Experimental study on the evolution of shock waves generated by high-pressure diesel spray

Yue Li¹, Bingbing Liu* and Gang Liu¹

¹ College of Navigation, Shandong Jiaotong University, Weihai, Shandong, 264200, China
*Corresponding author’s e-mail: 222012@sdjtu.edu.cn

Abstract. High fuel injection pressure leads to supersonic fuel jet and shock wave phenomenon. The characteristic of shock waves induced by supersonic jets under different working conditions were researched based on visualization experiments. The shock wave classification characteristics were studied. This paper indicates that the shock wave angle decreases with the increase of fuel injection pressure. And the shock wave angle increases with the time. The increase of ambient pressure will speed up the separation time of the spray and the shock wave. The classification of the shock wave is determined by the Mach number of the spray.

1. Introduction
High-pressure fuel injection is an effective measure to promote fuel atomization in the cylinder and improve the combustion and emission characteristics in a diesel engine. As the fuel injection pressure increases, the fuel jet velocity increases continuously. The fuel jet in the cylinder has entered the supersonic state with the application of multiple injection and low-temperature combustion technologies. When the fuel spray reaches supersonic speed, shock waves are induced. The shock waves will affect the spray macrostructure parameters (spray penetration, spray cone angle, etc.) and atomization characteristics. At present, there is little research on the characteristic of shock waves. Therefore, it is important to study the evolution law of shock wave induced by high-pressure diesel spray.

Nakahira et al. first used the schlieren method to observe the shock structure during diesel fuel injection in the 1990s, and pointed out that the shock waves has become an inevitable phenomenon in modern engines[1]. Kook et al. investigated the generation conditions of shock waves in diesel engines based on the schlieren method[2]. Pianthong et al. researched the influence of nozzle structure on shock wave structure[3]. Huang et al. found that the background gas density and temperature have an important influence on the type of shock wave[4]. Jia et al. investigated the shock wave characteristic in the process of ultra-high pressure diesel injection based on the schlieren method[5]. Song et al. studied the shock waves under supersonic fuel jet based on experiment[6]. The evolution characteristics of the shock wave induced by high-pressure fuel injection are investigated in this article based on the Schlieren method. And the shock wave characteristic parameters under different working conditions are analyzed. In addition, the classification of the shock wave is proposed based on the Mach number of the spray.
2. Experimental setup and parameter definition

The experiment is carried out based on the Schlieren method. The experimental setup is shown in Figure 1. The light path is arranged in a "Z" shape. Detailed experimental parameter settings have been introduced in the published paper[6]. The test shooting frequency is 50000 frames per second and the spatial resolution is 128*264 pixels.

The shock wave angle and shock wave penetration of oblique shock wave are indicated in Figure 2. The temperature of the experiment is 298K. The fuel injection pressure is set from 60MPa to 160MPa.

3. Experiment results

The evolution of the shock wave under different fuel injection pressures under atmospheric pressure are proposed in Figure 3. It is shown that the shock structure can be observed at the front of the fuel jet. The shock wave structure changes continuously with the time. The oblique shock wave is attached with the jet when tASOI<0.1ms. And the shock waves are separated from the spray head at tASOI=0.14ms. At this time, the shock wave type is detached bow shock wave. Comparing the visual images of different fuel injection pressures at the same time, the spray penetration increases and the shock wave angle decreases gradually according to the injection pressure increases.

\[ t_{ASOI}=0.04\text{ms} \quad 0.06\text{ms} \quad 0.08\text{ms} \quad 0.10\text{ms} \quad 0.12\text{ms} \quad 0.14\text{ms} \quad 0.20\text{ms} \]
Figure 3. Visualization results of high-pressure diesel spray with various fuel injection pressures (a): Pinj=100MPa, N2, (b): Pinj=120MPa, N2, (c): Pinj=140MPa, N2.

Figure 4(a) shows the Mach number of shock wave surface with the time. The shock wave Mach number is obtained by dividing the difference of shock penetration distance between two visualization images by the time interval. The shock wave Mach number decreases gradually with the development of time. When the speed of the jet front reaches subsonic, the shock wave and the spray front are separated. The shock wave velocity will not decrease further, but maintain the local speed of sound. Figure 4(b) presents that the shock wave angle increases with the time. The shock wave angle decreases with the increase of fuel injection pressure at the same time. The reason of the phenomenon indicates that the shock wave angle and the Mach number of the jet are negatively correlated.

Figure 4. Mach number and angle of shock wave surface with the time.

Figure 5 shows the visualization images under different ambient pressures when Pinj=160MPa. The images show that the shock wave type is attached oblique shock wave under the atmospheric pressure at tASOI=0.14ms. The increase of ambient pressure will speed up the separation time of the shock wave from the spray.
The curves of shock wave penetration with the time under different ambient pressures are shown in Figure 6. The figure shows that the ambient pressure determines the separation time of the shock wave. As the ambient pressure increases, the velocity of the spray decreases fast. On the curve of the shock wave penetration, the inflection point of the curves is advanced. Then the shock wave separates from the spray front and continues to propagate forward in the form of a detached bow shock wave.

The region of the shock wave generation is indicated in Figure 7. When the spray velocity exceeds the speed of sound, the shock wave is induced by diesel spray. The different types of shock waves are distinguished by the shock wave angle. When the shock wave angle is less than 60 degrees, the shock type is identified as an oblique shock wave. The generated region of the shock wave is divided into
two parts, but all the shock wave generation areas are in the area where the maximum Mach number is greater than 1. A previous study determined that the maximum velocity of the spray front is less than the local speed of sound, but the shock wave is observed. It is considered that although the observed spray front velocity is less than the speed of sound, the maximum Mach number of the spray at the nozzle exit is still greater than 1. The supersonic fuel spray induces a shock wave around the nozzle exit. The velocity of the spray front decreases quickly and the shock waves are detached from the spray front accordingly. Therefore, the shock wave is still observed when the spray front velocity is less than the speed of sound. The shock wave angle decreases with the continuous increasing spray front Mach number and the shock wave is changed from the bow type to the oblique type. Figure 7 can be used to predict the existing area and the type of shock wave under different fuel injection parameters in a diesel engine.

![Shock waves generation diagram in a diesel engine.](image)

**Figure 7.** Shock waves generation diagram in a diesel engine.

### 4. Conclusions
Schlieren imaging method is carried out to study the evolution of the shock wave induced by high-pressure diesel spray. The influences of fuel injection pressure and ambient pressure on the shock wave characteristic parameters were investigated. The conclusions are summarized as follows:

1. The shock wave angle and the Mach number of the jet are negatively correlated.
2. The ambient pressure determines the moment of separation of the shock wave and the fuel jet.
3. The shock wave generation diagram can be used to predict the existing area and the type of shock wave under different working conditions

### Acknowledgments
This work was funded by Shandong Jiaotong Natural Science Foundation(Z201939), Shandong Jiaotong University Doctoral Research Initiation Fund (BS201902054), and Shandong Jiaotong University “Climbing” Research Innovation Team Program(SDJTUC1802).

### References
[1] Nakahira T, Komori M, Nishida M. (1992) The shock wave generation around the diesel fuel spray with high pressure injection. SAE Technical Papers, No. 920460.
[2] Kook S, Pickett L M. (2008) Effect of ambient temperature and density on diesel-spray-generated shock waves. In: ILASS, Florida.
[3] Pianthong K, Matthujak A, Takayama K. (2008) Dynamic characteristics of pulsed supersonic fuel sprays. Shock Waves., 18(1):1-10.
[4] Huang W, Wu Z, Gao Y. (2015) Effect of shock waves on the evolution of high-pressure fuel jets. Appl. Energy., 159: 442-448.

[5] Jia T M, Li G X, Yu Y S. (2016) Propagation characteristics of induced shock waves generated by diesel spray under ultra-high injection pressure. Fuel, 180: 521-528.

[6] Song E, Li Y, Dong Q. (2018) Experimental research on the effect of shock wave on the evolution of high-pressure diesel spray. Exp. Therm. Fluid. Sci., 93: 235-241.