Fuel 183 (2016) 617–626

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Experimental study on primary breakup of diesel spray under cold start conditions

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ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form 13 June 2016
Accepted 14 June 2016
Available online 4 July 2016

Keywords:
Primary breakup
Low temperature
Breakup regime

ABSTRACT

Studies on primary breakup of diesel spray under room temperature (25 °C) and low temperature (−2 °C), were carried out by mass flow rate measurement and microscopic imaging. It was shown that under low injection pressure and low temperature, raised viscosity and surface tension caused slower penetration and poorer breakup. Under high injection pressure, higher chances of mushroom formation under low temperature due to higher viscosity surprisingly leaded to quicker penetration but still poorer dispersion during the initial spray stage. Low temperature retarded the start of atomization as the needle rose. The end of injection showed a large amount of compact liquid fuel with little dispersion, which was deteriorated by low temperature. In addition, a new equation including the influences of ambient gas on breakup, was proposed to quantify the spray stability, allowing quantitative analysis of the effects of temperature and ambient gas.

1. Introduction

Diesel spray theoretically involves a wide range of factors and mechanisms, for instance, nozzle structure, flow regimes (laminar, turbulent and cavitating flow), primary and secondary breakup and gas-liquid interaction [1,2]. Understanding of spray primary breakup can significantly enhance the understanding of spray atomization and mixture formation as spray characteristics of the initial stage are to be passed to later breakup stages [3–5]. Due to high spray density, high velocity and high sensitivity of the measurement for primary breakup study, special measures should be taken during the study [6]. However, some important studies on primary breakup have been carried out although difficulties faced. Many studies [5,7–9] reported that some residual fuel of the previous injection causes the formation of mushroom and stem, and the residual penetrates obviously faster than the fresh fuel initially. This phenomenon was observed during the transient injector opening stage when larger cone angle caused by throttling effect than that of quasi-steady stage can be seen [10]. During the other transient stage, namely the end of injection, lower effective injection pressure leads to lower initial penetrating velocity than that of quasi-steady state [5,10,11]. Lower injection pressure slows down the breakup of the droplets, leading to much larger ligaments.

Primary breakup shows high sensitivity to fuel properties (viscosity and surface tension) [12]. Generally, reduced surface tension enhances the breakup of the ligaments. For fuels with high viscosity and surface tension, the compact core may transit to sheet first rather than to ligaments or large droplets directly [5]. During the initial injection stage, smaller effective flow area for more viscous fuel results in higher boundary laminar layer and larger ligaments because of the stabilizing effect of the fuel properties [13]. Particles of more viscous fuel present more spherical shape than the same sized drops of its counterparts with low viscosity as high surface tension enhances the retention of the spherical shape [5]. In [4], the spray primary breakup was investigated with temperature varying from 440 to 1200 K, while back pressure ranging between 5 and 79 bar. The results show that high injection pressure and temperature diminish the influences fuel surface tension. A critical point for fuel properties exists, where the effect of fuel surface tension greatly weakens when the ambient condition changes.

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 [10]. The transition of breakup regimes during the transient spray stages

Abbreviations: ASOI, after start of injection; BEOI, before end of injection; LT, low temperature; MFR, mass flow rate; *Oh*, Ohsornge number; *Re*, Reynolds number; RT, room temperature; *We*, Weber number.

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http://dx.doi.org/10.1016/j.fuel.2016.06.067
0016-2361/

(injector opening and closing stages) is still unknown. In addition, the influence of fuel temperature on the primary breakup regimes has not been studied. Aim to study these unknowns, a long tube mass flow rate (MFR) measuring instrument was first used to study the influences of temperature on MFR. A highly resolved long distance microscope together with an ultrahigh speed CCD camera was then employed to investigate the primary breakup of spray.

2. Test condition and experimental setup

For all tests, the injection pressure was set to 60 MPa (low injection pressure) and 90 MPa (high injection pressure). MFR under various temperatures (−18 to 48 °C) was first measured with a long tube measuring instrument based on Bosch method. Pressurized fuel is delivered into a long tube through the injector and the pressure signal travels along with tube. Two strain gauges located at the outlet of injector are employed to detect the pressure signal. The real time mass flow rate could be calculated through the acquired pressure signal [14]. A freezer which can maintain fuel temperature stable was employed to carry out the tests under cold condition. The injector and its accessories were kept refrigerated during the low temperature tests and more details about this setup can be found in [14]. To carry out the tests under higher temperature, a container filled with warm water was employed and the injector parts were immersed in the warm water. The injection rate of one injection per second was used to allow the temperature of fuel to be kept at the desired ones.

Primary breakup tests were carried out under room temperature (RT, 25 °C) and low temperature (LT, −2 °C) for fuel temperature. However, ambient temperature was kept at RT and ambient pressure was atmospheric for both test conditions. The success of the tests is to keep the fuel temperature stable. A special cooling system, the blue part shown in Fig. 1, was employed to stabilize the fuel temperature. A pre-cooling barrel which was filled with ice and water was used to precool the pressurized fuel from the common rail. The high heat capacity of water and ice enables the system to precool the warm pressurized fuel effectively up to 5 h. A thermocouple was installed in the pre-cooling barrel to monitor the temperature of ice-water mixture. The temperature of the mixture varied between 0 and 1 °C during the tests.

To further effectively cool the pressurized fuel, the injector was cooled through a recycle cooling system. The recycle cooling system consists of an injector cooling barrel, a freezer and a low pressure pump. The injector was plugged into the cooling barrel and only the tip of injector was exposed in the air, cooling the injector and fuel sufficiently. The freezer can keep the temperature stable as low as −18 °C. The flow rate of the coolant was regulated by the low pressure pump controlled by a control module. Another thermocouple was employed to monitor the temperature of the coolant in the injector cooling barrel. The lowest stable temperature of the coolant in the injector barrel was −2 °C due to heat transfer between the coolant and the ambient environment. The temperature of the coolant in the injector cooling barrel generally varied between −3 and −1 °C. All the parts (pipes, barrels and low pressure pump) were wrapped with adiabatic material to minimize the heat transfer between the cooling system and the ambient environment. During the test, if any of the temperatures for the ice-water mixture in the pre-cooling barrel and the coolant in the injector cooling barrel varied beyond their corresponding ranges, the test was stopped to allow the coolant to be refrigerated. Generally, due to the superb cooling effect of the cooling system, the tests could be being carried out for up to 1 h continuously and high testing condition consistency was successfully achieved.

The imaging system consists of a xenon lamp (500 W), a convex lens, a long distance microscope and an ultrahigh speed CCD camera. The tests were carried out with frame speed of 1 million fps and constant resolution of 312 × 260 pixel^2. The view field was set to 2.3 mm downstream of the injector tip. More details about the imaging system can be found in [8,9]. The injector employed is a solenoid driven injector with sharp inlet. The diameter of the cylindrical hole is 0.18 mm and length-diameter ratio L/D is 4.4.

3. Test fuel

The employed fuel is winter grade pump-grade diesel which shows good flowing ability at low temperature. The significant variation of fuel properties with temperature is of great importance for spray characteristics. Two important properties, namely viscosity and surface tension, were quantified under various temperatures, as shown in Fig. 2. According to the measured values of the two properties, it can be seen that viscosity varies exponentially while the surface tension varies linearly. An exponential function and a linear function are proposed to fit the measured values respectively, shown in Eqs. (1) and (2).

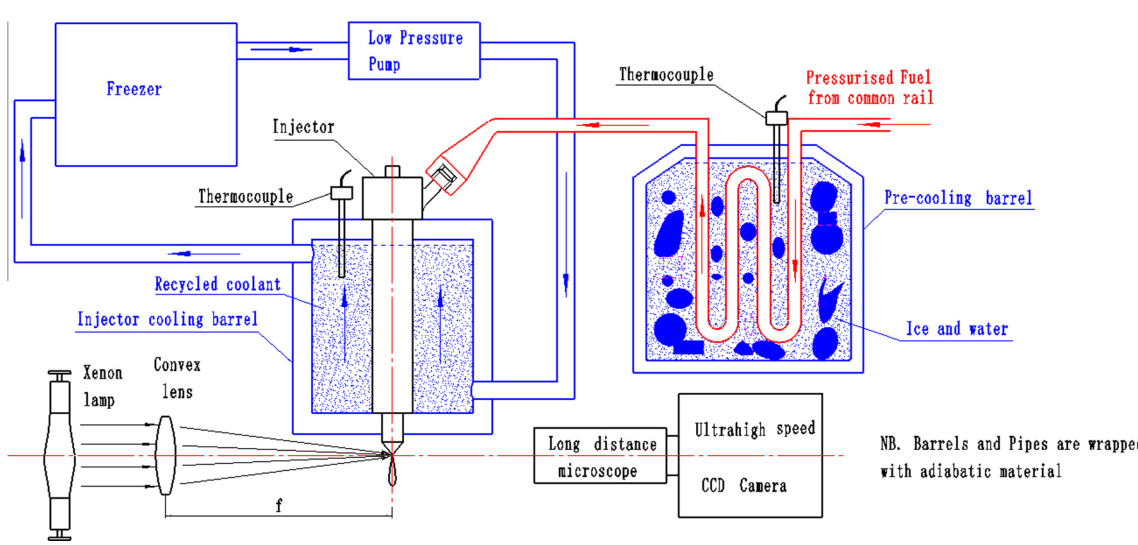

Fig. 1. Layout of the experimental setup.