Applied Energy 163 (2016) 105–117

Contents lists available at ScienceDirect

Applied Energy

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

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

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HIGHLIGHTS

- Ultra-high speed micro imaging was used to study diesel spray.
- Primary breakup of diesel spray from split injections were investigated.
- Factors affecting the primary breakup characteristics were studied.
- Combined effects of the factors on primary breakup were analyzed.

ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 22 September 2015
Accepted 24 October 2015

Keywords:
Primary breakup
Spray characteristics
Split injection strategy

ABSTRACT

This study focused on the primary breakup of diesel spray at the initial injector opening stage with split injection strategy at injection to atmospheric conditions. An ultrahigh speed CCD camera was employed to investigate the primary breakup of spray by photography technique with the help of backlighting. The injection pressure, dwell duration, distribution of injection duration between split injections and the number of the splits significantly affected the strength of primary collision and thus the primary breakup characteristics. Besides, the spray characteristics of the split injections except those of the first split injection were simultaneously affected by three main factors, namely, induced air driving force, lower mass flow rate and primary collision. The combined influence of the injection pressure, injection duration distribution and dwell duration determined the main effect on the affected split injections.

1. Introduction

The primary breakup of the spray is of great importance for combustion performance [1]. This is because the primary breakup dominates the spray characteristics, for instance the fuel mass distribution, spray penetration and size of droplets, thus the quality of the mixture when the combustion initiates [1–3].

So far, the characteristics of primary breakup with single injection strategy have been extensively studied. Cyril et al. [4] reported that at the initial injection stage the appearance of mushroom is closely related to the residue fuel of the former injection. The residue can be identified by its slower penetration rate compared with the fresh fuel. The air drag force and the resultant radial expansion of liquid jet are pivotal for the morphology of the mushroom head [4,5]. For the quasi-stationary phase, the characteristics of the primary breakup dominated by injection conditions tend to be different from those during the initial stage. Desantes et al. [6] and Akira et al. [7] reported that the strength of turbulence and cavitation strongly affect the initial breakup. Stronger turbulence and cavitation caused by higher pressure drop contribute to larger better dispersion thus larger microscopic cone angle. By employing microsecond quantitative X-ray tomography, Jin et al. visualized the four dimensional transient characteristics of fuel spray [8]. This special technique gave some unique and realistic information and it was reported that fuel dispersed completely just after the nozzle outlet.

The fuel properties and nozzle geometry are well known important factors for primary breakup. The fuel properties affect the spray behavior generally through the intensity of turbulence and stabilizing effect for the droplets. More viscous fuels tend to reduce the turbulence and initial velocity of the spray, thus lower air drag force and poorer dispersion are expected [9]. The stabilizing effect of high surface tension results in more stable droplets during the process of breakup, and larger droplets tend to exist [10,11]. By

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http://dx.doi.org/10.1016/j.apenergy.2015.10.155
0306-2619/© 2015 Published by Elsevier Ltd.

contrast, nozzle geometry influences the spray behavior mainly through the intensity of turbulence and cavitation. The redirection of fuel flow in the valve covered orifice (VCO) nozzles and nozzles with sharp inlet tends to induce the cavitation, augmenting the breakup [12–17].

The aforementioned studies mainly focused on the initial breakup with single injection strategy. However, the primary breakup characteristics when using split injection strategy are still unknown. The impact of the interaction between split injection events on the primary breakup also requires deep study. It is believed that the study on primary breakup with multiple-injection is of great importance for better understanding of combustion and spray for modern diesel engines because the primary breakup dominates the secondary breakup and air/fuel mixture preparation. Multiple injection strategy can also considerably stabilize the engine performances and reduce misfire [18–20]. Better fuel mass distribution and fuel mixture when split injection strategy is employed shorten the ignition delay. Higher flexibility of the innovative injection strategy can therefore control the combustion characteristics effectively. The emissions can also be considerably improved as a result of the better combustion [18]. The influence of dwell interval on spray/combustion interaction is thought to be profound because the interacting area (for the first spray/ the second spray interaction and spray/combustion interaction) between two split injections is dominated by the dwell and the injection pressure. With the aim to address these unknown questions, a long distance microscope together with an ultra-high speed CCD camera was employed to study the spray primary breakup by using split injection strategy.

2. Experimental setup

A single hole solenoid injector with the hole diameter of 0.18 mm was employed. It is a cylindrical injector with sharp edged inlet. The setup of the backlighting photography is shown in Fig. 1. A highly resolved long distance microscope with working distance varying from 15 to 35 cm was employed to visualize the spray morphology development. The maximum frame speed of the ultrahigh speed camera involved (Shimadzu HPV2 CCD digital camera) is 1,000,000 fps. This ultrahigh frame speed was employed in the present study, and the resultant time interval between two images is 1 microsecond. The constant resolution of the camera is 312×260 pixel^2. A 500 Watt xenon lamp was used as light source and a convex lens was employed to focus the light to sufficiently illuminate the spray. The application of the convex lens resulted in uneven illumination at the tip of the injector. This is because the uneven illumination makes the identification of the spray boundary inaccurate when the images are processed. Fortunately, this inaccuracy can be ignored due to the fact that the illumination in the small area studied (2–3 mm) is quite even. In addition, this inaccuracy can be further minimized through careful focusing. Due to the quite high variation of the spray characteristics (up to 14%) caused by strong interaction between closely coupled split injections, a large number of images for each test (15 images) were taken to obtain quite accurate averaged results. An in-house written Matlab code was used to process the images and the averaged calculated results are used in this study.

3. Test conditions

The tests were carried out under room temperature (25 °C) with atmospheric back pressure. The injection pressure ranged between 60 and 120 MPa. Single injection, 2-split and 3-split injections were carried out to study the influence of the increase of the number of splits. Under all injection pressures, the injection durations for 2-split injections were both equal to 0.5 ms and for 3-split injections three equal durations 0.5 ms were used. Dwell τ (time interval between the end of one split injection and the beginning of the next one) varied from 0.2 to 0.8 ms for 60 and 90 MPa injection pressure cases while dwell under 120 MPa ranged between 0.3 and 0.8 ms. To study the impact of the distribution of the duration of energization periods on the spray characteristics, an additional set of tests was carried out using 90 MPa injection pressure. For this set of tests, the injection duration is 0.6 ms injection followed by τ ms dwell time and then 0.4 ms second injection, with τ varying from 0.3 to 0.8 ms. Thus the energization periods were different than before, with dwell times repeated.

The investigated area is 2.3 mm long downstream of the injector tip. The study focused on the initial injector opening stage. The fuel used is winter grade pump-grade diesel. The density is 806 kg/m^3 and viscosity is 2.23 cSt @ 40 °C with surface tension of 24.56 mN/m.

4. Results and discussion

4.1. Morphology development of single injection

The morphology of spray with single injection under 60 MPa is presented in Fig. 2. The gradually enlarged mushroom shaped spray head is observed (The case with the most obvious mushroom shaped head is chosen (Fig. 2) although many cases with less obvious mushroom head were obtained during the test). The formation of this special shaped head is believed to be caused by the laminar flow regime in the injector nozzle hole and residue fuel of the former injection, while the growth of the mushroom head is thought to result from the air drag force [4,5]. The compact liquid column suggests the poor spray dispersion during the initial injector opening stage due to the low effective injection pressure [5]. More

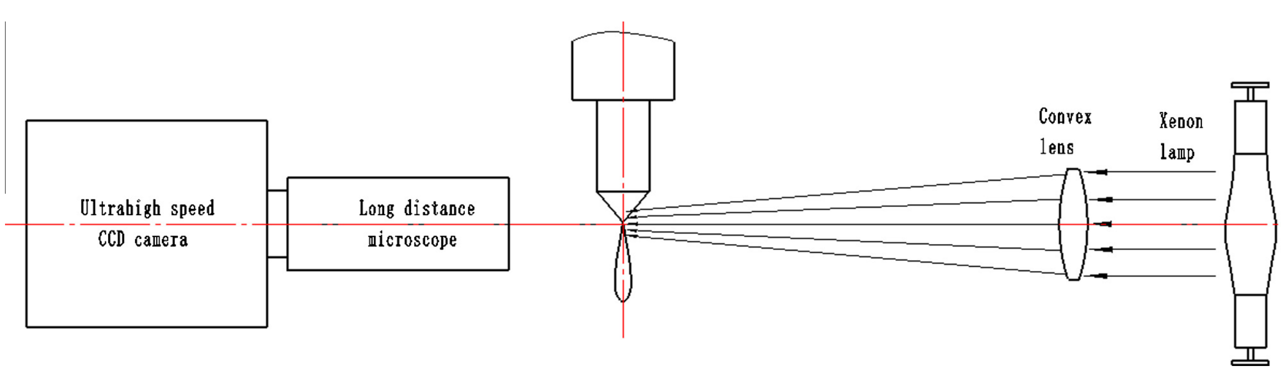

Fig. 1. The layout of the experimental setup.