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Full Length Article

Propagation characteristics of induced shock waves generated by diesel spray under ultra-high injection pressure

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HIGHLIGHTS

- Experimental study of fuel spray under ultra-high pressure (400 MPa) was conducted.
- A diaphragm rupture atomizer was designed to meet the ultra-high pressure demand.
- The results indicated leading edge shock wave shows two forms in the early stage.
- The propagation characteristics of multiple expansion waves were investigated.
- The correlation between spray and waves was confirmed by the velocity distribution.

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ABSTRACT

The phenomenon of shock waves can be commonly seen in fuel spray under ultra-high injection pressure conditions, where the spray jet penetrates at speeds greater than Mach 1. This paper focuses on the induction of shock waves and their propagation characteristics generated by a supersonic fuel jet at 400 MPa, and simultaneously considers the impact of jet atomization. A specially designed atomizer, utilizing diaphragm rupture, was adopted to replace the traditional electronic valves fuel system to meet the ultra-high injection pressure. Visualization of the spray field by using a high-speed camera was conducted, and a Schlieren apparatus was equipped for shock capturing based on a variable environmental density distribution. The experimental results indicated that the leading edge shock wave shows two forms in the early stage, and each penetrates in a unique way. Along with the spray development, multiple expansion waves were sequentially generated, followed by the leading shock wave. The evolution of wave velocity over time was calculated from the penetration results, and the results showed that the velocity first increased rapidly and then slowly decreased as a result of the effect of air resistance, with a gradual tendency of decreasing for the four peak velocities of the intensity weakened waves. In addition, the spray convex flow path had an inhibitive effect on the deceleration of the first expansion wave. These results give an insight into diesel spray and propagation process of induced shock waves at an under ultra-high injection pressure of 400 MPa.

1. Introduction

To meet the stringent emission regulations for urban pollutants, such as particulate matter (PM), soot, and nitrogen oxides, various improvements and advanced technologies have been developed, e.g., high injection pressure [1], new-type orifice structure [2], modified chamber profile [3], waste heat recovery [4], new and clean substitute fuel [5], as well as various new combustion modes, such as low temperature combustion (LTC) [6], premixed charge compression ignition (PCCI) [7], reactivity controlled compression ignition (RCCI) [8], and homogeneous charge compression ignition (HCCI) [9]. In particular, a higher injection pressure is considered a more efficient method for improving fuel economy, with low exhaust emissions [10] in the modern high-pressure common rail injection system (HPCR) of a direct injection diesel engine. Over the past few decades, high-pressure fuel spray underwent a significant development, from approximately 120 MPa [11] to 250 [12] to 300 MPa [13] after the 1980s, with a sustained and rapid upward trend, owing to its improvement in the atomization and air–fuel mixing performance, which further contributed to the combustion and emission processes. When the high-pressure spray

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is suddenly injected into the ambient environment, multiple waves are generated around the fuel jet [14]. Nevertheless, only a few studies have been conducted on ultra-high pressure spray and induced shock waves because of the unachievable experimental approach, and the complicated spray process involving in-nozzle flow [15], turbulent flow [16], and propagation characteristics [17]. Therefore, fundamental knowledge regarding spray morphology and wave propagation properties under ultra-high injection pressure is required.

In order to investigate factors, such as spray atomization, breakup mechanism, and macroscopic spray characteristics, Eagle et al. [18] studied penetration and cone angle by using high-speed photography in a constant volume chamber. Delacourt et al. [12] measured spray properties for a wider pressure range of up to 250 MPa. It was observed that the results obtained not only extended the pressure application of the current existing empirical formula suggested by Hyroyasu and Arai, but also established various new laws for other characteristics, such as cone angle, projected area, and volume. A comparative analysis was performed on spray configuration, and the penetration and cone angle under three elevated injection pressures of 100, 200, and 300 MPa [19]. It was observed that the penetration of the spray tip increased with injection pressure, but the increasing amplitude decreased (the same trend was confirmed through a numerical simulation method used by Ghasemi et al. [20]). However, the cone angle was expected to remain consistently near 20° and was less affected by the injection pressure. The Ejim model [21], which considered both the injection pressure and density of the fuel and gas, was proposed to investigate the distribution of droplet size in the spray field.

The penetration model proposed by Hiroyasu and Arai showed a positive correlation between injection pressure (ΔP) and jet velocity (U) as defined in the equation: $U = C_d\sqrt{\frac{2\Delta P}{\rho_f}}$, where C_d is the discharge coefficient of the orifice, and ρ_f is the liquid fuel density [22]. When the relative velocity of liquid and gas is sufficiently fast, the physical property of compressibility in the air becomes apparent, which is defined as Mach number (Ma) to represent the extent of compression [23]. Generally, the dimensionless parameters are introduced to describe the effects of liquid properties, pressure, or temperature on fluid-flow characteristics [24]. When $Ma > 1$, supersonic flow is generated and the enhanced unsteady flow, due to instabilities in the form of vortical structure, gradually grows until the final break-up for an improved atomization. The emergence and development of supersonic liquid jets in the quiescent compressible gas were mainly investigated to examine the effects of physical parameters, such as ambient pressure/inlet velocity, which indicated that the penetration of liquid jets decreased with increasing ambient pressure [25], and fuel properties/nozzle geometries [26], on the complex multiphase flow characteristics.

When a high-pressure liquid is instantaneously injected into an ambient environment, a strong disturbance in the form of shock waves is generated at the front of and around the jet [27]. Unlike conventional shock waves induced by the compression of a rigid body, the emergence and development mechanism of shock waves generated by highly transient liquid jets is affected by many factors, such as spray angle [28], so it is of great significance on a thorough understanding of the propagation characteristics. However, liquid spray under ultra-high pressure and the derivative phenomena of shock waves has received attention only in recent years, with incomplete conclusions. Earlier studies found that when the fuel velocity exceeded the sonic velocity in ambient gas, a shock wave was captured near the nozzle having the same propagation speed as sonic speed, with approximately 10% of ambient pressure at an amplitude of 150 MPa [29,30]. In addition, shadowgraph [31] and ultra-fast X-radiography [32,33] techniques were adopted to analyze the mechanism of morphologic transformation of shock waves, jets-generation process, and the interaction between supersonic liquid jets and jet-generated shock waves, where the X-ray technique can quantitatively probe the distribution of density of the ambient media inside and near the shock front by Jin Wang and his co-workers in Argonne National Lab [34]. Pianthong et al. [35] built a single-stage powder gun to fire a polycarbonate projectile on a liquid packet to generate supersonic liquid jets, and a one-dimensional analysis was performed on shock reflection and transmission in the nozzle after the impact of the projectile. Furthermore, it was observed that the shape of the leading shock wave, stand-off distance between the leading shock wave and stagnation point on the spray tip [36], and shock layer flow dynamics were closely related to the Mach number of the spray jet and the geometry of the blunt body [31]. Recently, the effects of a wider range of ambient temperature and density on shock wave generation by a high-pressure diesel spray were experimentally investigated, and it is concluded that a higher ambient temperature and density inhibit shock wave generation because of a larger local sound velocity and greater momentum loss [37]. Quan et al. [38] numerically simulated the dynamics of induced shock waves and their interactions with spray by using a volume-of-fluid method in the CFD software, and the simulated results were in good agreement with experimental results. The analysis indicated that a higher ambient density accelerated the detachment of tip shock waves, and a decreasing fuel injection rate inhibited shock wave generation. Previous studies mainly focused on the spray characteristics and propagation properties of leading shock waves under super-high injection pressure; however, the emergence and dynamic development mechanisms of leading shock waves, as well as those of multiple shock waves, were rarely investigated experimentally.

In this study, the objective was to achieve ultra-high injection pressure fuel spray by experiment, and to classify the propagation characteristics of induced shock waves. The spray process in quiescent air was visualized by a Schlieren system using high-speed camera. Some analysis based on the experimental results of exploring the potential mechanism of shock waves (leading shock wave and multiple expansion waves) was also conducted.

2. Experiments

The investigation was conducted at an ultra-high injection pressure facility capable of injecting a supersonic diesel spray from a diaphragm rupture atomizer, described in detail below. The cross, simultaneously connected to the fuel tank, pressure gauge, ultra-high pressure pump, and nozzle, was equivalent to constructing an ultra-high pressure chamber, and the high pressure was achieved by utilizing an ultra-high pressure pump driven by a motor. The measurement system mainly consisted of two parts, the Schlieren system and a high-speed photography system (Photron FASTCAM SA-X2, 160,000 fps with a resolution of 256 × 192 pixel), as shown in Fig. 1. In this experiment, the optical technique of the Schlieren setup was adopted to photograph the gas flow around the supersonic diesel spray, based on the principle of fluctuations in refractive index caused by density gradients. The Z-shaped Schlieren arrangement is composed primarily of one Xenon lamp, two flat reflectors, two concave mirrors with diameters of 100 mm and focal lengths of 2000 mm, and two slits. Light penetrating the slit was firstly collimated by the concave mirror M_1 for passing through the test section as a form of parallel light without refractive index fluctuations, and then focused by the concave mirror M_2 to the other slit on the focal plane for the Schlieren fulfillment.

Fig. 2 shows the detailed configuration of the diaphragm rupture atomizer, which is mainly composed of a gland, an orifice