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Experimental study of injector spray inconsistency based on a combined spray momentum and visualisat

Fuel Injection & Gas Admission and Engine Components

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ABSTRACT

Aiming at the inconsistency phenomenon of high-pressure common rail injector spraying, the experimental study on the liquid fuel injection/spraying characteristics of each injection hole of the injector is carried out in this paper by combining spraying momentum and spraying visualization. The influence of injection pressure and injection pulse width on the variability of liquid fuel injection/spray characteristics of each nozzle is analyzed, and at the same time, the mechanism of the variability of liquid fuel injection/spray of each nozzle is investigated based on the established simulation model. The results show that at small injection pressure and small injection pulse width, the inconsistency of injector spray is larger. With the increase of injection pressure, the liquid fuel injection/spray inconsistency of each hole decreases, and the effect of injection pressure on the inconsistency reduction becomes weaker at larger injection pressures. The effect of the injection pulse width on the liquid fuel injection/spray inconsistency of each hole is the same as that of the injection pressure. There exists a threshold value of injection pressure and injection pulse width above which the injector achieves smaller satisfactory injection inconsistency. The simulation points out that increasing the injection pressure or increasing the injection pulse width causes the needle valve to reach its maximum lift, which is the main reason for the reduced injection inconsistency across the injector holes.

1 INTRODUCTION

Diesel engines are widely used in agriculture, transportation, construction, aerospace and other industries due to their high thermal efficiency, good economy and wide power range. However, with the continuous consumption of fossil resources and environmental pollution, countries around the world have put forward increasingly higher requirements for the economy and emissions of diesel engines [1]. As an advanced fuel injection system, the high-pressure common rail system (HPCRS) has been widely applied in diesel engines because of its high injection pressure, flexible injection and multiple injection. As an important core component of HPCRS, the fuel injection characteristics of the fuel jet from the injector directly affect the mixture characteristics of diesel and air. In particular, the fuel injection consistency of the nozzle holes will directly affect the fuel injection quantity of each injection and the distribution of the fuel spray in the cylinder, thereby having an important impact on the combustion process in the cylinder of the diesel engine [2]. Therefore, the research on the fuel injection consistency of the injector is of great significance for the optimization of the power performance and emission performance of the diesel engine.

Scholars have carried out a large amount of research work on the collection of fuel injection rates of each nozzle of the injector and the analysis of consistency, and have achieved abundant research results. Payri et al. [3-5] proposed a method for measuring the mass flow rate of fuel injection from each injection hole based on the spray momentum method, and investigated the differences in the mass flow rates of each injection hole of the multi-hole injector. The results demonstrated that the momentum method is an effective way to study the differences among the injection holes of the multi-hole injector. Postrioti et al. [6] employed two methods, namely Zeuch and Bosch, to measure the fuel injection rate and compared the accuracy of the results. The results indicated that the start of injection measured by the Bosch method was delayed by 50-70 μs compared with that measured by the Zeuch method. Zhou et al. [7] obtained the variation of the flow coefficient of each injection hole by measuring the spray momentum and fuel injection pressure of each injection hole, and discovered that the variations of the flow coefficients among each injection hole were not the same under the same working conditions, and as the camshaft speed increased, the fluctuation of the flow coefficient at the maximum needle lift position tended to stabilize. Sangiah et al. [8] measured the spray momentum of two different injection holes based on the momentum method measurement device, and found that there were differences in the spray momentum among different injection holes, and the change of fuel injection pressure had a certain impact on the spray momentum of each injection hole. Luo et al. [9, 10] studied the influence of injection pressure and injection pulse width on the fuel injection consistency of the injector based on the spray momentum method. The research found that as the injection pressure and injection pulse width increased, both the fluctuation coefficient of the fuel injection quantity of the common rail injector and the difference coefficient among different injection holes decreased.

From the above-mentioned literature, it is observable that scholars have carried out research on the measurement approaches of injection rate and the non-uniformity of fuel injection from each injection hole, attaining the influencing factors and patterns of the inconsistent injection rates from each injection hole and achieving certain research outcomes. Nevertheless, there are scarce studies on the non-uniformity of fuel injection from each injection hole from the perspective of spray visualization, making it impossible to disclose the development and change process of fuel spray within the cylinder and the non-uniformity of its spatial and temporal distribution. There is also a deficiency in the systematic evaluation of the non-uniformity from injection rate to spray characteristics. Hence, in this paper, a method combining spray momentum and spray visualization is adopted to conduct experimental measurement studies of the injection rate/spray characteristics from each injection hole under different injection conditions. The variation patterns of the injection quantity fluctuation rate and the macro/micro parameters of the spray under different injection pressures and injection pulse widths are analyzed. The influence mechanism of injection parameters on the non-uniformity of fuel injection is revealed, and the operating condition combination area with lower fuel injection non-uniformity is obtained. Guiding suggestions are provided for the optimized design and reasonable operating conditions of the high-pressure common rail fuel injection system of diesel engines.

2 EXPERIMENTAL TECHNOLOGY AND METHODS

2.1 Fuel injection measurement experiment based on momentum method

Traditional commercial fuel injection rate measurement devices, such as the EFS8246 single injection fuel measurement instrument produced by the French EFS company, can only measure the overall fuel injection rate of the injector's injection hole, but cannot independently measure the fuel injection rate of each injection hole of the injector. The momentum method, as a non-intrusive measurement method, can measure the fuel injection rate of each injection hole in a multi-hole injector without any modification to the injector, and is applicable to injectors of different models and designs, providing an effective experimental means for the study of the fuel injection characteristics of each injection hole of the injector.

As shown in Figure 1, the schematic diagram of the measurement principle of the spray momentum method is presented. Once the fuel spray is ejected from the injection hole, it strikes the surface of the force sensor. The model of the force sensor is KISTLER 9217A, with a linear error of ±1% FS. In accordance with the momentum theorem, the momentum of the fuel spray is equivalent to the spray impact force *F* measured by the force sensor, which is:

$$F = m \cdot u \tag{1}$$

In the equation, *m* represents the transient mass flow rate of the fuel at the injection hole outlet of the injector, and *u* represents the fuel spray velocity.

According to the law of conservation of mass, the transient mass flow rate *m* of fuel at the injection hole exit is defined as:

$$m = \rho \cdot u \cdot A \tag{2}$$

In the equation, ρ represents the fuel density, and *A* is the flow area of the injection hole. Combining equations 1 and 2, the calculation formula for obtaining the mass flow rate of the spray based on the spray momentum is derived as:

$$m = \sqrt{\rho \cdot A \cdot F} \tag{3}$$

The fuel circulation injection quantity *Q* can be obtained by integrating the fuel mass flow rate curve.

$$Q = \int_0^t m \cdot dt = \int_0^t \sqrt{\rho \cdot A \cdot F} \times dt \tag{4}$$

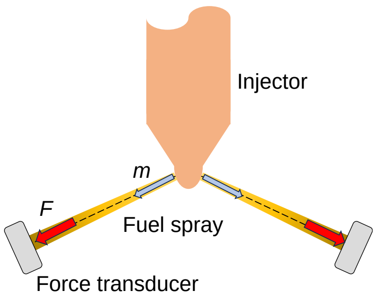


Figure 1 Schematic diagram of the measurement principle of the spray momentum method

Figure 2 depicts the experimental apparatus for the fuel injection characteristics of each injection hole established based on the momentum method, mainly comprising the measurement system, the air-bleed system, and the signal acquisition and processing system. The measurement system mainly consists of a constant volume device, a base, a rotating force arm, and a piezoelectric force sensor. The injector is inserted at the top of the constant volume device for injection measurement. Herein, the injector selected for this study is the BOSCH-CRIN2 injector. To investigate the injection inconsistency of each injection hole, the injection hole section of the injector was redesigned and processed to have four injection holes with the same aperture, each with a diameter of 0.3 mm, and all injection holes are uniformly distributed circumferentially on the same horizontal plane. The HPCRS realizes fuel supply, and the ECU synchronously controls the electrical parameters of the injector and the rail pressure. The electrical signal of the injection law measured by the force sensor will be collected in real time by the signal acquisition and processing system and transformed into visual data information. The air-bleed system is to ensure that the oil mist inside the constant volume device is promptly extracted to prevent environmental pollution and interference with the experimental results. The specific experimental conditions are presented in Table 1. Under each test condition, 50 repeated measurement experiments are carried out, and the final arithmetic average is obtained as the final result to reduce the influence of errors in the measurement process.

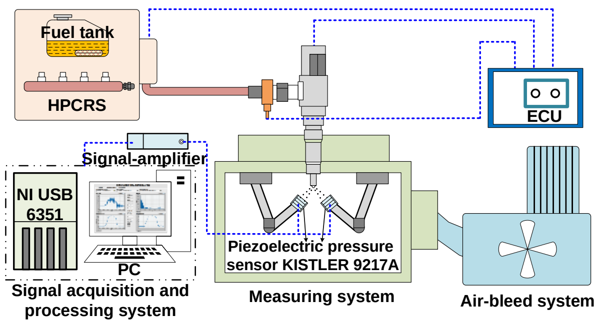


Figure 2 Experimental apparatus for the Injection characteristics of each Injection hole

Table 1. Experimental conditions for measuring Injection characteristics based on the momentum method

Parameter	Numerical value
Fuel injection frequency (Hz)	2
Environmental temperature (K)	293
Environmental pressure (bar)	1
Fuel injection pressure (MPa)	60-180

Fuel injection pulse width (ms)	0.4-1.2

For multi-hole injectors, due to the fluctuation of fuel pressure induced by injection, coupled with the influence of unstable actions of the internal needle in the injector, intensify the non-uniformity of the fuel flow within the injection hole. Furthermore, due to the constraints of the injection hole processing technology and the presence of processing errors, the internal geometries of each hole in the multi-hole injectors are not entirely consistent. Collectively, this leads to significant fuel injection non-uniformity among the holes of the injector, which in turn has adverse impacts on the subsequent combustion process. To assess the fuel injection non-uniformity among the holes, the fuel injection quantity fluctuation rate γ_m is defined as:

$$\gamma_m = \frac{\sum_{i=1}^{n}\left|\frac{Q_i - Q_a}{Q_a}\times 100\%\right|}{n} \tag{5}$$

In the equation, Q_i denotes the cyclic fuel injection amount of the i-th hole, Q_a represents the average value of the cyclic fuel injection amounts of multiple holes, and n indicates the number of holes.

2.2 Fuel spray measurement experiment based on visualization method

The macroscopic and microscopic characteristics of the in-cylinder spray of the engine are highly crucial for the engine's power performance and emission performance. To further disclose the inconsistent spatio-temporal distribution of the fuel spray after atomization within the cylinder and the development and variation process of the inconsistent spray from each hole, in this paper, the Mie scattering visualization technique is employed to realize the shooting of the spray development process of each hole of the injector.

Figure 3 presents the multi-hole spray visualization experimental apparatus based on the Mie scattering method, mainly consisting of a 20L constant volume device, the Mie scattering optical path system, the intake and exhaust systems, the common rail test bench, etc. The model of the high-speed camera utilized in the experiment is Phantom v2012, produced by VRI in the United States, with a resolution of 512×512 pixels and a maximum shooting rate of up to 1 million FPS/s. Before each measurement, the gas in the CVC is discharged through the exhaust valve, and then the ambient pressure is maintained at the set value by filling nitrogen into the intake valve. Table 2 provides the detailed visualization experimental conditions.

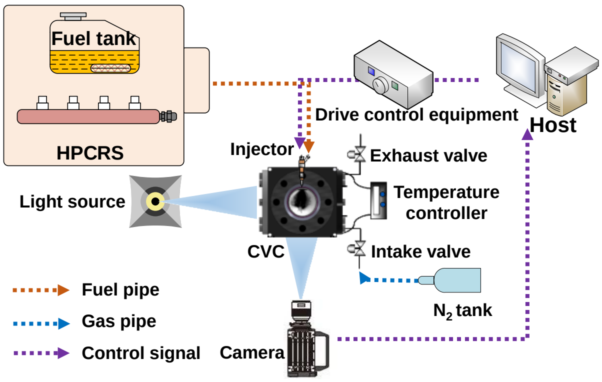


Figure 3. Visualization experimental setup for multi-hole spray

Table 2. Experimental Conditions for Spray Visualization

Experimental parameter	Numerical value
Environmental density (kg/m^3)	15
Environmental temperature (K)	293
Environmental pressure (bar)	1
Fuel injection pulse width (ms)	1.2
Fuel injection pressure (MPa)	60-180

After obtaining the spray images via a high-speed camera, initially, the background subtraction method is adopted to eliminate irrelevant regions and influencing factors such as the window boundary and spark plug. Subsequently, the morphological approach is utilized to remove the concave portions of the spray boundary through dilation and erosion. Again, image noise reduction processing is conducted to eliminate the isolated noise that does not belong to the spray, obtaining the entire multi-hole spray. Eventually, edge detection is employed to obtain the spray contour, and the multi-hole spray is zoned to accurately measure the penetration and spray cone angle of each hole spray. In this research, the spray penetration is defined as the distance from the hole position to the farthest position of the spray tip. To measure the spray cone angle more precisely, the spray is divided into left and right parts along the hole axis direction. By calculating and averaging the angle between each spray edge point and the hole axis within the range from the hole to 1/2 of the penetration, the average left half cone angle and the average right half cone angle of the spray are obtained. The spray cone angle is defined as the sum of the average of the left half cone angle and the average of the right half cone angle of the spray. Additionally, in this paper, the microscopic parameter spray equivalence ratio is introduced to further assess the non-uniformity of each hole spray. The spray equivalence ratio φ is defined as follows [11]:

$$\varphi = \frac{\xi}{m_{\text{air}} / m_{\text{fuel}}} \tag{6}$$

In the equation, ξ represents the theoretical air-fuel ratio of diesel, with a magnitude of 14.3, m_{fuel} denotes the mass of diesel ejected by the injector, m_{air} represents the mass of entrained gas, and the definition of the boundary gas entrainment mass is as follows:

$$m_{\text{air}} = \left(\frac{V_{\text{A}}}{\left(\sin\frac{\alpha}{2} \right)^3} - V_{\text{fuel}} \right) \rho_{\text{air}} \tag{7}$$

In the equation, V_{fuel} is the volume of diesel fuel ejected through the common rail injector, ρ_{air} is the density of the background gas, V_{A} is the projected spray volume, and α is the cone angle of injection hole.

To explore the non-uniformity of microscopic characteristics of spray under diverse working conditions, the difference coefficient of spray equivalence ratio of multi-hole injectors is defined as follows:

$$\hat{\sigma}_{\varphi} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\varphi_i - \bar{\varphi})^2}}{\bar{\varphi}} \cdot 100\% \tag{8}$$

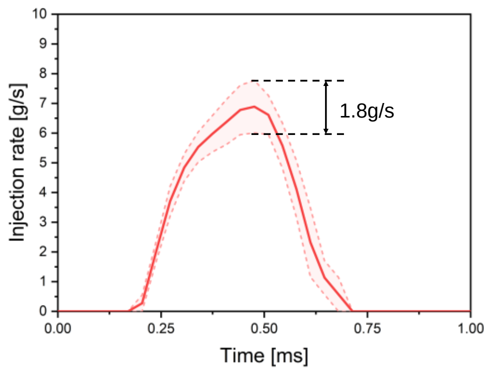
In the equation, φ_i represents the spray equivalence ratio of the i-th hole, and $\bar{\varphi}$ is the average value of the spray equivalence ratios of the four holes.

3 RESULTS AND DISCUSSION

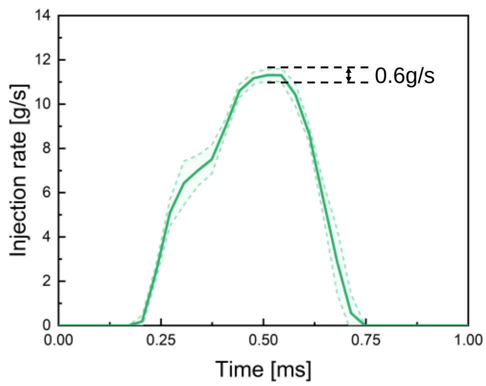
3.1 Inconsistency of injection rate of each injection hole

3.1.1 The influence of fuel injection pressure

An experimental apparatus established based on the momentum method was utilized. The fuel mass flow rate of each injection hole of the injector was separately measured under different fuel injection pressures. Fifty replicate experiments were conducted for each working condition, and the arithmetic average was taken as the mass flow rate of each injection hole. Subsequently, the average absolute error of the fuel injection rate of each injection hole was derived. Figure 4 presents the average fuel injection rate of each injection hole and the error band resulting from the fuel injection inconsistency among the injection holes under different fuel injection pressures. At a fuel injection pressure of 90 MPa, the disparity in the peak fuel injection rate reached 1.8 g/s, while at 180 MPa, the peak fuel injection rate decreased to 0.6 g/s. From the overall fuel injection rate curve, the inconsistency of the fuel injection rate among the injection holes also decreased. This indicates that an increase in the fuel injection pressure can effectively reduce the fuel injection inconsistency among the injection holes. The possible reason for the aforementioned phenomenon lies in that when the fuel injection pressure is relatively low, the needle opens at a slower pace and begins to descend before reaching the maximum lift position. Throughout the movement of the needle, the fuel flow area between the needle and the needle seat frequently varies due to the unstable movement of the needle, leading to poor fuel injection consistency among the injection holes. When the fuel injection pressure is high, the needle opens more rapidly, enabling it to reach the maximum lift position more quickly, thereby reducing the time during which the fuel injection process is influenced by the unstable movement of the needle and enhancing the fuel injection consistency among the injection holes.



(a)Fuel injection pressure 90 MPa



(b)Fuel injection pressure 180 MPa

Figure 4. Effects of different injection pressures on fuel injection from each injection hole (Injection pulse width: 0.4 ms)

Based on the definition in Equation 5, Figure 5 presents the variation of the fuel injection quantity fluctuation rate γ_m with the increase in injection pressure. Under a fixed injection pulse width of 0.4 ms, the γ_m of the injector exhibits a downward trend as the injection pressure rises. The γ_m at an injection pressure of 60 MPa is 13.9%, while it reduces to 2% at 180 MPa, a decrease of 11.9%. This indicates a reduction in the inconsistency of the fuel injection quantity from each injection hole of the injector obtained through time integration. Furthermore, as the injection pressure gradually increases, the overall decreasing trend of the fuel injection quantity fluctuation rate gradually slows. This suggests that when the injection pressure is relatively high, further increasing the injection pressure has a diminishing effect on reducing fuel injection inconsistency. The reason for this may be that as injection pressure increases, the improvement in needle response speed becomes less significant, and the impact duration of needle movement on the fuel injection process across each hole gradually converges. Even at higher injection pressures, there remains a certain γ_m within the injector. The variation in fuel injection quantity can primarily be attributed to differences in the geometric structure parameters among the holes. As shown in Figure 5, under a fixed injection pulse width of 1.2 ms, the γ_m of the injector decreases overall. The most substantial decrease occurs at an injection pressure of 60 MPa, which is 10.3% lower compared to the scenario with a fixed injection pulse width of 0.4 ms. This indicates a significant improvement in the fuel injection consistency across all holes.

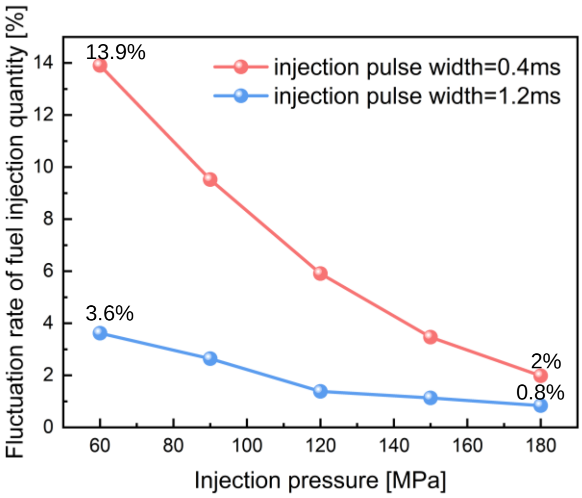
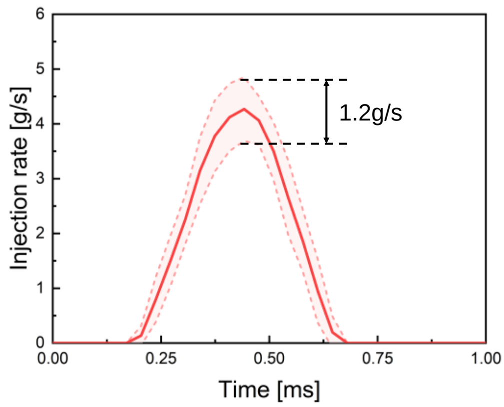


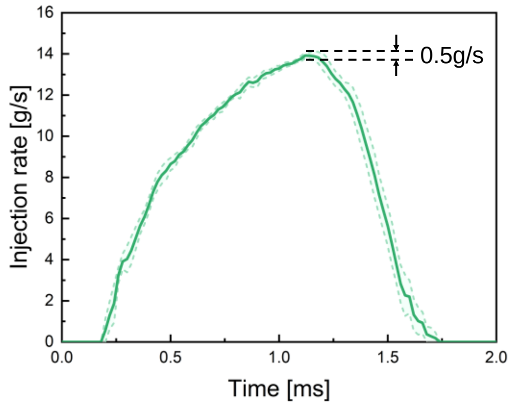
Figure 5. The influence of injection pressure on the inconsistency of fuel injection from the Injector

3.1.2 The influence of fuel injection pulse width

Besides the remarkable influence of injection pressure on the inconsistency of injection rates at each injection hole, we have discovered from the aforesaid experimental results that an increase in injection pulse width might have a beneficial role in reducing the injection inconsistency at each injection hole. Different injection pulse widths seemingly have a significant effect on the injection inconsistency. Figure 6 illustrates the average injection rates at each injection hole along with the error bands resulting from injection inconsistency across various injection pulse widths. At an injection pulse width of 0.4 ms, the peak injection rate disparity is 1.2 g/s. This disparity decreases to 0.5 g/s when the injection pulse width increases to 1.2 ms, representing a reduction of 58.3%. With shorter injection pulse widths, the needle lacks sufficient time to reach its maximum lift position, remaining in a partially open state and leading to significant variability in injection rates among the holes. As the injection pulse width increases, the energization time for the injector solenoid valve also increases, allowing the needle ample time to achieve full lift. This ensures complete opening of the needle, stabilizing its movement and thereby reducing injection inconsistency across the holes.



(a) Fuel injection pulse width 0.4 ms



(b) Fuel injection pulse width 1.2 ms

Figure 6 Effects of different injection pulse widths on fuel injection from each injection hole (Injection pressure: 60 MPa)

Figure 7 depicts the changing situation of fuel injection quantity fluctuation rate γ_m as the fuel injection pulse width increases. Under a fixed fuel injection pressure of 60 MPa, the γ_m of the injector shows a downward trend with the increase of the fuel injection pulse width, which indicates that the increase of the fuel injection pulse width can effectively reduce the fuel injection inconsistency among the injection holes of the injector. Similar to the influence of the fuel injection pressure, the overall trend of γ_m with the increase of the fuel injection pulse width also presents a "sharp decline followed by a gradual one", suggesting that when the fuel injection pulse width increases to a certain extent, the needle has reached its maximum lift position, and the fuel injection pulse width no longer affects the response speed of the needle. Continuing to increase the fuel injection pulse width will not further enhance the fuel injection consistency among the injection holes. Under a fixed fuel injection pressure of 180 MPa, the γ_m of the injector is at a relatively low level, and the injector exhibits good fuel injection consistency. It can thus be inferred that when the fuel injection pressure or pulse width is small, the injector has significant fuel injection inconsistency. Only within the appropriate range of fuel injection pressure and pulse width can a lower fuel injection inconsistency be obtained, thereby improving the performance of the engine.

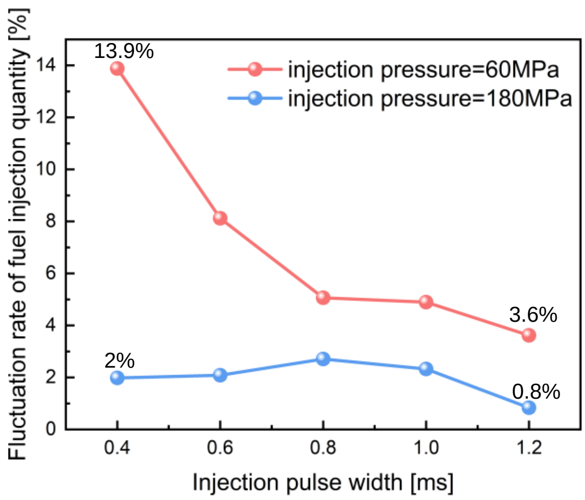


Figure 7 The Influence of injection pulse width on the inconsistency of fuel injection from the Injector

3.2 Inconsistency of spray characteristics of each injection hole

In previous research, scholars tended to study the fuel injection inconsistency of injectors from perspectives such as injection rate and fuel injection quantity. Nevertheless, the atomization development process of fuel after ejection from the injection holes is of great significance, as it directly affects the in-cylinder combustion process of the engine and influences the engine's economy, power performance and emission characteristics. Hence, based on the multi-hole spray visualization experimental setup proposed in this paper, the fuel injection inconsistency of multi-hole injectors is further comprehensively evaluated from the inconsistency of the development and change process of each injection hole's spray. Figure 8 depicts the multi-hole spray images under different injection pressures. It can be observed from the macroscopic development characteristics of the spray that with the increase of injection pressure and injection time, the disparity in the penetration of each injection hole spray gradually reduces, and the consistency of the macroscopic features of the spray is enhanced.

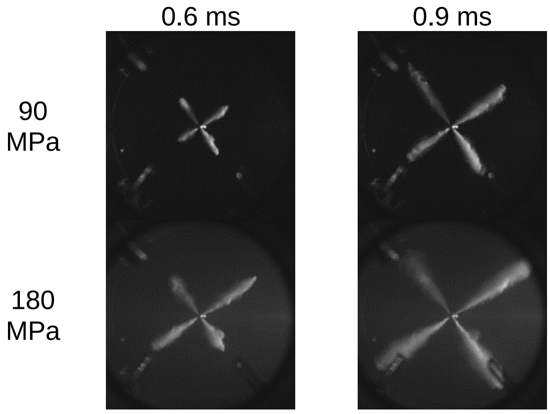


Figure 8 Images of the spray development over time at different injection pressures

3.2.1 The influence of injection pressure on macroscopic spray parameters

To facilitate clear presentation and analysis, we carried out the same data calculation operations for the macroscopic/microscopic parameters of the spray as those for the injection rate. Figure 9 presents the average variation trend of the spray cone angle of each injection hole under different injection pressures and the error bands of the spray cone angle of each injection hole. At an injection pressure of 60 MPa, after the fuel is ejected from the injection hole, the spray cone angle initially enters a rapid increase phase. During this stage, the maximum error of the spray cone angle of each injection hole is 8°, and then it enters a stabilization phase until fuel injection ceases. The maximum error of the spray cone angle of each injection hole in the maintenance stage is 4.8°. When the injection pressure increases to 150 MPa, the increase in pressure shortens the rapid increase phase of the fuel spray cone angle. During this stage, the maximum error of the spray cone angle of each injection hole is 8.6°. At this stage, the needle is in the ascending process, and the fuel injection process of each injection hole is influenced by the unstable movement of the needle. The maximum error of the spray cone angle of each injection hole is similar to that at an injection pressure of 60 MPa. In the stabilization phase, due to the higher injection pressure, the needle is more prone to reaching the maximum lift position, reducing the maximum error of the spray cone angle of each injection hole in the subsequent stabilization phase to 3.2°, a year-on-year decrease of 33.3%, and the inconsistency of the spray cone angle of each injection hole of the injector is reduced.

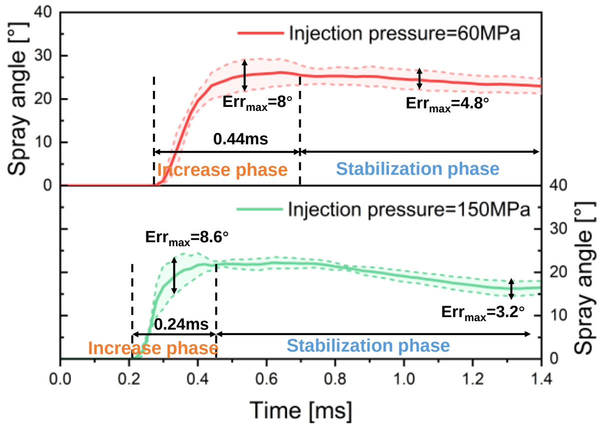


Figure 9 The influence of different injection pressures on the spray cone angles of each injection hole

Figure 10 depicts the average variation tendency of the spray penetration of each injection hole under different injection pressures and the error band of the spray penetration of each injection hole. At an injection pressure of 60 MPa, the needle remains incompletely open due to the relatively low injection pressure. The unstable movement of the needle and the pressure oscillation induced by fuel injection are superimposed, thereby exacerbating the differences in fuel injection among the injection holes. Simultaneously, the momentum exchange occurs between the spray and the ambient air, and the rate differences at the spray tips of each injection hole gradually accumulate, leading to considerable variations in the spray penetrations of the injection holes, with the maximum error reaching 7.5 mm. When the injection pressure increases to 150 MPa, with the rapid opening of the needle, the duration during which the injection process of each injection holes influenced by the needle movement is shortened. The maximum error of the spray penetration reduces to 4.8 mm, which decreased by 36%. The consistency of the spray penetration of the injection holes is enhanced. In addition, as the injection pressure increases to 150MPa, the spray can be observed about 0.05ms earlier, because the injection pressure increase reduces the opening time of the needle.

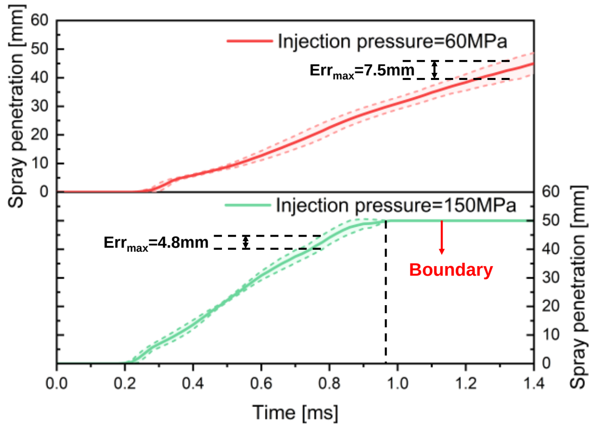


Figure 10 The influence of different injection pressures on the spray penetration of each injection hole

3.2.2 The influence of injection pressure on the microscopic parameters of spray

Both the macroscopic and microscopic features of the spray are highly significant for the combustion process of the engine. The macroscopic characteristics of the spray are only part of the evaluation of the inconsistency of spray development across the spray holes. Exploring the non-uniformity of the microscopic characteristics of the spray from each injection hole of the injector enables a more comprehensive assessment of the non-uniformity in the development of the spray from each injection hole.

Figure 11 presents the average variation trend of the equivalence ratio of the spray from each injection hole under different injection pressures and the error band of the equivalence ratio of the spray from each injection hole. As can be observed from the figure, the equivalence ratio is relatively high in the initial stage of spray development. With the increase in injection time, the entrainment of air by the fuel spray intensifies, augmenting the air content in the spray. The increase in the mass of entrained air results in a reduction in the equivalence ratio. Under an injection pressure of 60 MPa, the maximum discrepancy in the equivalence ratio of the spray from each injection hole is 33, while under an injection pressure of 150 MPa, it is 13, representing a decrease of 60.6%. From the overall analysis and comparison of the injection pressures of 60 MPa and 150 MPa, when the injection pressure increases to 150MPa, the dynamic response of the needle is accelerated, and the spray speed from the outlet of the injection hole is also increased. The air enrolling capacity of the spray is stronger than that under 60MPa. The inconsistency of the spray equivalent ratio of each injection hole decreases significantly with the increase of the injection pressure.

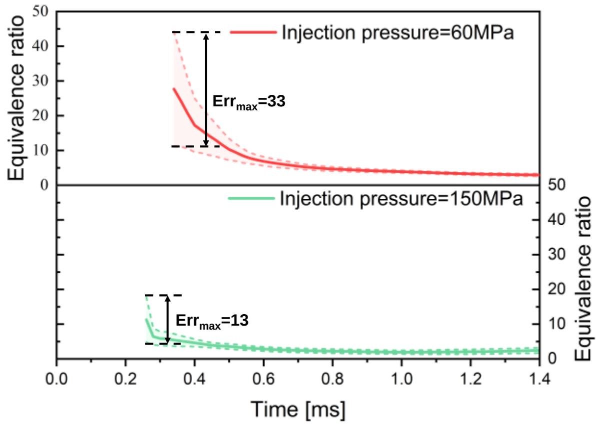


Figure 11 The influence of injection pressure on the spray equivalence ratio of each injection hole

Figure 12 presents the variation relationship of the difference coefficient $\hat{\sigma}_{\varphi}$ of the spray equivalence ratio of each injection hole with the injection time under different injection pressures. Under the same injection time, the increase in injection pressure accelerates the opening speed of the needle, reduces the duration during which the injection process of each injection hole is influenced by the needle action, and leads to a gradual decrease in the $\hat{\sigma}_{\varphi}$ of each injection hole, thereby reducing the injection non-uniformity. When the injection time is relatively large, the $\hat{\sigma}_{\varphi}$ of each injection hole still exhibits a gradually decreasing trend, but the difference in their values becomes insignificant. Under the same injection pressure, as the injection time increases, the $\hat{\sigma}_{\varphi}$ of each injection hole also gradually decreases and tends to stabilize. Moreover, the higher the injection pressure, the smaller the final stabilized value of the $\hat{\sigma}_{\varphi}$ of each injection hole.

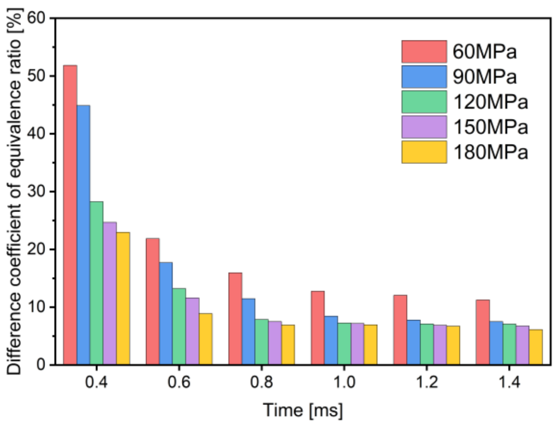


Figure 12 The influence of different injection pressures on the coefficient of variation of spray equivalence ratios at each injection hole

3.3 Analysis of the operational conditions affecting fuel injection consistency

The foregoing research demonstrates that increasing the injection pressure and injection pulse width can mitigate the inconsistencies in the injection rate, injection quantity among each injection hole, as well as the development process of the spray from each injection hole, thereby improving the injection consistency among each injection hole. The primary reason lies in that under higher injection pressure and injection pulse width, the needle can reach the maximum lift position rapidly and easily, thereby reducing the impact of unstable needle movements on the injection process of each injection hole. Consequently, the inability of the needle to reach the maximum lift is the main cause of the injection inconsistency among each injection hole of the injector, while the injection pressure and injection pulse width are the principal factors influencing the injection inconsistency among each injection hole.

In our previous work, we have modeled the common rail injector presented in this paper and accomplished the model verification using experimental data [12]. Based on the established simulation model, the minimum pulse width T_{min} for the needle to reach the maximum lift under different injection pressures is obtained as shown in Figure 13. With the increase of injection pressure, the response speed of the needle accelerates, and the needle can reach the maximum lift within a shorter period. At an injection pressure of 60 MPa, an injection pulse width of 1.4 ms is necessary for the needle to reach the maximum lift, while at 180 MPa, only a pulse width of 0.65 ms is needed for the needle to reach the maximum lift, with a reduction of 53.6%. The entire curve exhibits a trend of "sharp at the beginning and then gradual moderation", indicating that when the injection pressure is relatively high, the effect of further increasing the injection pressure on enhancing the response speed of the needle decreases. This is consistent with the theoretical analysis results derived from Figure 5.

As depicted in Figure 13, the region A above the curve implies that under the injection pressure and injection pulse width within this region, the needle valve has a high opening speed and can reach the maximum lift. Conversely, the region B beneath the curve indicates that under the injection pressure and injection pulse width within this area, the needle fails to reach the maximum lift. Hence, when the combination parameters of the injection pressure and injection pulse width are in region B, it will result in more pronounced inconsistency in fuel injection from each injection hole of the injector. When they are in region A, it can effectively mitigate the inconsistency in fuel injection from each injection hole of the injector and enhance the overall performance of the engine.

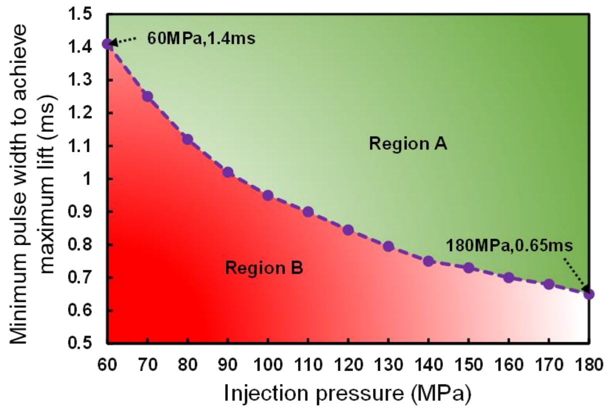


Figure 13 Minimum pulse width for the needle to reach the maximum lift under different injection pressures

4 CONCLUSIONS

To conduct a multi-dimensional and comprehensive assessment of the fuel injection inconsistency among the multiple holes of multi-hole injectors and explore the main influencing mechanisms of such inconsistency, this paper has established an experimental setup for the fuel injection characteristics of each hole and a multi-hole spray visualization experimental apparatus. Experimental investigations on the fuel injection rate/spray characteristics of each hole were carried out under varying injection pressures and injection pulse widths. The main research findings are as follows:

(1) When the injection pulse width is fixed, the fuel injection quantity fluctuation rate γ_m of each injection hole of the injector decreases as the injection pressure increases. At a fixed injection pulse width of 0.4 ms, when the injection pressure rises from 60 MPa to 180 MPa, γ_m decreases by 11.9%. The inconsistency of fuel injection from each injection hole reduces as the injection pressure increases. With a further increase in the injection pressure, the overall decreasing trend of γ_m gradually slows down.

(2) When the injection pressure is fixed, the γ_m of the injector exhibits a downward trend as the injection pulse width increases. At an injection pressure of 60 MPa, when the injection pulse width increases from 0.4 ms to 1.2 ms, γ_m decreases by 10.3%. Continuing to increase the injection pulse width has a weaker influence on reducing the inconsistency of fuel injection from each injection hole.

(3) The inconsistency of the spray characteristics of each injection hole gradually reduces with the increase in injection pressure. The maximum differences in spray cone angle, spray penetration, and spray equivalence ratio decrease by 33.3%, 36%, and 60.6%, respectively. The difference coefficient $\hat{\sigma}_\varphi$ of the spray equivalence ratio of each injection hole gradually decreases and tends to stabilize with the increase in injection pressure and injection time. During the stable stage, $\hat{\sigma}_\varphi$ of each injection hole gradually decreases with the increase in injection pressure.

(4) The main cause of the high inconsistency of fuel injection from each injection hole under low injection pressure or short injection pulse width is that the needle fails to open completely. It is advisable to increase the injection pressure or injection pulse width as much as possible and arrange the combination of injection pressure and injection pulse width in region A as much as possible, enabling the needle to open fully and rapidly, so as to improve the inconsistency of fuel injection.

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