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Experimental investigation of effects of super high injection pressure on diesel spray and induced shock waves characteristics

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ABSTRACT

Modern diesel engines employ higher injection pressure in the common-rail injection system that utilizes high-speed fuel jet to achieve rapid fuel-air mixing for spray atomization improvement. However, the spray characteristics under super high pressure are not well understood. To provide more information on spray characteristics, both the macro- and micro-characteristics of spray have been investigated under super high pressures (up to 300 MPa) via an experimental method. The spray penetration and spray cone angle were measured using a high speed camera and the microscopic characteristic of Sauter mean diameter (SMD) was obtained via Malvern Spray Tec to analyze the influence of super high injection pressure on diesel spray atomization. Induced shock waves were captured using a Schlieren system when the spray tip velocity was greater than the local sound velocity accompanied by diesel spray. The results obtained show that higher injection pressures lead to larger spray velocities and a smaller shock wave angle if it exists, with connection between spray and shock waves, and generates a smaller SMD with less decreasing amplitude. Additionally, two different types of leading shock waves—bow and oblique shock wave appeared sequentially with increasing injection pressure.

1. Introduction

In the direct injection diesel engine, fuel combustion in the cylinder has been extensively studied [1,2], and the fuel combustion rate depends mainly on the liquid evaporation rate due to the initial state transformation from liquid fuel to vapor phase. Hence fuel spray and air-fuel mixture techniques have been utilized to transform fuel from the liquid jets into tiny droplets to increase the evaporation area [3]. In the meanwhile, improved fuel combustion efficiency directly benefits from a more uniform combustible mixture providing more complete combustion [4,5]. Thus, the diesel spray atomization and mixture formation are key factors in affecting the combustion efficiency, engine performance, and reducing emissions in a direct injection diesel engine. Amongst the use of various technologies in atomization improvement, including high-pressure fuel injection [6], supercharged air intake [7], and induction swirl [8,9], increasing the injection pressure is now being considered a most effective method for more uniform atomized droplets and the formation of lean mixture in cylinder after decades of development [10]. Therefore, high-pressure fuel jets have become investigative emphasis and hot spot in improving quality of fuel spray atomization in recent years. However, since the process of jets breakup and atomization involves the complexity of gas-liquid two-phase flow and quite short time scale, it is a long way to fully understand the internal mechanism of spray atomization.

The pressure of the automotive fuel injection system can be traced from around the mid-20th century at 60–100 MPa to the rapid development after the 1980s. Actually the injection pressure of common rail system has been going up over the past decades, such as that of system developed by BOSCH was 135 MPa for the first generation, 160 MPa for the second generation, 180 MPa for the third generation, and 220 MPa for the fourth generation. Currently, the injection pressure of commercial injection system has been reached 250 MPa, and the pressure of injection system in the laboratory even has been elevated up to 350 MPa [11]. For instance, Delacourt et al. [12] modified or established several evolution laws of spray penetration, angle, area, and volume for a wider injection pressure range up to 250 MPa. It was found that the evolution law suggested by Hiroyasu and Arai agreed well with the experimental data of spray penetration for the extended application field, which was also validated in this work under super high injection pressure. Furthermore, many investigations have been conducted to explore the effects of higher injection pressure

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on spray characteristics. Zhang [13] studied the flat-wall-impinging spray and mixture formation process under ultra-high injection pressure up to 300 MPa, and drew a conclusion of better atomization quality from a more effective penetration and a higher air entrainment rate. The similar conclusion was obtained by Wang [14] and Kuti [15] concentrating on the effects of fuel properties, ultra-high injection pressure, and micro-hole nozzle diameter on spray characteristics on the basis of large number of experimental researches. The results showed that the spray penetration increased along with the pressure while the amplitude decreased, and the spray cone angle was less affected by the injection pressure at approximately around 20°, which was well verified in our previous research [16] of the effects of injection pressure (200 MPa, 300 MPa, and 400 MPa) on spray penetration, calculated spray tip velocities, and spray cone angle at atmospheric pressure. A similar conclusion was obtained about the diminished penetration spacing with increasing injection pressure at a given time and gradually increased difference over time, which was mainly due to the greater air resistance.

The microscopic characteristic parameter of Sauter Mean Diameter (SMD) has been defined to quantity characterize the average droplet size of fuel spray as the evaluation standard for atomization quality to facilitate better understanding of the atomization mechanism [17]. Many studies and correlations for different models described the SMD depending on the difference between fuel injector pressure and ambient gas or on the injection velocity. Through all these correlations showed a negative relation between SMD and injection pressure, the pressure application range in the empirical formula method was confined to a small limit. For example, Wang et al. [14] found that the estimated SMD decreased remarkably with increasing injection pressure from 100 MPa to 300 MPa on the basis of a correlation suggested by Elkotb [18] where, however the application scope of pressure term in the equation was far too narrow [19]. Thus, more experiments on the distribution of droplet diameters under super high injection pressure should be urgently carried out for further modification of the pressure range.

Due to the continuous increasing injection pressure, the speed of liquid jets increases accordingly even to the supersonic state, which will produce some new phenomenon such as shock waves and relevant characters affecting the evolution of spray atomization [20]. However, whether or not be a supersonic jet is related to not only jets speed but also the local sound velocity, which is a function of media property, temperature, and other parameters. For the condition of 0.1 MPa and 1.205 kg/m^3 as the ambient medium, the multi-value function for the local sound velocity can be transformed into a single-value function only to temperature, such as 345 m/s (25 °C) in air. Therefore, in a vehicle diesel engine, the fuel ejected speed is in a range of 260–520 m/s based on the real environment of diesel engine as follows: fuel injection pressure of 80 –200 MPa, orifice diameter of 0.1–0.25 mm, and orifice flow coefficient of 0.6–0.75. In the meantime the typical temperature of air in cylinder is about 750 K during the initial stage of fuel injection, thus the local sound velocity is around 550 m/s. In other words, the theoretical maximum speed of fuel jets is subsonic under the injection pressure in general use. It can also be concluded that the critical pressure to achieve supersonic liquid jets is around 350 MPa in the cylinder of diesel engine, where the local sound velocity is 550 m/s. If, for instance, advanced injection in low-temperature environment, then the fuel jets would travel faster than sound under injection pressure of 300 MPa.

From the analysis above, the speed of fuel jets increases correspondingly with the elevated injection pressure and easily penetrates beyond the local sound velocity at ambient temperature and pressure conditions investigated in this article (it is of course possible to conduct further research under higher environmental temperature and pressure in the future). When a supersonic jet is instantaneously injected into atmosphere, a strong disturbance is generated, namely shock wave. The process of investigating supersonic fuel jet is a difficult one involving turbulent flow, multiphase flow, and the interaction between spray and shock waves. According to the action carried out the problem can be classified into subsonic sprays passively accepting the external influence of shock waves in the supersonic flow field [21–23], and the spray or fuel droplets actively producing shock waves via supersonic jets, which has received relatively less study because of the immature equipment and techniques currently available.

In the early 1990s, Nakahira et al. [24,25] confirmed firstly the existence and formation condition of shock wave generated by high-pressure fuel spray using the Schlieren technique, and the results showed that the shock wave travelled at sonic speed under relatively low injection pressure. X-radiography was introduced by MacPhee et al. [26] for quantitative analysis of the propagation of the spray-induced shock waves under injection pressure of 50–135 MPa with the ambient gas of sulfur hexafluoride. The experimental results were also used to verify the accuracy of subsequent numerical simulation on shock wave generation [27]. However, a low frame rate of camera or narrow injection pressure range prevented a more comprehensive analysis. Pianthong et al. [28–32] developed a supersonic liquid jet experimentation device that harnessed the impact of the supersonic projectile to generate the supersonic liquid jet, whose instant injection pressure could reach an astonishing 8600 MPa. A leading edge shock wave was recorded in front of the supersonic jet, whose development process in the initial period appeared in two different propagation modes [16,33]; however, both the massive and complex structure and the technique generating the high pressure, as well as the fuel injection modes were distinguished from those of the automotive fuel injection system. As a consequence, a deep analysis of the spray-induced shock waves under wider injection pressure range could provide a better understanding on the development process and effect laws.

Previous studies have indicated that shock waves will appear in front of and around the spray body when fuel jets in air travel at supersonic speeds. Owing to the deformation behavior of liquid jets, which presents a substantial correlation with liquid viscosity, surface tension, density, and aerodynamic effects, the configuration of shock wave generated by supersonic fuel jets is apparently more complicated than that induced by supersonic solid. Then it is necessary to focus on the effects of shock wave on the supersonic liquid spray and the interaction between them. Roisman et al. [34] investigated the characteristics of supersonic spray jets penetrating through a region of compressible air (behind the shock) considering the existence of shock wave as a normal adiabatic compression wave by numerical method. Research carried out by Huang et al. [20] found that the shock wave other than pressure drop differences and the enhancement of gas density had a predominant effect on the evolution of spray penetration. Although similar researches of effects of shock wave on fuel spray penetration have been conducted, a detailed investigation on evolution laws of both can develop a more in-depth understanding of interaction mechanism.

The objective of this paper is to investigate the macroscopic characteristics, such as spray penetration and spray cone angle, and the microscopic characteristic, such as SMD and evolution of the induced leading shock waves, under the condition of increasing injection pressure up to super high of 300 MPa using Schlieren technologies. The injection pressure in this study covers an appropriate range for the fuel jets velocity from subsonic to supersonic, unlike previous research [16,33] within the scope of supersonic range, to explore the spray characteristics with or without the effect of induced shock waves. Additionally, the micro-analysis of