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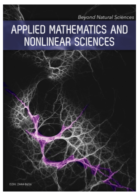


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# Modelling and Simulation Analysis of High-Pressure Common Rail and Electronic Controlled Injection System for Diesel Engine

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**Abstract**

The electronically controlled fuel injection system of the diesel engine has multi-disciplinary characteristics and strong coupling. The programming method based on a mathematical model cannot be applied to the fuel system with a diversified structure arrangement. With the rapid development of hydrodynamics, more and more simulation software is applied in the actual research. Hydsim simulation platform is one of the best software for the simulation of the electronic control injection system. In this paper, the Hydsim simulation platform is used to simulate the electronic control injection system, and a test-bed for verification is built. Based on the experimental results, the injection characteristics of high-pressure common rail are studied. The validity and accuracy of the simulation model are verified by comparing the simulation value with the test value and the standard value. Finally, the influence of the structural parameters such as the inlet and outlet orifices and control pistons of the injection system on the injection characteristics is analysed, and the selection principle of each parameter in the system design is proposed, which provides a reliable basis for the structural optimisation.

**Keywords:** electronic control injection system; diesel engine; high-pressure common rail; injection characteristics; structural parameter; modelling and simulation
**AMS 2010 codes:** F18838

## 1 Introduction

The Italian Company, Fiat, developed the ‘Unijet’ system. The high-pressure pump in the system has its pressure regulator, which enables the system to better control the injection pressure in the pre-injection stage, thus reducing the emissions of nitrogen oxides and carbon dioxide [1]. Besides, the system can adjust the injection timing and injection pressure flexibly, which further reduces the combustion noise and soot emissions. The Common Rail (CR) system was developed by Bosch, a German company. The system is equipped with a new type of injector with a pressure conversion device, which accelerates the injection response speed of the system and improves the injection effect [2]. Besides, the system has good adaptability in practical application and can match with different types of diesel engines. It is one of the most widely used high-pressure common

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rail fuel injection systems at present. ECD-U2 system has been developed by an electric equipment company in Japan. The system has a throttle hole and piston control that can obtain the ideal injection rate. Besides, by adjusting the solenoid valve, the system can achieve multiple injections, further improve the stability of the diesel engine, and reduce the noise of the diesel engine and the emission of nitrogen oxides [3].

Domestic studies have put forward some new fuel injection control methods. Wu Qinglin of the Chongqing University of Technology measured fuel injection through a high-speed flowmeter and designed a fuel injection fuzzy controller, which used a genetic algorithm to optimise control parameters and improve control accuracy [4]. Finally, the hardware test platform on the ring shows that the control effect has reached the expected level, and it is necessary to conduct in-depth research. In 2016, Zhang Yue of Zhenjiang Shipping College established the control model of the main fuel injection volume and carried out a bench test with its control algorithm [5]. The control algorithm was calibrated by calibration software to verify the correctness of the control algorithm model. The results show that the fluctuation of the fuel volume is small and the fuel supply is stable during the idling process. Li Degang of Jilin University put forward the control method of fuel injection quantity by analysing the traction demand for high-pressure common rail diesel engine [6]. According to the expected torque required by diesel engine traction during starting acceleration, the fuel injection quantity was calibrated. The data show that the deviation between the calibrated torque and the expected value is small. Chen Liyong of Tianjin University proposed a new control strategy for the system solenoid valve [7]. Huang Zheng of Shanghai Jiaotong University mainly studied the relationship between emission particles and combustion characteristics [8]. Zhang Peng of the Beijing University of Technology designed a new solenoid valve and further improved its response speed [9].

At first, experimental research was widely used to develop the fuel injection system. But because of its long development cycle and high consumption of manpower and material resources, it cannot effectively adapt to the development of the system. With the rapid development of computers, simulation research has become an indispensable part of the electronic control fuel injection system development and is widely used. The electronic fuel injection system of the diesel engine has the characteristics of multidiscipline and strong coupling. The programming method based on a mathematical model cannot be applied to the fuel system with a diversified structure layout. With the rapid development of fluid mechanics, more and more simulation software is applied in practical research. Hydsim simulation platform is one of the better software for simulation research of the electronic control fuel injection system.

Hydsim simulation platform is mainly used in the field of fuel injection simulation. Each specific part of the fuel injection system can be simplified by the module provided by the platform, and each module only needs to be connected in different ways. On this basis, the whole fuel injection system is controlled by connecting with the control system model of MATLAB/Simulink. Besides, the Hydsim simulation platform also has strong post-processing capability. In summary, this paper uses the Hydsim simulation platform to build the simulation model of the fuel injection system. This model does not need to write complex programmes and can be seamlessly connected with the control unit, which greatly reduces the difficulty of simulation model construction.

At present, commercial software is mostly used in the simulation of the fuel injection system at home and abroad, such as MATLAB/Simulink, AMESim and Hydsim. MATLAB/Simulink can simulate and analyse each structure of the system, but it needs to write a complex simulation programme. It is difficult for non-professional programmers to build a system simulation model [10]. AMESim can build a multidisciplinary and interdisciplinary system model, but it needs to build a complex model scheme by itself, which requires experimenters of rich experience in model building [11]. The simulation model of the fuel injection system is established by the modular modelling method of the Hydsim simulation platform. The simulation model can simulate and analyse the structural parameters of the system without writing complex programme and constructing complex schemes, which greatly reduces the difficulty of simulation model construction. Given this, the paper will use the Hydsim simulation platform to simulate and model the fuel injection system. Based on experimental research, the fuel injection characteristics of the fuel injection system will be studied in depth.

## 2 Modelling of the injection system

The electronic fuel injection system of diesel engines consists of low-pressure system and high-pressure system, respectively [12], as shown in Figure 1.

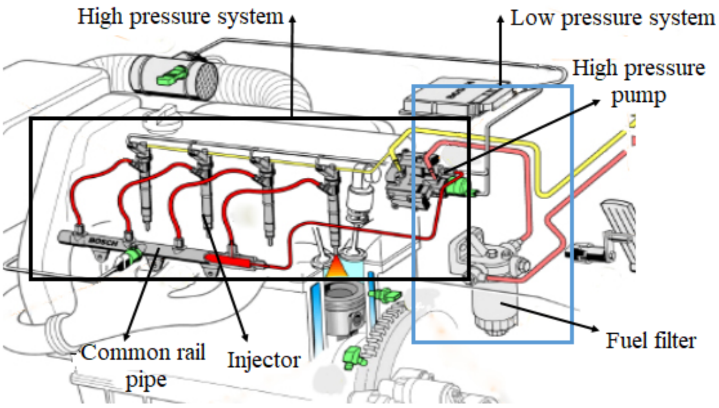


**Fig. 1** Electronic fuel injection system.

### 2.1 High-pressure oil pump module

The high-pressure oil pump pressurises the clean fuel in the low-pressure system to provide enough pressure to break through the restriction of the oil valve. Its structure is shown in Figure 2.

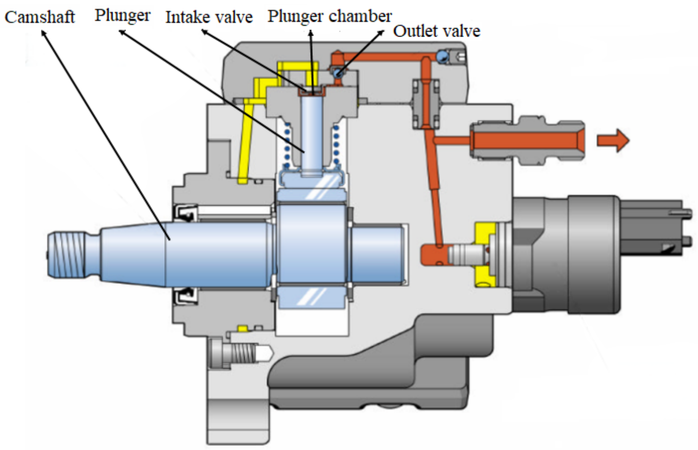


**Fig. 2** Structure of high-pressure oil pump.

### 2.2 High-pressure common-rail tube module

The high-pressure common rail tube can stabilise the high-pressure fuel in the tube at the preset value, thus ensuring that the fuel pressure output to the injector is constant. Its structure is shown in Figure 3.

### 2.3 Injector module

The solenoid valve is controlled by the injector to inject high-pressure fuel of constant pressure and quantity from high-pressure common rail tube into the cylinder so that the high-pressure fuel can be fully mixed and

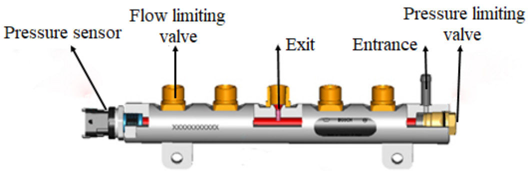


**Fig. 3** High-pressure common rail pipe.

atomised with air in the cylinder. Its structure is shown in Figure 4.

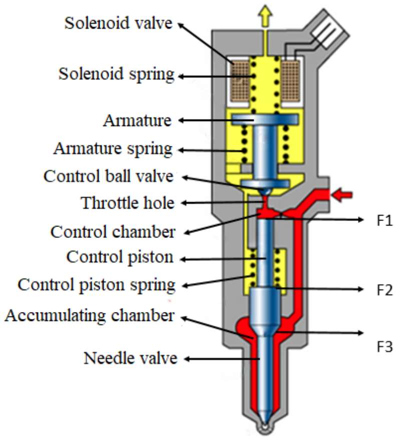


**Fig. 4** Solenoid-controlled injector.

The high-pressure common rail and electronic control injection system of diesel engines involves mechanical, electrical, hydraulic and control fields, and there is strong coupling among various fields. It is unrealistic and unscientific to consider all the factors in modelling. So it is necessary to simplify the calculation model as far as possible on the premise of ensuring the accuracy of the injection system. The simplification of the whole fuel injection system is shown in Figure 5. The Hydsim simulation model of the fuel injection system is shown in Figure 6.

Hydraulic connection: Internal combustion oil in the plunger chamber is connected to high-pressure common rail tube chamber through the oil outlet valve chamber and fuel pipeline [13]. The fuel in the common rail tube chamber passes through the fuel pipeline and is divided into two branches at the junction of the fuel chamber. One is connected to the accumulator through the fuel pipeline, the needle valve and the nozzle , and the nozzle is connected to the cylinder pressure. The other is connected to the control chamber through the fuel pipeline and the intake throttle valve, and the control chamber is connected to the control piston and the outlet throttle valve, respectively, and the outlet throttle valve is connected to the solenoid valve, which controls the switch of the fuel outlet. The fuel enters the fuel tank through the overflow chamber and the throttle valve of the fuel tank.

Mechanical connection: The cam and plunger are connected by a spring with larger stiffness, indicating that the elastic deformation is not taken into account at the connection of the cam and plunger, and the motion of the plunger is completely determined by the cam. Needle valves have two mechanical connections. A spring with smaller stiffness represents a needle valve spring, which is connected with a mechanical boundary without movement (nozzle seat), indicating that the needle valve spring is fixed on the mechanical boundary (nozzle seat). The other spring with larger stiffness is connected with the control piston, indicating a fixed connection between the needle valve and the control piston.

Special connection: The special connection between plunger and plunger leakage indicates that fuel leakage occurs when passing through the plunger motion pair. The special connection between the control piston and

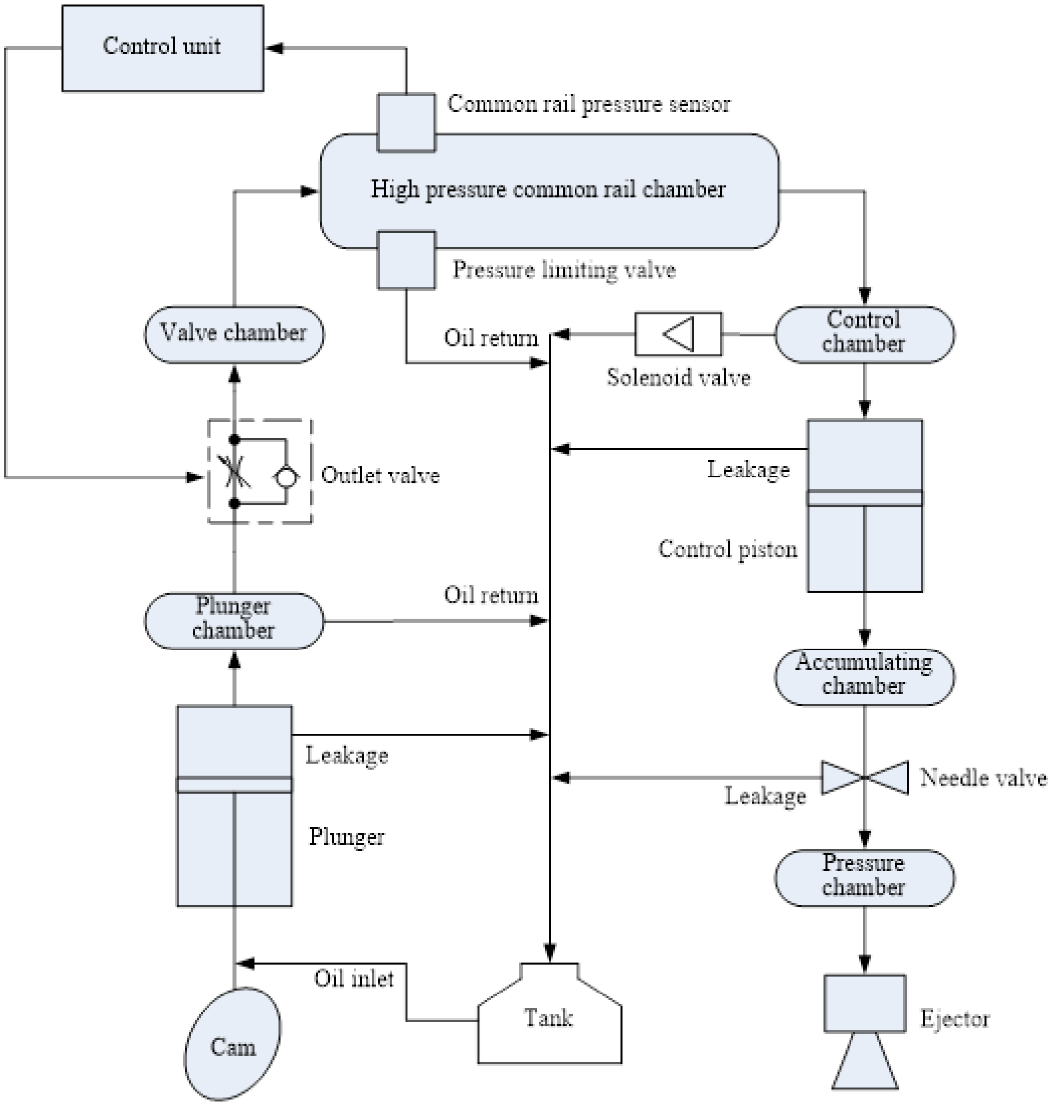


**Fig. 5** A simplified model of the fuel injection system.

control piston leakage indicates that fuel leakage occurs when passing through the control piston motion pair. The special connection between the needle valve and needle valve leakage indicates that fuel leakage occurs when passing through the needle valve motion pair. Besides, there are also special connections between the needle valve and nozzle.

## 3 Analysis results of the simulation

The influence of structural parameters such as inlet and outlet throttle hole and control piston on injection characteristics is analysed. The selection principle of each parameter in system design is mastered, and the basis for optimum design of system structure is provided.

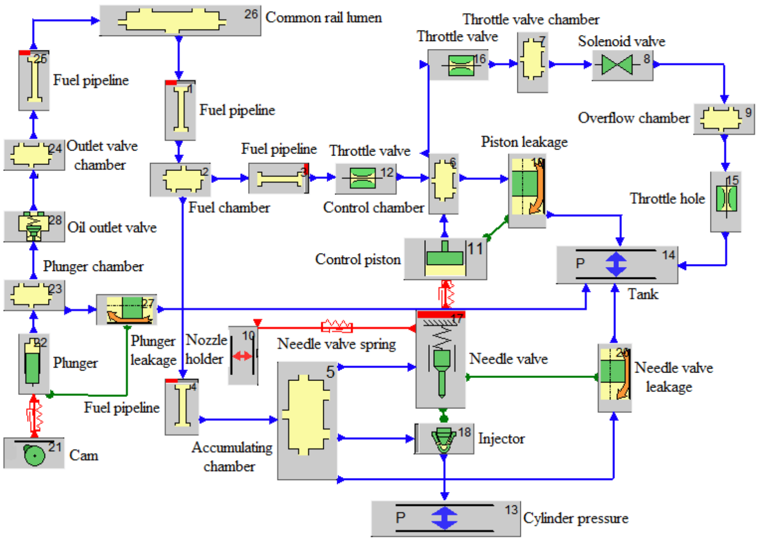


**Fig. 6** Hydsim simulation model of the fuel injection system.

## 3.1 The influence of inlet throttle hole on injection characteristics

Keeping the other parameters of the injection system unchanged, the area of the inlet throttle hole is defined as 3.6e-8 $m^2$, 4.1e-8 $m^2$, 4.6e-8 $m^2$, 5.1e-8 $m^2$ and 5.6e-8 $m^2$, respectively, to ensure that the maximum area of the inlet throttle hole is smaller than the area of the outlet throttle hole. Otherwise, the high-pressure fuel outlet velocity in the control chamber will be less than the inlet speed, and the pressure in the chamber cannot be reduced, and the needle valve cannot be opened. The relationship between the area of the inlet throttle hole and the fuel pressure in the control chamber is shown in Figure 7. The relationship between the area of the inlet throttle hole and the needle valve lift is shown in Figure 8. The relationship between the area of the inlet throttle hole and the injection rate is shown in Figure 9.

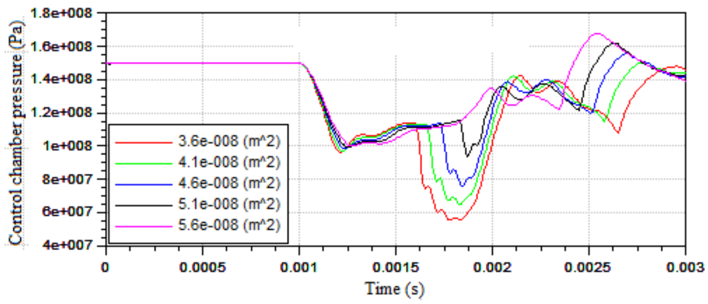


**Fig. 7** The relationship between the area of the oil inlet orifice and the fuel pressure in the control chamber.

According to the trend analysis from a group of data in Figures 7–9, when the oil outlet valve is opened, the outlet rate of high-pressure fuel in the control chamber increases. When the net oil output in the control chamber is greater than zero, the fuel pressure in the chamber begins to drop. When it drops to a certain value, the needle valve is opened, and at the same time, the high-pressure fuel enters the pressure chamber. This part of fuel acts on the bottom of the needle valve, pushing it upwards. The fuel pressure in the control chamber rises somewhat, but the increase is not very large until the needle valve is fully opened and the fuel is injected into the cylinder at the maximum injection rate. At this time, the fuel pressure in the control chamber decreases to the minimum. After the solenoid valve closes, the oil outlet valve closes, and when the net oil intake in the control chamber is greater than zero, the oil pressure in the chamber begins to rise. When it rises to a certain value, the needle valve

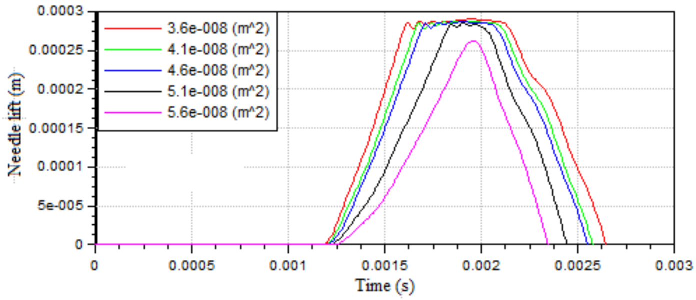


**Fig. 8** The relationship between the area of oil inlet orifice and the lift of the needle valve.

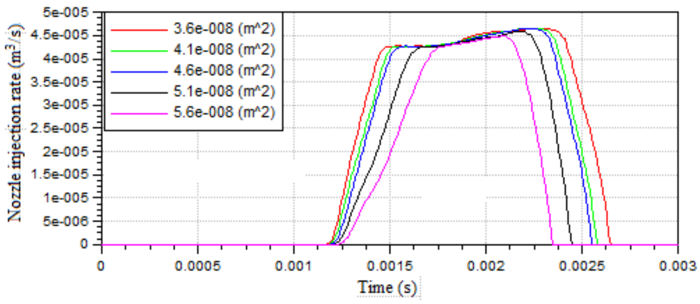


**Fig. 9** The relationship between the area of the oil inlet orifice and the injection rate.

closes and the fuel injection stops at the same time.

From analysing five groups of data, we can observe that with the increase of the area of the inlet throttle hole, the net oil output in the control chamber decreases when the outlet valve opens. When the decline rate of the fuel pressure in the chamber slows down, the opening speed of the needle valve slows down, and thereby decreases the injection speed, but the maximum injection rate is almost unchanged (when the needle valve is fully opened). On the contrary, when the outlet valve is closed, the net oil inflow in the control chamber becomes larger, the needle valve seats faster and the injection rate decelerates faster. But when the area of the intake throttle hole is too large, the net oil output in the control chamber is too small or even negative, and the needle valve can not be fully opened or even slightly opened. As shown in the case of 5.6e-8 in Figures 7–9, the area of the intake throttle hole is too large, and the needle valve cannot be fully opened.

### 3.2 Effect of outlet throttle hole on injection characteristics

Keeping other parameters of the injection system unchanged, the area of the outlet throttle hole is defined as 4.7e-8 $m^2$, 5.2e-8 $m^2$, 5.7e-8 $m^2$, 6.2e-8 $m^2$ and 6.7e-8 $m^2$, respectively, to ensure that the minimum outlet throttle hole area is larger than that of the intake throttle hole. The relationship between the outlet throttle hole area and fuel pressure in the control chamber is shown in Figure 10. The relationship between the outlet throttle hole area and needle valve lift is shown in Figure 11. The relationship between the outlet throttle hole area and the injection rate is shown in Figure 12.

According to the trend analysis from a group of data in Figures 10–12, the conclusion is similar to that of intake throttle hole, which will not be repeated here. From analysing five groups of data, with the increase of outlet throttle hole area, the oil outlet valve is opened, the net oil output in the control chamber becomes larger, the fuel pressure in the chamber decreases faster, the opening speed of the needle valve accelerates, and the injection rate also accelerates. But the maximum injection rate is almost unchanged (when the needle valve is fully opened). On the contrary, when the outlet valve is closed, the net fuel inflow in the control chamber remains unchanged, the seating speed of the needle valve remains almost unchanged, and the deceleration of the fuel injection rate is almost unchanged. Therefore, the two curves almost coincide when the needle valve

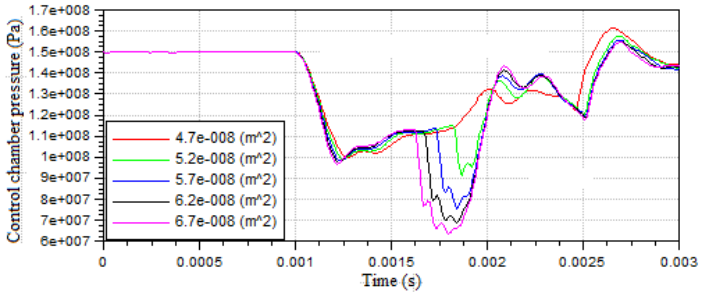


**Fig. 10** The relationship between the area of the oil outlet orifice and the fuel pressure in the control chamber.

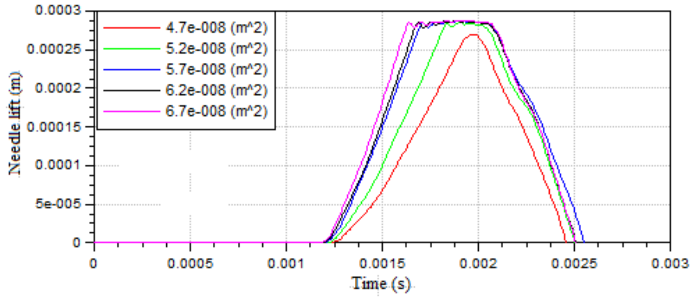


**Fig. 11** The relationship between the area of oil outlet orifice and the lift of the needle valve.

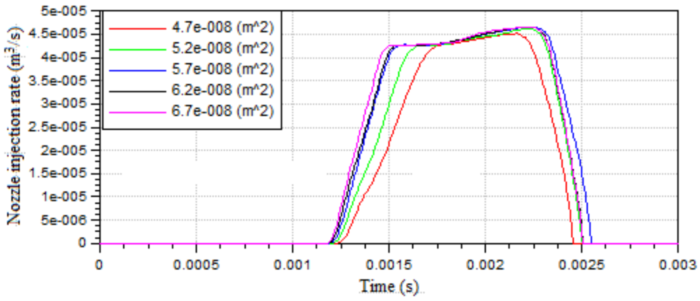


**Fig. 12** The relationship between the area of the oil outlet orifice and the injection rate.

is closed. But when the outlet throttle hole area is too small, the net fuel output in the control chamber is also too small or even negative, and the needle valve cannot be fully opened or even cannot be opened. As shown in the case of 4.7e-8 $m^2$ in Figures 10–12, the outlet throttle hole area is too small, and therefore the needle valve cannot be fully opened.

### 3.3 Effect of control piston on fuel injection characteristics

The control piston diameters are defined as 3.7e-3 m, 4e-3 m, 4.3e-3 m, 4.6e-3 m and 4.9e-3 m, respectively, keeping other parameters of the injection system unchanged. The relationship between the piston diameter and the needle valve lift is shown in Figure 13. The relationship between the piston diameter and the injection rate is shown in Figure 14.

According to the trend analysis from a group of data in Figures 13 and 14, when the diameter of the control piston is small, that is, the effective contact area between the high-pressure fuel and the control piston in the control chamber is relatively small, and when the outlet valve is opened, the fuel pressure in the chamber decreases. Because the effective contact area is relatively small, the pressure applied to the needle valve is relatively small. At this time, the needle valve opens quickly and the injection rate is fast. When the needle

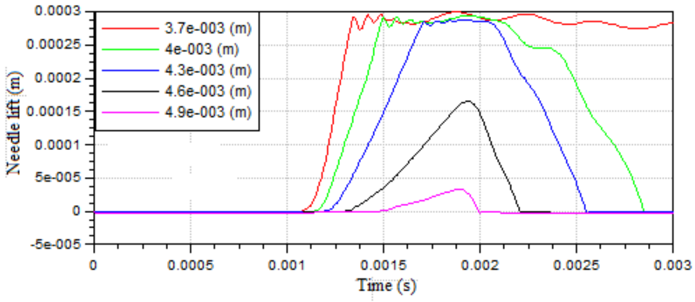


**Fig. 13** The relationship between the diameter of the control piston and the lift of the needle valve.

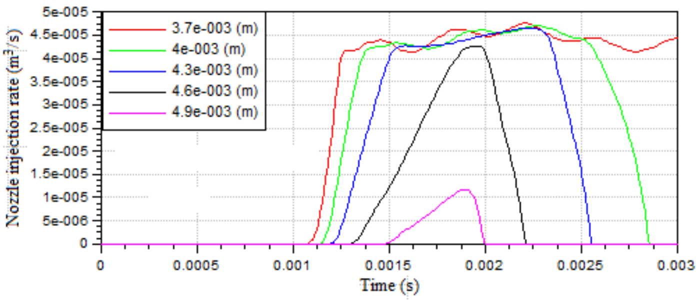


**Fig. 14** The relationship between the diameter of the control piston and the injection rate.

valve is fully opened, the fuel is injected into the cylinder at the maximum injection rate, during which the fuel pressure in the control chamber will fluctuate within a certain range, and the corresponding needle valve will also fluctuate within a certain range. After the valve closes, the fuel pressure in the control chamber rises. The needle valve seats slowly and the injection rate also decreases slowly.

From analysing five groups of data, the control piston diameter increases, the pressure applied on the needle valve increases, the opening time of the needle valve delays, the opening speed slows, and the injection rate increases slowly. But the maximum injection rate is almost unchanged (when the needle valve is fully opened). On the contrary, after the oil outlet valve is closed, the needle valve seats faster and the injection rate decelerates faster. But when the diameter of the control piston is too large, the needle valve cannot be fully opened or even slightly opened because of the excessive pressure applied to the needle valve. As shown in the case of 4.9e-3 m in Figures 13 and 14, the needle valve cannot be fully opened. When the diameter of the control piston is too small, the needle valve cannot be seated on time or even cannot be seated at all. As shown in the case of 3.7e-3 m in Figures 13 and 14, the needle valve cannot be seated.

## 4 Test system and experimental verification

To verify the accuracy of the simulation model of the fuel injection system, this paper designed and built the test system of the fuel injection system independently. It mainly consists of three parts: control host, low-pressure system and high-pressure system. There are the fuel injection parameters of the common type injectors in the control host, including the structure parameters, control parameters, standard values and error parameters. Its function is to control the fuel injection process of the test system and to compare and analyse the test values. The low-pressure system mainly includes a fuel tank and fuel filter. Its function is to provide clean fuel for the system. The high-pressure system mainly includes a high-pressure oil pump, high-pressure common rail pipe, solenoid valve and injector. Its function is to complete the timing, constant pressure and quantitative injection.

The comparison of the simulation value, test value and the standard value of fuel injection rate is shown in

Figure 15, and the comparison of the simulation value, test value and the standard value of fuel injection quantity is shown in Figure 16.

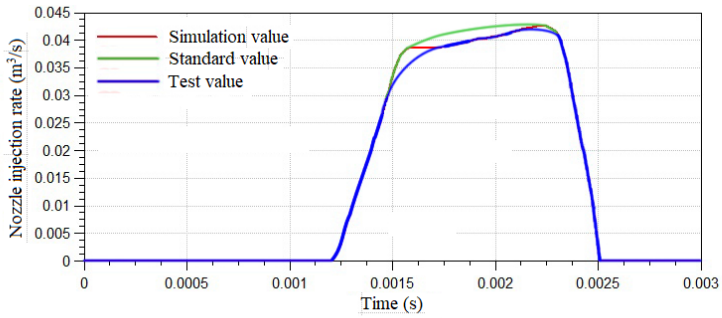


**Fig. 15** Comparison of simulation value, test value and the standard value of fuel injection rate.

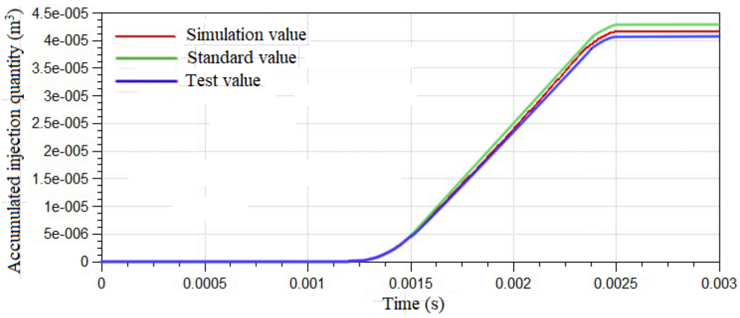


**Fig. 16** Comparison of simulation value, test value and the standard value of fuel injection quantity.

The errors between simulation value, test value and standard value are analysed and compared. The results show that the maximum error between simulation value and test value for the fuel injection rate is 6.5%, and the maximum error between simulation value and test value for fuel injection quantity is 2.5%. It shows that the test platform can accurately reflect the simulation model. The maximum error between the test value and the standard value of the injection rate is 6%, and the maximum error between the test value and the standard value of the injection quantity is 5%. The test value is within the error range of the standard value, that is, the test result is also true and effective. Besides, the maximum error between the simulation value and the standard value of injection rate is 6%, and the maximum error between the simulation value and the standard value of injection quantity is 3.5%. The trend of the simulation value, the test value and the standard value is the same, all within the 7% error range of the standard value. Therefore, the simulation model built in this paper is correct and effective and can describe the actual working process of the injection system relatively and accurately.

## 5 Conclusion

From the above analysis, it can be concluded that:

1. With the increase of the area of the inlet throttle hole, the opening speed of the needle valve becomes slower and the seating speed becomes faster. When the area is too small, the injection rate curve of 'first urgent and then slow' is contrary to the ideal curve. When the area is too large, the needle valve cannot be lifted completely.
2. With the increase of the area of the outlet throttle hole, the opening speed of the needle valve is accelerated,

and the seating speed changes little. When the area is too large, the injection rate increases rapidly when the needle valve is opened. It is contrary to the 'first slow' in the ideal injection characteristics. Therefore, under the condition of meeting the demand, a relatively small outlet throttle area is selected.

3. With the increase of piston diameter, the opening speed of the needle valve becomes slower and the setting speed becomes faster. When the diameter of the needle valve is too small, the injection rate increases rapidly when the needle valve is opened and the needle valve cannot be seated when the outlet valve is closed. When the diameter of the needle valve is too large, although the injection rate curve generally meets the requirement of 'first slow and then urgent', it cannot be opened fully and the injection rate cannot meet the injection requirements. Therefore, under the condition of meeting the requirements, the control piston with a relatively large diameter is selected.

Hydsim simulation platform is used to establish the simulation model of the fuel injection system, and the simulation analysis is carried out under the rail pressure of 150 MPa. Based on the simulation model, the test platform of the fuel injection system is built, and the test analysis under the rail pressure of 150 MPa is carried out. The validity and accuracy of the simulation model are verified by comparing the simulation value with the test value and the standard value. The influence of structural parameters such as inlet throttle hole, outlet throttle hole and control piston on injection characteristics, and the selection principle of each parameter in system design are mastered to provide the basis for the system structure optimisation.

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