Simulation Study on the Influence of Injector Coupling Leakage on Fuel Injection

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Abstract. In order to study the effect of fuel leakage of an ultra-high pressure common rail injector control valve coupling on fuel injection performance, a simulation model was established by AMESim and the accuracy was verified by fuel injection test data. The leakage law of couples with different clearances was analyzed by using numerical simulation method and then the influence of control valve coupling on fuel injection performance was analyzed. The results demonstrate that the increase of the matching clearance of the slide valve coupling makes the start time of needle valve advanced and delay its end time. The injection rate and injection duration increase with the increase of the matching clearance of slide valve coupling. The increase of the matching clearance of the control plunger coupling keeps the start time of the needle valve unchanged at first, and then delay slightly, while the end time remains unchanged at first, and then show the trend of advance. The injection rate and injection duration decrease with the increase of the matching clearance of plunger coupling.

Keywords. Fuel leakage, Common rail injector, Injection performance, Slide valve coupling, Plunger coupling.

1. Introduction
In order to reduce the fuel consumption and emission of diesel engine to a greater extend and improve its power performance, the high pressure common rail system should improve the performance of ultra-high pressure, injection precision and multi waveform injection controllability [1]. The fuel injector works in the harsh environment of high pressure, high temperature and vibration in multi working cycles. Unreasonable design of precision coupling can accelerate friction and wear, and even affect the sealing performance. The injector coupling has high matching accuracy with high motion speed. With the increase of the working cycle of the injector, the wear of coupling intensifies. Under the combined action of wear on the mating surface and fuel pressure in the matching clearance, the fuel leakage increases excessively [2]. Excessive leakage rate can affect the fuel injection performance, reduce fuel injection energy and increase the loss of driving power.

The research on fuel leakage of injector coupling can provide theoretical guidance for the design and performance optimization of an ultra-high pressure injector. This paper takes an ultra-high pressure injector as the research object, in which the control valve parts include control plunger coupling and slide valve coupling. The injection process was tested and simulated. The leakage characteristics of injector control plunger and slide valve coupling and the influence of leakage under different coupling clearance on injection performance were studied by numerical simulation.

2. Structure and Working Process of Fuel Injector
Figure 1(a) is a schematic diagram of the structure of the common rail injector, which mainly includes...
a solenoid valve part, a hydraulic servo part and a nozzle assembly. Figure 1(b) is a schematic view of the structure of the injector control valve assembly comprising the slide valve coupling and the control plunger coupling.

The working process of the fuel injector is described as follows: as the ECU sends an injection command, the solenoid valve coil is energized to make the electromagnetic valve lift, and the fuel in the control chamber leaks out through the small hole at the lower end of the slide valve and flows into the low-pressure cavity. The needle valve is raised by upward force, and high pressure fuel is ejected from the jet hole [3].

When the ECU sends fuel injection stop signal, the solenoid is powered off and the armature returns to its original position. The high pressure fuel flows into the pressure storage chamber through the small hole on the slide valve [4]. When the fuel in the pressure storage chamber exceeds a certain pressure, the slide valve falls under the action of hydraulic pressure and then the fuel injection cycle ends.

![Figure 1](image1)

**Figure 1.** Structural diagram of common rail injector.

### 3. Simulation Model and Experimental Verification

According to the structure and working principle of high pressure injector, the simulation model of the injector is established by using software AMESim. Figure 2 shows the one dimensional simulation model, including electromagnetic force control module, fuel supply module, solenoid valve control module and fuel injection control module [5]. The parameters of simulation model are illustrated in table 1.

![Figure 2](image2)

**Figure 2.** Simulation model of injector.
Table 1. Parameter setting of simulation model.

| Parameter            | Value   |
|----------------------|---------|
| Common rail pressure | 200 MPa |
| Cylinder pressure    | 4 MPa   |
| Injection frequency  | 33 Hz   |

In order to confirm the validity of the model, the injection test of the injector was carried out. The single cycle fuel injection quantity was measured under the conditions of 140 MPa and 200 MPa rail pressure and injection pulse width of 0.6 ms, 0.7 ms, 0.8 ms, 0.9 ms and 1 ms respectively. Figure 3 shows the comparison between simulation results and test results. It can be seen from figure 3 that the error between the test results and the simulation results is less than 10%, and the error is within the engineering error range [6]. The simulation model can effectively simulate the injection process.

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After the reliability of the model is verified, the fuel leakage of the control plunger and the slide valve with different coupling clearance, and the influence of fuel leakage on the hydraulic response and fuel injection performance of the injector are simulated and analyzed.

4. Results and Discussion

4.1. The Influence of Clearance on the Fuel Leakage

Figures 4 and 5 show the variation of flow rate of the plunger couples and slide valve couples with different coupling clearance. The range of coupling clearance is between 0.002 mm and 0.006 mm. It can be seen from the figure that the leakage law of coupling parts under different coupling clearances is similar, but the flow rate increases greatly with the increase of clearance.
4.2. Effect of Slide Valve Coupling Clearance on Injection Performance

The response of components in the injector to the electromagnetic signal is realized through the transmission of hydraulic pressure. The movement of the needle valve is driven by the pressure difference between the needle valve chamber and the control chamber, and the opening and closing of the control slide valve is driven by the pressure difference between the control chamber and the annular chamber at the top of the slide valve. As mentioned above, the size of the injector precision coupling clearance can produce different leakage rate, and which affects the establishment of fuel pressure in control valve chamber. Thus, the response time of the injector components to the electromagnetic signal is changed [7].

As shown in figure 6, when the clearance of slide valve coupling changes from 0.002 mm to 0.022 mm, the start time of needle valve is decreased and the end time is longer, resulting in the increase of injection duration. As shown in figure 7, when the clearance of slide valve coupling changes from 0.002 mm to 0.022 mm, the fuel injection duration increases from 1.02 ms to 1.18 ms, with an increase of 15.68%.

The reason for this phenomenon is that when the solenoid valve is energized, the fuel in the control chamber flows out through the small hole at the lower end of the control slide valve and into the low-pressure chamber, and the needle valve is lifted under the action of upward force. The fuel leakage of the slide valve coupling accelerates the pressure drop in the control chamber, while the
pressure fluctuation in the needle valve chamber is almost unchanged, resulting in the early opening of the needle valve. When the solenoid valve is powered off, high pressure is established in the control chamber, and the needle valve is closed and then fuel injection ends [8].

As shown in figure 8, when the clearance of the control slide valve coupling is 0.022 mm, the lift of the needle valve is increased by about 0.2 mm compared with that when the clearance is 0.002 mm. The clearance not only makes the needle valve open in advance and close in delay, but also makes the needle valve lift increase significantly. As can be seen from figure 9, when the clearance of slide valve coupling changes from 0.002 mm to 0.022 mm, the maximum injection rate increases from 0.17 L/s to 0.23 L/s, with an increase of 35.29%; The injection duration increased from 1.2 ms to 2.22 ms, with an increase of 85%.

Figure 8. Needle valve lift depending on slide valve coupling clearance.

Figure 9. Injection rate depending on slide valve coupling clearance.

As shown in figure 10, when the clearance of slide valve coupling changes from 0.002 mm to 0.022 mm, the cycle fuel injection quantity increases from 230 mm³ to 280 mm³, with an increase of 21.7%. Figure 11 shows the change curve of the ratio of the single cycle leakage of the slide valve coupling with different clearances to the single cycle return fuel when the slide valve coupling clearance is 0.002mm. It can be seen from the figure that the slide valve coupling clearance has little impact on the performance of the injector.

Figure 10. Cycle fuel injection quantity depending on slide valve coupling clearance.

Figure 11. The ratio of leakage to return fuel depending on slide valve coupling clearance.
4.3. Effect of Plunger Coupling Clearance on Injection Performance

As shown in Figure 12, when the clearance of the control plunger coupling changes from 0.002 mm to 0.012 mm, the start time of the needle valve remains unchanged at 1.32 ms and the end time remains unchanged at 2.38 ms. When the clearance of the control plunger coupling is greater than 0.012 ms, the start time of the needle valve is prolonged and the end time is shortened. As shown in Figure 13, when the coupling clearance of the control plunger changes from 0.002 mm to 0.012 mm, the injection duration remains unchanged for 1.02 ms. When the coupling clearance changes from 0.017 mm to 0.022 mm, the injection duration decreases from 1 ms to 0.96 ms, and the injection duration of the injector shows a trend of first unchanged and then shortened.

As shown in Figure 14, when the control plunger coupling clearance is 0.022 mm, the needle valve lift is about 0.1 mm lower than that when the clearance is 0.002 mm. The increase of the control plunger coupling clearance not only delays the opening and early closing of the needle valve, but also significantly reduces the needle valve lift. As shown in Figure 15, when the clearance of the control plunger coupling changes from 0.002 mm to 0.022 mm, the maximum injection rate decreases from 0.185 L/s to 0.175 L/s, with a decrease range of 5.4%. The injection duration decreased from 1.7 ms to 1 ms, with a decrease of 41.18%. From the above analysis, as the matching clearance of the control plunger coupling increases to a certain extent, the fuel injection duration can be shortened and the fuel injection quantity is reduced. By comparing Figure 8 and Figure 14, Figure 9 and Figure 15, we know that the change of the control plunger coupling clearance has a greater impact on the fuel injection performance compared with the change of the slide valve coupling clearance.
As shown in figure 16, when the clearance of the control plunger coupling changes from 0.002 mm to 0.022 mm, the cycle fuel injection quantity decreases from 230 mm$^3$ to 202 mm$^3$, with a decrease range of 12.17%. Figure 17 shows the curve of the ratio of the single cycle leakage of the control plunger coupling with different control clearance to the single cycle return fuel when the plunger coupling clearance is 0.002 mm. It can be seen from the figure that when the single cycle leakage of the couple is small compared with the reference oil return, the coupling clearance has little impact on the injection performance.

![Figure 16. Cycle fuel injection quantity depending on plunger coupling clearance.](image1)

![Figure 17. The ratio of leakage to return fuel depending on plunger coupling clearance.](image2)

5. Conclusion
A one-dimensional simulation model of ultra-high pressure common rail injector was established, which was used to simulate injection process. The influence of fuel leakage of precision coupling on hydraulic response and injection performance is analyzed. The main conclusions are as follows.

With the increase of the matching clearance of the slide valve coupling, the start time of the needle valve is advanced and the end time is delayed, and the fuel injection duration of the injector increases rapidly. The change of the hydraulic response of the injector caused by the increase of the clearance of the slide valve coupling leads to the increase of the fuel injection rate and fuel injection quantity. Besides, when the single cycle leakage of the slide valve is too small compared with the reference return fuel, the impact of the coupling clearance on the fuel injection performance of the injector is also small.

With the increase of the matching clearance of the control plunger coupling, the start time of the needle valve remains unchanged first and then slightly delayed, while the end time remains unchanged first and then shows an early trend. In addition, the injection duration of the injector shows a trend of unchanged first and then shortened. Moreover, the increase of the matching clearance of the control plunger coupling leads to the decrease of the injection rate and fuel injection quantity. The amount of cycle fuel injection quantity decreases with the increase of the matching clearance of the control plunger coupling.

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