-nozzle conditions generally can be

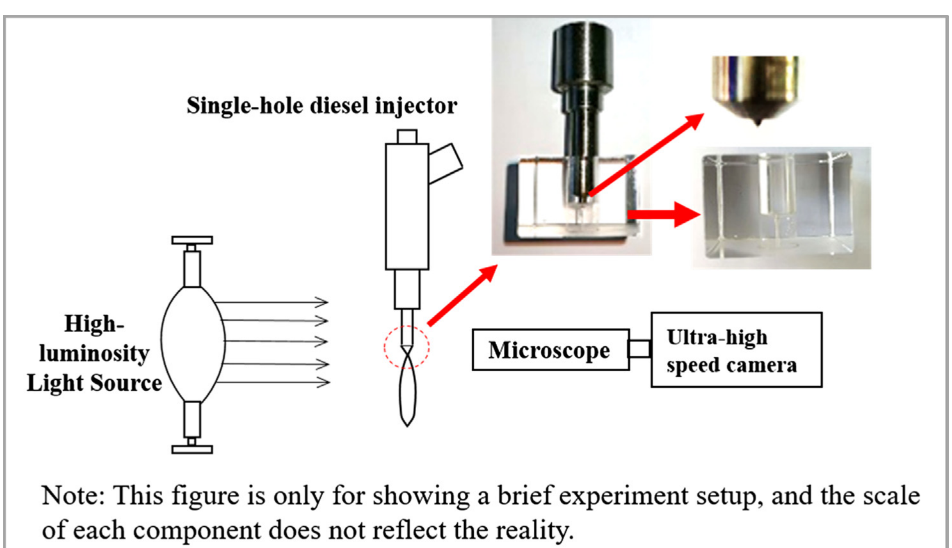

Fig. 1. Schematic of experimental setup.