Development of spray atomization test system at elevated temperatures and back pressures

Hongyu Pan¹, Herui Zheng¹, Siyuan Wu², *, Cangsu Xu², Weinan Liu²
¹Changfa Agricultural Equipment Co., Ltd, Changzhou, 213000, China
²College of Energy Engineering, Zhejiang University, Hangzhou, 310027, China
*Corresponding author e-mail: 21760034@zju.edu.cn

Abstract. To simulate the authentic in-cylinder spray environment in the diesel engines, a spray atomization test system was developed. In this test platform, the pre-combustion of mixed gas was adopted to establish the elevated temperatures and back pressures, and the timing process among the ignition, injection, high-speed imaging and data acquisition was accurately controlled by a dedicated electronic control unit (ECU). The pre-combustion process was tested at different initial pressures and the spray pattern was studied. The experimental results showed that the maximum temperature and back pressure generated after the pre-combustion was proportional to the initial pressure, so different in-cylinder conditions could be simulated by adjusting initial conditions of the pre-combustion. The images and transient data of the spray process could be recorded completely and clearly, which laid a solid foundation for the measurement of macroscopic spray parameters.

1. Introduction
As a kind of internal combustion engine with high thermal efficiency, diesel engine is widely used in the fields of vehicle power, agricultural machinery and ship power [1]. However, it will emit more NOx and particulate pollutants during combustion, which is contrary to the enhancement of people's environmental awareness and the increasingly stringent emission regulations. Therefore, it becomes essential to optimize the combustion process and improve the emissions of the diesel engine.

In the combustion process of the diesel engine, the spray atomization of the fuel directly affects the formation quality of fuel-air mixtures, which in turn affects the combustion quality and ultimately affects the economy efficiency, power and emission behavior of the engine [2]. Based on the significance of fuel atomization, the related issues have always been the focus of research, mainly including the simulation study of spray atomization mechanism and the experimental study of macroscopic parameters such as the spray cone angle and the spray penetration distance.

For experimental studies, Balaji Mohan et al. [3] studied macroscopic injection characteristics such as the momentum flux and the spray penetration at the normal temperature and high pressure (6 MPa) in a constant volume combustion chamber (CVCC). Qiu et al. [4] and He et al. [5] studied the effect of back pressures and nozzle shapes on the internal flow and injection characteristics of the nozzle. Raul Payri et al. [6] examined the velocity field of diesel spray at high back pressures of 11-33 bar and a temperature of 500 K using particle image velocimetry (PIV). Feng et al. [7] studied the injection and atomization characteristics of a diesel-gasoline-ethanol mixture at back pressure of 20-40 bar in a high pressure common rail injection system. Hongming Xu’s team [8-10] studied the effects of injection
and ambient pressure on the spray behaviors at the initial stage of spray development by ultra-high-speed imaging.

For simulation studies, J. Shinjo and A. Umemura [11] investigated the atomization characteristics of diesel jet front tip at the ambient pressure of 3 MPa. B. Yin et al. [12] numerically studied the effect of the cavitation and high injection pressure on the diesel injection and atomization process at the ambient temperature of 293 K and back pressure of 5 MPa using the Large Eddy Simulation (LES) turbulence model. Yu et al. [13] proposed a new breakup model and simulated the atomization process at the same ambient temperature using KIVA-3V software. M. Ghijii et al. [14] studied the primary atomization at the early stage of diesel injection. Zhang et al. [15] studied the effect of droplet bouncing on simulating the impinging spray under a back pressure of 30 bar and a temperature of 298 K and proposed a simplified droplet collision model.

However, to the best of authors’ knowledge, most researches on spray atomization have focused on the spray at the normal temperature and pressure or just high back pressures, which is different from the actual conditions of spray generation in the diesel engines. Therefore, the spray atomization characteristics at elevated temperatures and back pressures must be studied.

2. Experimental setup
The experimental setup for measuring atomization characteristics at elevated temperatures and back pressures is shown in figure 1. It is mainly composed of a CVCC, a heating system, an ignition and fuel injection system, a synchronous control system, a transient high temperature and pressure measurement system and a high-speed photography system.

Figure 1. Spray atomization test system.

The CVCC is designed as the octagon pillar, and each side is machined with some mounting holes for installing the injector, temperature and pressure sensors, ignition electrodes and optical windows. The combustion chamber has a volume of 1.286 L with a designed pressure of 20 MPa.

Since it is difficult to achieve the conditions of simulating the in-cylinder spray environment by pressurizing and heating directly, the pre-combustion of mixed gas is adopted to establish an elevated temperature and back pressure in this study. The research reported by Xu et al. [16, 17] show that the pressure inside the CVCC will rises drastically to the maximum value and then drops gradually after pre-combustion, but during the spray process, the decrease in pressure is relatively low so that it can
be neglected. They also find that initial conditions (pressure, temperature and equivalence ratio) have a significant effect on the maximum pressure, so it is feasible to establish the elevated temperatures and back pressures required for spray atomization test by adjusting the initial conditions of the pre-combustion.

Based on the above arrangement, this test system can be used to study the spray atomization process of the electronically controlled injector under different injection pressures, injection durations, ambient temperatures and back pressures.

3. Working process of subsystems

3.1. Initial temperature control
In this study, the initial temperature of premixed gas is increased indirectly by heating the CVCC. Six heating resistors are installed evenly on each side of the CVCC, each of which has a power of 60W. The heating power can be adjusted by controlling the voltage and the K-type thermocouple is used to monitored the temperature inside the chamber. Compared with the heating mode in which the heating device is directly arranged in the chamber, the heating efficiency of this method is lower, but the occurrence of glow-ignition can be effectively avoided.

3.2. Timing control of ignition, injection and high-speed photography
The combustion process of premixed gas lasts only about 0.1 s, and the spray process is within 1ms. When the premixed gas is ignited, the temperature and pressure inside the CVCC should be recorded to control the injection timing. Therefore, the timing sequence between ignition, injection and data acquisition needs to be precisely controlled. The schematic diagram of the timing control system is shown in figure 2.

![Timing control system](image)

The timing control process is as follows: when the combustible gas in the CVCC is evaporated and uniformly mixed with the air for a period of time, press the start button and the dedicated electronic control unit (ECU) outputs three sequential driving signals, as shown in figure 3. $T_1$, $T_2$ and $T_4$ are the trigger signal of the digital delay pulse generator DG645 (SRS Company of USA), ignition control module and fuel injector, respectively. $T_3$ is the interval between the ignition and injection. At the falling edge of the trigger signal, DG645 will output two channel of synchronous control signals. One controls the high-speed CCD to record images with 250,000 fps at a fixed resolution (312×260), and the other controls the oscilloscope to collect the transient temperature and pressure inside the CVCC. The ignition control module also inputs an instantaneous high voltage to the center electrodes at the falling edge of the trigger signal, and a spark is generated in the electrode gap to ignite the combustible gas. When the temperature and pressure reach the test requirement after the interval $T_3$, the fuel injector is activated to generate the spray.
3.3. Measurement of transient high temperature and pressure

The collection of transient temperature and pressure data is mainly used as a reference for the determination and inspection of injection timing. The data acquisition process of the measurement system is showed in figure 4.

In this experiment, the piezoelectric sensor (Kistler 6115A) is adopted. Since the pressure sensor has a high output impedance, the charge amplifier (Kistler 5018A) is equipped to convert the output charge into voltage signals which can be recognized by the oscilloscope. To accurately measure the transient pressure, the measurement function of the charge amplifier needs to be turned off after the single spray test to reduce the error caused by the accumulation of charge.

The transient thermocouple used is an E12 type produced by Nanmac Company with a response time of less than 20 μs. It is also connected with an amplifier (INA 141U) and calibrated to obtain a fitting equation between the temperature and the output voltage. The ice-water mixture and boiling water are measured as standard temperature objects. Then the mercury thermometer and the thermocouple are placed simultaneously in the CVCC to measure the heated air to verify the accuracy of the temperature-voltage relationship. The calibration data is shown in table 1.

| Temperature (℃) | Output voltage (V) |
|-----------------|-------------------|
| 0               | -0.180            |
| 100             | 0.182             |
| 150             | 0.361             |
| 200             | 0.542             |

During the spray test, the temperature and pressure data are simultaneously recorded by the oscilloscope at a frequency of 125 kHz, and the noise filter is set to 75 MHz. All data can be transmitted to the computer via USB, but they need to be filtered in the data processing to eliminate oscillations caused by the channel effect of the sensors.

4. Experimental result

4.1. Pre-combustion test
The pre-combustion test is conducted at the initial temperature of 358K, initial pressure of 1-6 bar and the fuel is analytical anhydrous ethanol with a 99.7% purity. The equivalence ratio of 1.1 is selected to ensure that there is no oxygen left after the pre-combustion and the fuel injected will not be ignited. The synchronization among the ignition, high speed imaging and data acquisition is achieved successfully. The transient pressure curves are shown in figure 5.

![Figure 5. History of in-cylinder pressure in the pre-combustion process](image)

Figure 6 clearly illustrates the relationship between the maximum pressure and temperature and the initial pressure. Both of $P_{\text{max}}$ and $T_{\text{max}}$ get higher with the increase of the initial pressure $P_0$. It can be realized that there is a linear relationship between the $P_{\text{max}}$ and $P_0$, and the boost ratio is about 6, which can be used to calculate the initial pressure required to reach the conditions of the spray atomization test. The change in $T_{\text{max}}$ is not quite obvious. There is only a variation of 23 K from $P_0 = 1$ bar to $P_0 = 5$ bar and the temperature difference between the different initial pressures gradually shrinks with the increase of $P_0$, indicating that the ambient temperature can always reach a high level after the pre-combustion and the back pressure is the only factor to consider when selecting the initial conditions.

4.2. Spray atomization test

Based on the result of the pre-combustion test, the initial condition of $P_0 = 6$ bar, $T_0 = 358$ K and $\phi = 1.1$ is selected to generate the spray environment. The interval between the ignition and injection is set to 140 ms, the injection duration is 0.5 ms and the fuel injection pressure $P_{\text{in}}$ is 75 MPa. The images of the spray process are recorded completely, as shown in figure 7.

Referring to the figure, the changes in the macroscopic size and morphology of the spray at different time can be clearly observed. The diesel spray has a small cone angle and a long penetration at the above test condition. The droplets mainly concentrate in the central area of the spray field due to its high viscosity and surface tension. Based on these images, the spray characteristics can be further quantitatively analysed using an image processing program.
Figure 6. Relationship between (a) $P_{\text{max}}$ and $P_0$, (b) $T_{\text{max}}$ and $P_0$ at $T_0 = 358$ K and $\phi = 1.1$.

Figure 7. Spray process at $P_{\text{in}} = 75$ MPa.

5. Conclusion

A spray atomization test system was developed to study the spray atomization process at elevated ambient temperatures and back pressures. The pre-combustion of mixed gas was used to establish the required test conditions, and the initial conditions of pre-combustion can be adjusted to meet different experimental requirements. The timing process among the ignition, injection, high-speed imaging and data acquisition was accurately controlled by a dedicated electronic control unit (ECU). The pre-combustion and the spray atomization test are conducted to prove the reliability of this system. The transient temperature and pressure data inside the CVCC is recorded completely and the images of the spray process at the corresponding time are captured clearly, which lays a solid foundation for the measurement of macroscopic spray parameters.

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References

[1] L Peng. (2018) Study on spray characteristics coupled with internal nozzle flow in high pressure common rail injector. Beijing Jiaotong University.

[2] Z He, F Wang, J Liu, Z Jiang, Q Wang. (2014) Coupled simulation of the effect of diesel nozzle structure on spray characteristics. Journal of Mechanical Engineering, 50: 145-151.

[3] B Mohan, W Yang, K L Tay, et al. (2014) Macroscopic spray characterization under high ambient density conditions. Experimental Thermal and Fluid Science, 59: 109-117.

[4] T Qiu, X Song, Y Lei, et al. (2016) Effect of back pressure on nozzle inner flow in fuel injector, Fuel, 173: 79-89.

[5] Z He, G Guo, X Tao, et al. (2016) Study of the effect of nozzle hole shape on internal flow and spray characteristics. International Communications in Heat and Mass Transfer, 71: 1-8.
[6] R Payri, J P Viera, H Wang, et al. (2016) Velocity field analysis of the high density, high pressure diesel spray. International Journal of Multiphase Flow, 80: 69-78.

[7] Z Feng, C Zhan, C Tang, et al. (2016) Experimental investigation on spray and atomization characteristics of diesel/gasoline/ethanol blends in high pressure common rail injection system. Energy, 112: 549-561.

[8] Y Li, H Xu. (2016) Experimental study of temporal evolution of initial stage diesel spray under varied conditions. Fuel, 171: 44-53.

[9] H Ding, Z Wang, Y Li, et al. (2016) Initial dynamic development of fuel spray analyzed by ultra-high speed imaging. Fuel, 169: 99-110.

[10] Y Li, H Guo, X Ma, et al. (2016) Droplet dynamics of DI spray from sub-atmospheric to elevated ambient pressure. Fuel, 179: 25-35.

[11] J Shinjo, A Umemura. (2011) Detailed simulation of primary atomization mechanisms in Diesel jet sprays (isolated identification of liquid jet tip effects). Proceedings of the Combustion Institute, 33: 2089-2097.

[12] B Yin, S Yu, H Jia, et al. (2016) Numerical research of diesel spray and atomization coupled cavitation by Large Eddy Simulation (LES) under high injection pressure. International Journal of Heat and Fluid Flow, 59: 1-9.

[13] Y Yu, G Li, Y Wang, et al. (2016) Modeling the atomization of high-pressure fuel spray by using a new breakup model. Applied Mathematical Modelling, 40: 268-283.

[14] M Ghiji, L Goldsworthy, P A Brandner, et al. (2016) Numerical and experimental investigation of early stage diesel sprays. Fuel, 175: 274-286.

[15] Z Zhang, Y Chi, L Shang, et al. (2016) On the role of droplet bouncing in modeling impinging sprays under elevated pressures. International Journal of Heat and Mass Transfer, 102: 657-668.

[16] C Xu, K Zhou, X Li, A Zhong, et al. (2018) Laminar Burning Characteristics of Two Rice-Husk-Derived Biofuels. Energy & Fuels, 32: 9872-9882.

[17] C Xu, A Zhong, X Li, et al. (2017) Laminar burning characteristics of upgraded biomass pyrolysis fuel derived from rice husk at elevated pressures and temperatures. Fuel, 210: 249-261.