Study on Influencing Factors and Laws of Fuel Injection Consistency of Common Rail Injector

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Abstract. In order to study the influence of parameters of common rail injector internal components on cycle injection consistency, its simulation model is established by AMESim, and the model is validated by the experimental injection rate data. The effects of solenoid valve spring preload, gag bit lift, fuel discharge hole diameter, fuel inlet hole diameter, needle valve lift, needle valve preload and nozzle diameter on the change of injection quantity under different operating conditions are studied by simulation method, and the impact weight of each parameter on fuel injection consistency is analyzed. The results show that the preload of solenoid valve, fuel discharge hole diameter, oil inlet hole diameter, needle valve lift and nozzle diameter are the main parameters affecting the consistency of cycle injection. The percentages of five parameters influencing on the consistency of cyclic injection are 8.68–16.84%, 11.41–23.68%, 17.2086–37.74%, 12.772–18.34% and 9.69–37.27% respectively.

Keywords. Common rail injector, Injection consistency, Operating condition, Impact weight.

1. Introduction
Due to the high injection pressure, it is very important for the common rail injection system to realize the stable and accurate control of injection quantity. The injector injects high-pressure fuel into cylinder, which is the key component of the system [1]. The solenoid valve on the injector generates electromagnetic force to control the action of ball valve and the control chamber pressure, so as to realize the needle valve movement control, and then flexibly adjust the injection duration, pulse width and injection frequency. The internal components of fuel injector are matched precisely and complexly [2]. The change of parameters of each component will cause the fluctuation of injection quantity, lead to the deterioration of injection consistency, and affect the working stability and reliability of diesel engine.

The research on the influence of structural parameters on the injection consistency can provide theoretical guidance for the design of injector, and is of great significance to improve the working stability and reliability of common rail. Through simulation analysis, this paper studies the influence of common rail injector solenoid valve spring preload, gag bit lift, fuel discharge hole diameter, fuel inlet hole diameter, needle valve lift, needle valve spring preload and nozzle diameter on the fluctuation of injection quantity, and analyzes the influence law of various parameters on injection consistency [34].

2. Simulation Model and Validation
Fuel pump, common rail pipe, injector are the main components of common rail system. On the basis of the operating principle of the system, the simulation model of the system is established by using
AMESim software, as shown in Figure 1.

![Simulation model diagram](image)

**Figure 1.** Simulation model.

**Table 1.** System parameters.

| Parameter                        | Value   |
|----------------------------------|---------|
| Rail pressure                    | 180 MPa |
| Injection frequency              | 13.33 Hz|
| Solenoid air gap                 | 0.065 mm|
| Solenoid valve coil turns        | 37      |
| Inner diameter of common rail pipe | 14 mm  |
| Length of common rail pipe       | 720 mm  |

In order to validate the simulation model and enable it to reflect the injection characteristics of common rail system, it is verified by using the test data measured. Table 1 illustrates the main control and structural parameters of the system. Figure 2 shows the comparison between test values and simulation of fuel injection rate with two operating conditions, which are 180 MPa rail pressure and injection pulse of 0.7 ms and 0.8 ms respectively. From figure 2 we can know that the injection rate calculated by simulation is in high agreement with the test values, indicating that the established simulation model can accurately predict the fuel injection characteristics.

![Injection rate comparison](image)

(a) Injection rate at 0.7 ms injection pulse  
(b) Injection rate at 0.8 ms injection pulse

**Figure 2.** Model verification.
3. System Parameters and Test Condition

On the basis of the injector model shown in figure 1, the solenoid valve spring preload, gage bit lift, fuel discharge hole diameter, fuel inlet hole diameter, needle valve lift, needle valve spring preload and nozzle diameter are selected as influencing factors to study the injection consistency, and the fluctuation of cycle fuel injection is evaluated as an estimation index [5]. In addition, according to the injector structural parameters and their changes in the production assembly process and service cycle, the reference values and variation range of each parameter are illustrated in table 2. The injection pulse range of 0.6-1.9 ms and rail pressure range of 50-80 MPa are used for operating conditions during the research.

Table 2. Parameters of injector.

| System parameter                  | Minimum value | Reference value | Maximum value |
|-----------------------------------|---------------|-----------------|---------------|
| Spring preload of solenoid valve  | 62 N          | 64 N            | 66 N          |
| Gage bit lift                     | 0.058 mm      | 0.06 mm         | 0.062 mm      |
| Diameter of fuel discharge hole   | 0.268 mm      | 0.27 mm         | 0.272 mm      |
| Diameter of fuel inlet hole       | 0.218 mm      | 0.22 mm         | 0.222 mm      |
| Needle valve lift                 | 0.24 mm       | 0.25 mm         | 0.26 mm       |
| Needle valve spring preload       | 24 N          | 32 N            | 40 N          |
| Nozzle diameter                   | 0.231 mm      | 0.241 mm        | 0.251 mm      |

The maximum absolute value of the deviation between the injection quantity as the structure parameter is the maximum or minimum value and the quantity under the condition of reference value is taken as the fluctuation of the quantity caused by the change of parameters [6]. The calculation formula is as follows.

$$\sigma_f = \max\left(\text{abs}(\sigma_{\max} - \sigma_{\text{ref}}), \text{abs}(\sigma_{\min} - \sigma_{\text{ref}})\right)$$

(1)

where $\sigma_f$ is the fluctuation of injection quantity, $\sigma_{\max}$ is the quantity corresponding to maximum parameter value, $\sigma_{\text{ref}}$ is the quantity corresponding to reference parameter value, and $\sigma_{\min}$ is the quantity corresponding to minimum parameter value.

4. Analysis of Parameters Effect on Fuel Injection Consistency

4.1. Spring Preload of Solenoid Valve

Figure 3 shows the fluctuation characteristics of injection quantity at three different solenoid valve spring preload levels 62 N, 64 N and 66 N. In figure 3, the injection pulse range is 0.6-1.9 ms and the rail pressure range is 50-180 MPa. The maximum injection fluctuation is 6.42707 mm3 in figure 3, which occurs at the operating point of 180 MPa rail pressure and 0.4 ms injection pulse. When the injection pulse is more than 1.1 ms, the quantity fluctuation changes smoothly. As the rail pressure increases, the fluctuation increases. Under the same rail pressure, the change of injection pulse has little effect on the quantity fluctuation. The spring preload of solenoid valve determines its action response speed and the needle valve falling speed, then causes the injection fluctuation [7].
4.2. Gag Bit Lift

Figure 4 shows the fluctuation characteristics of injection quantity at three different gag bit lift levels – 0.058 mm, 0.06 mm and 0.062 mm. In figure 4, the injection pulse range is 0.6-1.9 ms and the rail pressure range is 50-180 MPa. The maximum injection fluctuation is 8.4341 mm$^3$ in figure 4, which occurs at the operating point of 180 MPa rail pressure and 0.6 ms injection pulse. When the injection pulse is more than 1.6 ms, the injection fluctuation is small, and the average fluctuation is less than 2.4 mm$^3$. With small injector pulse, the simultaneous motion of the ball valve and control plunger causes significant fuel pressure fluctuations in the control chamber. The change of gag bit lift can affect the fuel discharge speed of control chamber [8]. In addition, it will also affect the ball valve reset time and change the control chamber fuel discharge time, thus increasing the impact on the control chamber pressure and injection duration and resulting in greater fluctuation of cycle fuel injection quantity.

4.3. Fuel Discharge Hole Diameter

Figure 5 shows the fluctuation characteristics of injection quantity at three different fuel discharge hole diameter levels-0.058 mm, 0.06 mm and 0.062 mm. In figure 5, the injection pulse range is 0.6-1.9 ms and the rail pressure range is 50-180 MPa. The maximum injection fluctuation is 6.9282 mm$^3$ in figure 5, which occurs at the operating point of 160 MPa rail pressure and 0.7 ms injection pulse. The injector with small injection pulse has short the fuel injection duration, and the fuel pressure setup time of control chamber is short. The injection fluctuates strongly due to the simultaneous action of the control valve and the control plunger. At this time, the change of fuel discharge hole diameter has a great impact on the control chamber pressure, resulting in dramatic injection fluctuation. With large injector pulse, the control chamber pressure has enough stability time. The change of fuel discharge diameter has little impact on the control chamber pressure before injection termination, and its impact on the injection quantity is mainly reflected in the initial stage of injection, so the fluctuation of cycle fuel injection quantity changes smoothly.
Figure 5. Fuel outlet hole diameter effects on cycle fuel injection.

Figure 6. Fuel inlet hole diameter effects on cycle fuel injection.

4.4. Fuel Inlet Hole Diameter
The diameter of fuel inlet determines the throttling effect and flow characteristics of fuel, and its change affects the setup speed of control chamber pressure. Figure 6 shows the fluctuation characteristics of injection quantity at three different fuel inlet hole diameter levels: 0.218 mm, 0.22 mm and 0.222 mm. In figure 6, the injection pulse range is 0.6-1.9 ms and the rail pressure range is 50-180 MPa. The maximum injection fluctuation is 9.6332 mm$^3$ in figure 6, which occurs at the operating point of 160 MPa rail pressure and 0.7 ms injection pulse. When the injection pulse is more than 1.6 ms, the injection fluctuation changes smoothly. The reason for the large injection fluctuation at small injection pulse is that the fluctuation of control chamber pressure is caused by the movement of ball valve and control plunger, and the difference of control chamber pressure due to the inlet hole diameter variation has a more obvious impact on the fuel injection duration, resulting in severe fluctuation of cycle fuel injection quantity.

4.5. Needle Valve Lift
The needle valve lift determines its motion duration, the change of which can result in the fluctuation of injection quantity. Figure 7 shows the fluctuation characteristics of injection quantity at three different needle valve lift levels: 0.24 mm, 0.25 mm and 0.26 mm. In figure 7, the injection pulse range is 0.6-1.9 ms and the rail pressure range is 50-180 MPa. The maximum injection fluctuation is 7.797 mm$^3$ in figure 7, which occurs at the operating point of 180 MPa rail pressure and 1.9 ms injection pulse. Besides, the fluctuation of injection quantity caused by the change of needle valve lift is 0 on the low pressure and small pulse width area of figure 7. The reason for this is when the low-pressure pulse width is small, the injection duration is short, and the needle valve cannot reach the maximum lift. Accordingly, the change of needle valve lift has no effect on injection quantity.
Figure 7. Needle valve lift effects on cycle fuel injection.

Figure 8. Needle valve spring preload effects on cycle fuel injection.

4.6. Needle Valve Spring Preload
The preload of needle valve spring affects its motion response, resulting in the fluctuation of injection quantity. Figure 8 shows the fluctuation characteristics of injection quantity at three different needle valve spring preload levels-24 N, 32 N and 40 N. In figure 8, the injection pulse range is 0.6-1.9 ms and the rail pressure range is 50-180 MPa. The maximum injection fluctuation is 13.1237 mm$^3$ in figure 8, which occurs at the operating point of 50 MPa rail pressure and 1.5 ms injection pulse. Taking into account all operating conditions, the fluctuation of injection quantity caused by the change of needle valve preload decreases with rail pressure increasing. The fluctuation of injection quantity caused by the change of needle valve preload has significant effect on the small injection pulse area, and the change of pulse width has no significant effect on the injection quantity fluctuation in the large pulse width area.

4.7. Nozzle Diameter
The nozzle diameter directly determines the flow area of fuel injection into the cylinder, so it has the impact on the injection quantity. Figure 9 shows the fluctuation characteristics of the quantity at three different nozzle diameter levels-0.231mm, 0.241mm and 0.251mm. In figure 9, the injection pulse range is 0.6-1.9 ms and the rail pressure range is 50-180 MPa. The maximum injection fluctuation is 16.1671 mm$^3$ in figure 9, which occurs at the operating point of 180 MPa rail pressure and 1.9 ms injection pulse. The injector with large nozzle diameter has large the flow area, which makes injection quantity increase. In figure 9, the injection quantity fluctuation changes linearly with the rail pressure and injection pulse.

Figure 9. Nozzle diameter effects on cycle fuel injection.
5. Quantitative Analysis of Injection Fluctuation

From the above analysis, it can be known that the parameters of injector have a certain impact on the injection quantity, and the influence degree and reasons of each parameter are different due to the complex internal structure of the injector. In order to reveal the main parameters affecting the consistency of cycle injection, we quantitatively analyze the influence of each parameter on the injection quantity. We define the influence factor of cycle fuel injection quantity to eliminate the influence caused by different parameter variation ranges, and its calculation formula is as follows.

\[ S_R = \frac{\Delta Q_t}{Q_t} \frac{(A_{\text{max}} - A_{\text{min}})}{A_{\text{ref}}} \]  

(2)

where, \( S_R \) is the influence factor of the quantity when pulse width is \( t \), \( \Delta Q_t \) is the cycle fluctuation caused by the change of parameter value under the corresponding operating conditions, \( Q_t \) is the cycle injection quantity when the parameter takes the reference value, \( A_{\text{max}} \) is the maximum value of the parameter, \( A_{\text{min}} \) is the minimum value of the parameter, and \( A_{\text{ref}} \) is the reference value.

Figure 10 shows the influence factors of injection quantity under different operating conditions. Since there are many operating points, the injection pulse of 0.6 ms, 1 ms and 1.5 ms are selected to analyze the variation law of the fluctuation percentage of injection quantity caused by the parameter variation under different rail pressure conditions.

![Figure 10](image)

Figure 10. Variation law of injection quantity fluctuation percentage.

It can be seen from figure 10 that the quantitative indexes of the fluctuation percentage of the quantity corresponding to the change of solenoid valve spring preload and gag bit lift are 8.68‒16.84% and 4.3‒7.58% respectively. The quantitative index of the percentage is consistent with the change of
fuel pressure, but opposite to the change of injection pulse. The quantitative indexes of the fluctuation percentage of the quantity corresponding to the changes of fuel discharge hole diameter, fuel inlet hole diameter and needle valve spring preload are 11.41-23.68%, 17.2086-37.74% and 0.319-1.23% respectively. The quantitative indexes of the percentage is opposite with the change of fuel pressure and injection pulse. The quantitative indexes of the percentage fluctuation of cycle fuel injection caused by needle valve lift and nozzle diameter are 12.772–18.34% and 9.69–37.27% respectively. The quantitative index of the percentage is consistent with the change of fuel pressure and injection pulse.

6. Conclusion

By using AMESim simulation, the influence law of parameters of injector system on injection fluctuation under all operating conditions is obtained.

The influence of parameters on injection fluctuation is more obvious in small injection pulse. Since the injector needle valve cannot reach the maximum lift in this case, the fluctuation of the quantity shows large nonlinearity and great fluctuation under the influence of parameters.

The quantitative index of the fluctuation percentage of injection caused by the change of each parameter is obtained. The analysis shows that the quantitative index caused by parameter change is mainly affected by fuel pressure. The spring preload of solenoid valve, the fuel discharge hole diameter, the oil inlet hole diameter, the needle valve lift and nozzle diameter are the most significant parameters affecting the fuel injection consistency. The quantitative indexes of the fluctuation percentage of injection caused by the changes of the above five parameters are 8.68-16.84%, 11.41-23.68%, 17.2086-37.74%, 12.772-18.34% and 9.69-37.27% respectively.

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