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Near-nozzle microscopic characterization of diesel spray under cold start conditions with split injection strategy

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HIGHLIGHTS

- Ultra-high speed imaging and cooling system were developed.
- Effects of low fuel temperature on spray were studied.
- Impact of split-injection strategy on spray behavior was studied.
- Effects of fuel properties on spray characteristics were studied.

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ABSTRACT

Near-nozzle microscopic characteristics of diesel spray under room temperature (25 °C) and low temperature (−2 °C) were investigated by microscopic imaging technique. The primary breakup of winter diesel (WD) and rapeseed methyl ester (RME) sprays were investigated with single and split injection strategies. It was shown that increased viscosity and surface tension under low temperature lead to much poorer dispersion. Under low injection pressure with split injection strategy, the first split injection was unexpectedly severely affected by both temperature and dwell, with significant breakup characteristic differences when dwell varied. By contrast, the second split under low injection pressure tended to be affected only by temperature rather by dwell. High injection pressure considerably alleviated the breakup characteristic difference of the first split injection caused by temperature and dwell although the effects of fuel properties were still seen, leading to better fuel dispersion and more predictable spray characteristics. In addition, RME with higher viscosity and surface tension consistently presented much poorer dispersion quality compared with WD even under high injection pressure where the influence of fuel properties may be insignificant.

1. Introduction

Fuel temperature is believed to considerably influence the spray behavior because of the varied fuel properties [1]. The processes of injection and spray, for instance, primary breakup and secondary breakup correspondingly change significantly with the variation of fuel temperature, thus the resultant combustion performance. The primary breakup in the near field tends to present great useful information for the study of spray and combustion. More viscous fuels generally lead to smaller effective flow area in the nozzle, higher boundary laminar layer and larger droplets due to the stabilizing effect of the fuel properties [2,3]. It can be expected that lower temperature makes fuels more viscous and causes larger fuel droplets. More viscous fuels tend to present particles which are more spherical than those with low viscosity because high surface tension enhances the retention of the spherical shape [2]. In [4], however, it was shown that high injection pressure and temperature (1200 K) make the effects of fuel surface tension negligible.

Compared with single injections, multiple injections cause higher IMEP and lower emissions [5,6]. Dwell interval is an important parameter that governs spray behavior and combustion performance. Shorter dwell leads to stronger spray-combustion interaction [7]. The flame interacting surface between the first split injection and the second split injection increases with shortened dwell. The combustion of the first injection influences that of the second one by changing the temperature and gas compositions [7]. Therefore, shorter dwell results in higher temperature in the middle of the second spray due to raised temperature by the closely coupled first injection. On the other hand, short dwell leads

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to insufficient oxygen, contributing to insufficient combustion for the second injection. With overlong dwell, the hot gas produced by the combustion of the first split injection cools down, showing little combustion interaction [7].

Engine cold start requires the studies on the unknown primary breakup characteristics under low temperature which are expected to be significantly affected by the variation of fuel properties [8]. Split injection strategy is assumed to significantly impact the spray primary breakup characteristics due to strong interaction between splits. In addition, how the variation of temperature changes the primary breakup features when split injection strategy is employed still requires deep study. To bring more insights on these unknowns, a highly resolved long distance microscope together and an ultrahigh speed CCD camera were used to study the primary breakup of spray during the initial injector opening stage by using both single and split injection strategies.

2. Test condition and experimental setup

For single injection, low injection pressure (60 MPa) and high injection pressure (120 MPa) were used and injection duration was set to 1 ms. When split injection strategy was employed, 60 and 90 MPa injection pressures were used.

Tests were performed under both room temperature (RT, 25 °C) and low temperature (LT, −2 °C) for fuel temperature with ambient temperature kept at RT. Ambient pressure was set to atmospheric condition for all tests. The stability of fuel temperature is of great importance for the success of the tests. An in-house built cooling system (the blue[1] part shown in Fig. 1) which kept fuel temperature constant was employed. The mixture of ice and water filled in the pre-cooling barrel was employed to precool the warm pressurized fuel from the common rail. The temperature of ice–water mixture was monitored by a thermocouple installed in the pre-cooling barrel. The temperature of the ice–water mixture ranged from 0 to 1 °C during the tests, keeping nearly constant for up to 5 h because of the high heat capacity of water and ice.

To further cool the precooled fuel, another recycle cooling system consisting of an injector cooling barrel, a freezer and a low pressure pump was employed to cool the injector. The injector was installed into the cooling barrel, only leaving injector tip exposed in the air, maximizing the cooling effect for the injector. The lowest stable temperature in the freezer can be as low as −18 °C. The low pressure pump completed with a control module was employed to control the flow rate of the coolant to achieve stable fuel temperature. The temperature of the coolant in the injector cooling barrel is monitored by another thermocouple. Because of the heat transfer between the ambient environment and the recycling coolant, −2 °C is the lowest stable temperature that could be achieved for the coolant in the injector barrel. The temperature of the coolant in the injector cooling barrel generally ranged from −3 to −1 °C. To keep the temperature stable by minimizing heat transfer between the ambient environment and the cooling system, all components (pipes, barrels and low pressure pump) were wrapped with adiabatic material. During the test, if the temperature for the pre-cooling or the temperature for coolant in the injector cooling barrel varied beyond their corresponding values, the test was stopped to allow the coolant to be sufficiently refrigerated. Generally, the superb cooling effect of the cooling system enabled the tests to be carried out for up to 1 h continuously, achieving high testing condition consistency.

The key components of the imaging setup are the long distance microscope, ultrahigh speed CCD camera, xenon lamp (500 Watts) and convex lens. The frame speed of 1 million fps with corresponding constant resolution of 312×260 pixel^2 for the camera was employed in this study. The imaging field in this study is from the injector tip to 2.3 mm downstream. A solenoid driven injector with sharp inlet was used. The diameter of the cylindrical hole of the employed injector is 0.18 mm with length–diameter ratio L/D of 4.4.

3. Test fuel

The employed fuels are rapeseed methyl ester (RME) and winter grade pump-grade diesel (WD). It is expected that the spray characteristics considerably depend on two fuel properties, namely viscosity and surface tension which are obtained from experimental measurement, as shown in Fig. 2. The varying trends have been published in [10,11]. It can be seen that viscosity varies exponentially while the surface tension varies linearly. RME tends to be more viscous than WD and the difference is enlarged under low temperature. Considerably higher surface tension for RME than for WD is also observed. The variation of fuel density (806 kg/m^3 for WD and 892 kg/m^3 for RME @ 15 °C) is not quantified due to its relatively small variation with temperature [9].

4. Results

This study mainly focused on the initial injector opening stage when the development of the spray can be captured within the limited view field. The penetration and spray dispersion area were quantified by processing the images with an in-house built Matlab code. The penetration is defined as the farthest point the plume tip reaches (Fig. 3(a)), while the spray area is obtained by summing the area of the pixels the plume occupies in the view field (the area of each pixel is gained by calibration and scaling). Each test was repeated for 15 times to obtain sufficient accuracy. The spray characteristics, namely penetration and area, show quite small variation under RT. By contrast, under LT, larger variation for penetration and spray area, up to 11%, is observed. Generally, the overall accuracy and repeatability are satisfying.

4.1. Single injection

Spray at the initial stage showed a special mushroom shaped head which is widely reported in the literature [2], as the one presented for WD with 60 MPa injection pressure in Fig. 3(a) where the penetration is defined. The mushroom and neck which is followed by the main spray are typical components for spray during the initial stage. These special shaped parts are generally generated by the residual fuel in the injector and laminar flow regime in the nozzle hole due to the low effective injection pressure when the injector begins to open [2]. The air resistant force is thought to boost the enlargement of the mushroom. By contrast, as presented in Fig. 3(b) the compact liquid pre-jet column was only observed for RME under LT and low injection pressure in present study. The pre-jet is also believed to be related to the residual fuel left by the former injection [2,12,13].

The much lower viscosity and surface tension of WD enable the spray to disperse much better than RME spray. RME spray initially shows smooth intact liquid main spray as shown in Fig. 4. Even 70 μs after start of injection (ASOI), the compact liquid column was still observable at the very outlet of the nozzle. However, 30 μs ASOI, the intact liquid main spray for WD disappeared (Fig. 5), meaning almost full atomization. The much better dispersion of WD can be further verified by the dispersed spray area, as presented in Fig. 6(a). WD consistently shows higher area under both low and high injection pressures. The area difference between

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.