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Experimental research on the effect of shock wave on the evolution of high-pressure diesel spray

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A B S T R A C T

With the increase in the diesel injection pressure in modern diesel engines, the velocity of the diesel spray increases accordingly, and shock waves are induced when the spray is supersonic. To better understand the effect of shock waves on the spray development, the evolution of the high-pressure diesel spray and shock wave under different diesel injection pressures and ambient pressure has been investigated using the Schlieren imaging method. The results show that the shock wave affects the development of the spray and the mixing effect between the spray and surrounding air. The shock wave promotes development of the spray tip penetration and enhances the gas entrainment effect. However, the shock wave has an inhibitory effect on the spray development in the radial direction. In addition, the shock wave angle determines the range of influence on the ambient air, which affects atomization of the spray. The shock wave angle increases with the decrease in the spray front Mach number. An empirical correlation of the shock wave angle and spray front Mach number was proposed in this paper. The calculated results are in good agreement with the experimental data. In addition, a diagram of the shock wave generation and classification in a diesel engine is proposed.

1. Introduction

Energy conservation and emission reduction have become the most important issues for internal combustion engines. High diesel injection pressure is regarded as one of the most effective methods to improve diesel spray atomization and optimize engine combustion and emission processes [1–3]. With the continuous development of the high pressure common rail injection system, the fuel injection pressure has increased to more than 250 MPa [4,5]. The speed of the diesel spray also increases with the increased fuel injection pressure. When a supersonic spray is generated, a shock wave forms in the cylinder. The generation and propagation of the shock wave affect the breakup and development of the spray [6–8].

In addition, multiple injection strategies have been widely used in diesel engine. The pre-injection of fuel makes a relatively lean fuel mixture in the cylinder, and this can effectively shorten the delay of ignition and reduce NO_x emissions [9,10]. However, the increase of average molar mass of the working medium in the cylinder produces a lower sonic speed [11]. Therefore, the generation of a shock wave in the high-pressure diesel injection process of a modern diesel engine is inevitable [12,13].

Nakahira et al. first observed the existence of the shock waves during the fuel injection process of a diesel engine using the Schlieren imaging method. The results showed that shock waves could promote the combustion process in a cylinder [14]. MacPhee et al. found the oblique shock wave structure in a SF_6 environment by an X-ray technique. The results showed that the shock wave affected the atomization of the spray, and the gas density had an average 15% increase near the shock front [11]. It can be seen that the generation of shock wave has affected the working process of the modern diesel engine. Researchers first studied the types and propagation characteristics of the shock waves [15–18]. Pianthong et al. investigated the spray dynamic characteristics and induced shock waves under ultra-high fuel injection pressures (up to 300 MPa). It was found that the shape of the leading edge shock wave was related to the Mach number of the spray and the geometry of the nozzle [15,16]. Jia et al. studied the propagation behavior of the induced leading edge shock wave, and two modes were observed [17,18].

Further studies have focused on the generation mechanism of shock waves and the effect of shock waves on the diesel spray characteristics [19–22]. The effect of the ambient temperature and density on the shock wave was experimentally investigated, and it was found that an increase in the ambient temperature and density both inhibited the generation of the shock waves because of the high local speed of sound and high momentum loss of the spray [12]. Milton et al. found that the nozzle structure obviously affected the shock wave structure [16]. Payri

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Nomenclature

ASOI	after the start of the injection	SMD	Sauter mean diameter
I	intensity of shock wave	*S*	spray tip penetration
k	specific heat ratio	*t*	time
m_a	mass of entrained air		
Ma	Mach number	*Greek symbols*	
P_{inj}	diesel injection pressure	θ	spray cone angle
P_b	ambient pressure	β	shock wave angle
		ρ_a	gas density

et al. compared the spray tip penetration in N_2 and SF_6 environments under the same fuel injection pressure and environmental density to analyze the effect of the shock wave on the spray development. The results showed that the spray tip penetration in the SF_6 is on average around 6% higher than for the N_2 case. It was considered that the shock wave promoted the spray tip penetration development [19]. Huang et al. made similar experiments, but the study got the opposite conclusion. It was found that the shock wave had a predominant effect on the evolution of the diesel spray [20]. Jia et al. investigated the induced shock wave characteristic and Sauter mean diameter (SMD) of the supersonic diesel spray. They found that the SMD and spray cone angle decreased with the increase in the fuel injection pressure [7]. Quan et al. studied the dynamics of the induced shock waves and their interactions with the spray using a volume-of-fluid method. The results indicated that the increase in the gas density accelerated the detachment of the leading edge shock waves [13]. Im et al. numerically investigated the generation mechanism and the effect of the shock wave on the spray behavior. It was found that the shock waves were related to disintegration of the fuel jets [21]. Huang et al. developed a computational model to predict the spray tip penetration considering the Mach number. The model's calculated results had a good agreement with the experimental data [22].

However, the effect of the shock wave on the spray mixing characteristic and the generation mechanism and existing range of different types of leading edge shock waves in a diesel engine have rarely been investigated. In addition, further research is needed to understand the influence of the shock wave on the evolution of the spray structure parameters. Based on the above analysis, this paper investigated the evolution of the high-pressure diesel spray and shock waves under different diesel injection pressures, ambient pressure and gaseous medium using the Schlieren imaging method. The present paper has three objectives: (1) Understand the evolution law of the shock wave angle and study the relationship between the shock wave angle and spray front Mach number, (2) Determine the generation mechanism and the existing range of different types of leading edge shock waves in a diesel engine (3) Analyze the effect of the shock wave on the spray macroscopic structure and mixture characteristics.

2. Experimental setup

2.1. Experimental apparatus

The evolution of the high-pressure diesel spray and shock wave has been experimentally investigated using the Schlieren imaging method. The experimental setup is shown in Fig. 1. The experimental setup consists of six parts; i.e., the Schlieren system, fuel supply system, fuel injection system, control system, monitoring system and a constant volume vessel. A xenon lamp was used as the incident light source. The white light passes through a 1 mm aperture, and turns into a point light source. The light from the point light source is reflected through the reflect mirror and spherical mirror, then forms a parallel light whose diameter is 190 mm. The parallel light passes through the quartz windows of the constant volume vessel and transmits the information of the diesel spray and shock wave to the high speed camera (Phantom V7.3) through the symmetrical arrangement of the spherical mirror, reflect mirror and a knife edge at the focus. The frame rate is set to 50,000 frames per second with a pixel spatial resolution of 128 ∗ 264 pixels. The diameter of the injector is 0.14 mm.

In this study, SF_6 and N_2 were used to investigate the effect of the shock wave on the spray characteristics. This is because the speed of

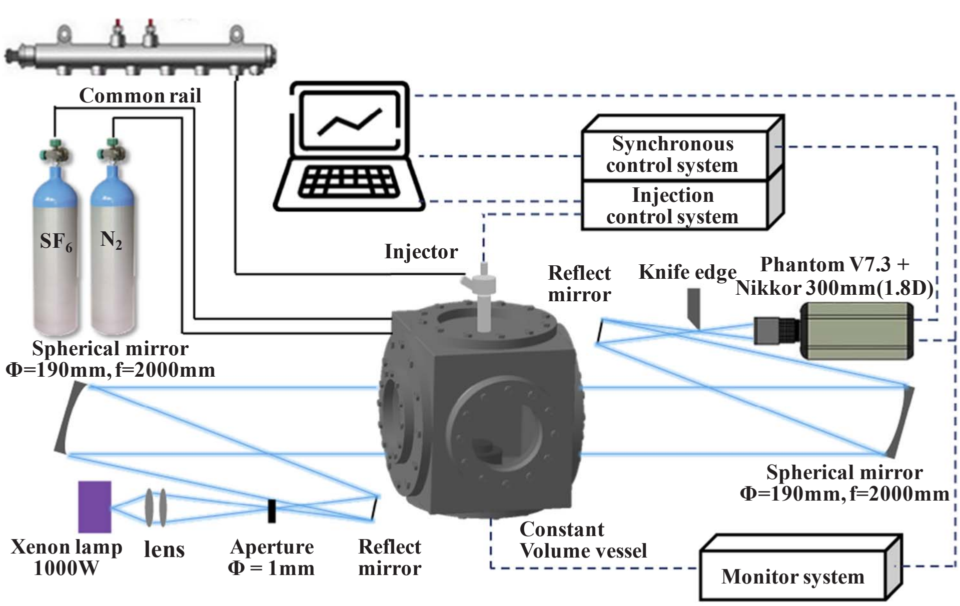

Fig. 1. Schematic plan of experimental setup.