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Effect of shock waves on the evolution of high-pressure fuel jets

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HIGHLIGHTS

- A new criterion of shock wave generation for high-pressure fuel jets is proposed according to the experiments.
- Penetration characteristics of shock wave and non-shock wave fuel jets are acquired and major difference is found.
- A modified numerical model, which has wide application range from subsonic state to supersonic state, is introduced.

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ABSTRACT

In the modern diesel engine, with increasingly higher injection pressures, shock waves will appear with high velocity fuel jets. To better understand the effect of shock waves on the atomization of fuel sprays, diesel fuel injected at a pressure of 60 to 120 MPa was studied using a schlieren imaging visualisation system. The initiation and boundary conditions of the shock wave initiated by fuel jets were examined. A clear difference of spray penetration between the shock-wave state and the non-shock-wave state was recorded in a nitrogen (N_2) and sulphur hexafluoride (SF_6) gas atmosphere. By eliminating the other potential explanations, such as pressure drop differences and the enhancement of gas density, it is shown that the shock wave itself had a predominant effect on the evolution of high-pressure fuel jets. Additionally, a computational model considering the Mach number was developed to predict the spray penetration. The model was found to have excellent agreement with the presented experimental results.

1. Introduction

High-pressure fuel jets are an essential technology for many applications, including fuel injection systems, thermal and plasma spray coatings, and supersonic combustion [1–3]. In the case of a fuel injection system, improving spray atomization is crucial for the clean and efficient combustion process in a diesel engines. For this purpose, different studies that aimed to comprehend the fundamentals of fuel injection have been conducted over decades. The investigations proved that the quality of spray atomization correlates strongly with the injection and environment conditions [4–6]. The hydraulic behaviour inside the diesel nozzle also helps to determine the spray evolution and air–fuel mixing process [7–9]. Nevertheless, due to the highly transient and multiphase process of fuel injection, the inherent mechanism of spray atomization and evaporation still has not been conclusively determined [10–12].

Currently, the most common approach to improve the quality of spray atomization in a diesel engine is to increase the injection pressure [13–17]. The common-rail system is capable of delivering fuel at a pressure of over 160 MPa and has been widely applied to modern diesel engines; however, even higher injection pressures (approximately 300 MPa) have been achieved in the laboratory. For example, Wang et al. [15] conducted a spray flat-wall-impinging experiment under ultra-high pressure (300 MPa). The results showed that injections under ultra-high pressure generated a higher momentum, providing better atomization quality throughout the entire injection process.

With the elevated injection pressure, the speed of the fuel spray increases accordingly, and a supersonic spray jet could eventually be generated. Therefore, the generation of a shock wave in the injection process of a modern diesel engine is inevitable. A shock wave is a type of propagating disturbance that is potentiated by a supersonic velocity that travels through a medium and carries energy. By utilising the schlieren image technique, Nakahira et al. first found the existence of a shock wave during the injection process of a diesel engine [18]. Then, with the X-ray radiograph image technique, MacPhee et al. more clearly observed the shock wave

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phenomenon in diesel sprays. Moreover, they also found that there was an average of a 15% increase in the gas density near the shock front [19].

The existence of shock wave generation in diesel sprays has been proved, and an increased effort has been given to investigate the influence of shock waves on the diesel spray characteristics. In one aspect, different from the other supersonic processes, the diesel fuel injected by the common rail system is continuous, compressible and multiphase. Therefore, it is important to consider the initial shock wave condition in the diesel injection process to better evaluate the possibility and range of shock wave existence under practical diesel engine working conditions. The majority of the previous investigations used a spray tip velocity that exceeded the local sound speed as the initial condition for shock wave generation in the diesel spray [20–22]. Research indicates that Pickett et al. provided the most representative investigation [22]. It was concluded that increasing the ambient temperature and density both inhibit shock wave generation. Thus, spray-generated shock waves are not expected at the injection timings typical of a diesel engine [22].

However, the measuring results of the mass flow rate and the momentum at the nozzle exit indicate that the speed of fuel jets initially increase, stabilize and finally decrease throughout the injection process [23–26]. Therefore, if fuel injection is simply considered as diesel droplets that successively exit from the nozzle, the velocity of the first droplet (the spray tip velocity) is not the highest. Moon et al. also found that the liquid jets decelerate in both the axial and transverse directions after exiting the orifice through the use of the multi-exposed X-ray phase-contrast image technique [27]. As a consequence, the initial shock wave condition in the diesel injection process should be reconsidered.

In another aspect, various studies have been conducted to unveil the interaction mechanism experimentally and numerically between the diesel spray and the shock wave. Amongst the experimental investigations, Sittiwong et al. found that diesel sprays under actual conditions may deviate from the theoretical predictions of the injection pressure fluctuation, the gas density unevenness and the shock wave occurrence [28]. Payri et al. found a 6% difference of spray tip penetration between the results from N_2 and SF_6 and attributed this difference to shock wave generation. However, they did not present any further analysis [29].

Amongst the numerical investigations, Roisman et al. proposed a correlation to simulate the spray penetration in the supersonic state by approximating the shock as a normal adiabatic compression wave [30]. However, the results calculated with the correlation were underestimated compared to the experimental data given by MacPhee et al. [19]. Im et al. [31] also analysed the mechanism of shock wave generation and its impact on spray behaviour numerically. Although these simulation results achieved excellent agreement in the excess air density with the experimental data, their ability to predict spray tip penetration still lacks precision. The spray tip penetration and prediction model are very important in diesel spray investigations and engine design [32–34]. A detailed study of the supersonic-state spray evolution can help researchers to better understand spray behaviour in the modern diesel engine.

The main objective of the present work was to investigate the effect of shock wave on the evolution of high-pressure diesel jets. For this purpose, the study first focused on the shock wave initiation condition during the injection process. Then, based on the property that local sound speeds at different atmospheres differ greatly, spray jets of the shock wave state and non-shock wave state were achieved under the same injection pressure and same gas densities. By comparing the variance of the spray characteristics at these two states, the influence of the shock wave on the spray development was effectively and quantitatively analysed. Furthermore, a modified model was developed to estimate the penetration behaviour of supersonic liquid jets.

2. Experimental details

2.1. Experimental apparatus

The experiment was conducted using the schlieren imaging visualisation test system, which is illustrated in Fig. 1. The test rig consisted of a common rail injection system, a control unit, a constant volume vessel and an imaging system. The schlieren images of the shock waves were collected at 150,000 fps, a 1 μs exposure time and a resolution of 256×24 pixels. Detailed descriptions of the experimental method were given in a previous publication [35].

2.2. Image processing

An imaging processing program was developed with Matlab to analyse the original schlieren images captured by the high-speed camera. Fig. 2 shows a typical image before and after imaging processing (the nozzle tip was added afterwards to work as a reference). The spray is characterised by spray tip penetration (S), which has been widely applied in previous investigations. The velocities of the spray tip and the shock wave were accordingly calculated by the displacement of the leading-edge position and the imaging rate. To better present the shock-wave structure, the images were re-coloured according to the image grayscale. Re-coloured blue[1] and red areas corresponded to the original light-coloured area (small gas density) and the original dark-coloured area (large gas density), respectively, while the white area represented the background.

2.3. Experimental conditions

Two single-hole nozzles (HEG-0 and HEG-9.0) with similar internal geometries were employed for the investigation. Four structural parameters, including the outlet diameter, inlet diameter, orifice length and inlet rounding radius, were used to characterise the nozzle internal geometries. Their definitions can be found in Refs. [36,37]. The nozzle geometries were measured by Huang [36] and are summarised in Table 1. It should be mentioned that the inlet diameter and the outlet diameter of these nozzles were designed to be 180 μm and 160 μm, respectively. Thus, the orifice is divergent and the K-factor equals 2. However, it can be seen in Table 1 that the measuring results are different from the design values. These deviations correlate strongly with the manufacturing values. More in-depth analysis regarding the relationship of the nozzle internal geometry and manufacturing can be drawn from Ref. [37].

To create variation in the initial speed of the jets, four injection pressures of 60 MPa, 80 MPa, 100 MPa and 120 MPa were selected. For each tested injection pressure, two ambient gas densities were used, 11.5 kg/m^3 and 34.5 kg/m^3. The experimental conditions and properties of the two types of gases are listed in Table 2.

3. Results and discussion

3.1. Boundary condition of shock wave initiation

To characterise the fuel spray in the shock-wave state and non-shock-wave state, the boundary conditions of shock-wave initiation should first be defined. The shock wave was initiated in all of the tested conditions in a SF_6 atmosphere; therefore, Fig. 3(a) only illustrates the spray developments and initiation of the shock

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[1] For interpretation of colour in Fig. 2, the reader is referred to the web version of this article.