Analysis of Operation Rule of Check Valve in High Pressure Tubing Based on Improved Euler Method

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Abstract. When the fuel injection nozzle of the engine works, the actual fuel injection quantity will change due to the pressure change of the high-pressure fuel pipe, which will affect the working efficiency of the engine. Therefore, it is necessary to adjust the operation rule of the check valve in the high-pressure fuel pipe so that the pressure is relatively stable at a certain value, the working process of the engine is more reasonable, and the engine loss is reduced. In this paper, the recursive formula of the mathematical model of the check valve and the high-pressure tubing is established, and the improved Euler method is used to solve the problem. It simulates its working condition at stable pressure and pressurization at different speeds, and then analyzes the reasonable operating cycle of the check valve accordingly, so that the pressure in the high-pressure fuel pipe meets the requirements.

1. Introduction
The fuel injection system of diesel engines is mainly composed of high-pressure fuel pumps, high-pressure fuel pipes and fuel injection nozzles. Its performance optimization and parameter design have always been one of the important research projects in the field of diesel fuel injection systems. The matching options of components are very important. If the options are unreasonable, it will directly affect the performance of the diesel engine.

2. Description of the problem
Fuel entering and ejecting high-pressure fuel pipes is the basis of many fuel engines. Figure 1 shows the working principle of a high-pressure fuel system. Fuel enters the high-pressure fuel pipe from A through the high-pressure fuel pump, and is then ejected from nozzle B. The intermittent working process of fuel entry and ejection will cause the pressure in the high-pressure fuel pipe to change, which will cause the deviation of the amount of fuel injected, thus affecting the working efficiency of the engine. This article mainly discusses the pressure changes in the high-pressure fuel pipe due to the intermittent work of fuel entry and ejection. The pressure in the high-pressure fuel pipe is controlled by solving the following problems: by giving the length of the inner cavity of the high-pressure oil pipe, the inner diameter, the diameter of the small hole of the oil supply inlet, the intermittent working time of the fuel injector, the constant pressure value provided by the high-pressure oil pump at the inlet, and the initial pressure value in the high-pressure oil pipe, calculate the length of time the check valve opens when the pressure in the high-pressure oil pipe is as stable as possible at 100MPa. And when the pressure is 100MPa, the fuel density is 0.850 mg/mm³.
Figure 1. Schematic diagram of high pressure tubing.

If the scatter plot of elastic modulus and pressure is interpolated to obtain the relationship curve shown in Figure 2, and the relationship \( E = E(p) \) is given, where \( p \) represents the fuel pressure.

![Figure 2. Fitting curve of elastic modulus and pressure.](image)

The relationship between fuel pressure change and density change is:

\[
\Delta \rho = \Delta p \frac{\rho}{E}
\]  \hspace{1cm} (1)

As in equation (1), \( \Delta \rho \) represents the fuel density change; \( \rho \) represents the fuel density; \( \Delta p \) represents the fuel pressure change.

As in equation (1), we can get:

\[
\rho_{n+1} = \rho_n + \Delta p \frac{\rho}{E}
\]  \hspace{1cm} (2)

As in equation (2), \( \rho_n \) represents the fuel density of the high-pressure fuel pipe at time \( n \).

Since the fuel density \( \rho \) and the elastic modulus \( E \) both change with the pressure, it is difficult to calculate, so it is necessary to list the recursive formula and use the improved Euler method to calculate its numerical solution, get the following relationship:

\[
\begin{align*}
\frac{\rho_{n+1}}{\rho_{n}} &= \frac{\rho_{n+1}}{\rho_{n}} + \Delta p \frac{\rho}{E(p_n)} \\
\rho_{n+1} &= \rho_n + \frac{1}{2} \Delta p \left[ \frac{\rho_n}{E(p_n)} + \frac{\rho_{n+1}}{E(p_{n+1})} \right] \\
\rho_0 &= 0.85 \text{mg/mm}^3 \\
p_0 &= 100 \text{MPa}
\end{align*}
\]  \hspace{1cm} (3)

As in equation (3), \( p_n \) represents the pressure at time \( n \); \( \rho_0 \) represents the fuel density when the pressure is 100MPa; \( p_0 \) represents the pressure at 100MPa.

Thereby obtaining the relationship curve of \( \rho - p \), as shown in Figure 3.
Obtained from the flow equation $Q = CA \sqrt{\frac{2\Delta p}{\rho}}$ into the high-pressure oil pipe:

$$Q_n = Cm^2 \sqrt{\frac{2(p_n - p_{n-1})}{\rho_{n-1}}}$$  \hspace{1cm} (4)

As in equation (4), $Q_n$ represents the flow rate of the check valve at time n; $C$ represents the flow coefficient; $r$ represents the inner radius of the check valve inlet; $A$ represents the area of the check valve inlet.

3. Establish a time series model of fuel inlet and outlet high-pressure fuel pipes

Assuming that both the Check valve and the fuel injection nozzle work in a certain regular cycle, 1s is divided into 10 cycles and each cycle is divided into three situations for discussion: (1) Fuel enters first and then ejects (2) Fuel is injected after entering (3) Fuel enters into injection at the same time.

First, build a model of fuel entering the high-pressure fuel pipe based on time series:

The initial state of the high-pressure oil pipe is as follows:

$$Q_{enter,0} = CA_{enter} \sqrt{\frac{2\Delta p}{\rho}}$$
$$m_{enter,0} = \rho_{tubing} V_{tubing}$$
$$p_{enter,0} = 0.85\text{mg/mm}^3$$
$$\rho_{enter,0} = 100\text{MPa}$$  \hspace{1cm} (5)

As in equation (5), $Q_{enter,0}$ represents the initial rate of fuel entering the high-pressure fuel pipe; $m_{enter,0}$ represents the initial value of the mass when the fuel enters the high-pressure fuel pipe; $\rho_{enter}$ represents the initial value of the fuel density when the fuel enters the high-pressure fuel pipe; $p_{enter,0}$ represents the initial value of the pressure when the fuel enters the high-pressure fuel pipe; $A_{enter}$ represents the area of the check valve port.

The prediction formula at time $n+1$ in the recursive model of the high-pressure tubing is as follows:

$$\tilde{m}_{enter,n+1} = m_{enter,n} + \Delta t_{enter} \frac{Q_{enter,n} \rho_{enter,n}}{V_{tubing}}$$
$$\tilde{\rho}_{enter,n+1} = \rho_{enter,n} + \frac{\Delta t_{enter} Q_{enter,n} \rho_{enter,n}}{V_{tubing}}$$
$$\tilde{p}_{enter,n+1} = p(\rho_{enter,n+1})$$  \hspace{1cm} (6)

The correction formula at time $n+1$ in the recursive model of this high-pressure tubing is as follows:
As in equation (6)(7), $Q_{\text{enter}}$ represents the rate of fuel entering the high-pressure fuel pipe at time $n$; $\rho_{\text{enter}}$ represents the fuel density of fuel entering the high-pressure fuel pipe at time $n$; $V_{\text{tubing}}$ represents the volume of the fuel pipe; $p_{\text{enter}}$ represents the pressure of fuel entering the high-pressure fuel pipe at $n$.

Establish a fuel injection high-pressure fuel pipe model based on time series:

The initial state of the high-pressure oil pipe is as follows:

$$
\begin{align*}
\rho_0 &= \rho_{\text{ejection}_0} V_{\text{tubing}} \\
p_0 &= 100 \text{MPa} \\
m_0 &= m_0 + \Delta m_0
\end{align*}
$$

As in equation (8), $\rho_{\text{ejection}}$ represents the initial value of fuel density when fuel is injected from the high-pressure fuel pipe; $p_{\text{ejection}_0}$ represents the initial value of pressure when fuel is injected from the high-pressure fuel pipe.

The prediction formula at time $n+1$ in the recursive model of the high-pressure tubing is as follows:

$$
\begin{align*}
\rho_{\text{ejection}_n+1} &= \rho_{\text{ejection}_n} + \frac{\Delta t_{\text{ejection}} Q_{\text{ejection}_n} p_{\text{ejection}_n}}{V_{\text{tubing}}} \\
p_{\text{ejection}_n+1} &= p(\rho_{\text{ejection}_n+1})
\end{align*}
$$

The correction formula at time $n+1$ in the recursive model of this high-pressure tubing is as follows:

$$
\begin{align*}
Q_{n+1} &= Q(t_{n+1}) \\
p_{\text{ejection}_n+1} &= p_{\text{ejection}_n} + \frac{\Delta t_{\text{ejection}} Q_{\text{ejection}_n} p_{\text{ejection}_n}}{V_{\text{tubing}}} \\
m_{\text{ejection}_n+1} &= m_{\text{ejection}_n} + Q_{\text{ejection}_n} \Delta t_{\text{ejection}} p_{\text{ejection}_n+1}
\end{align*}
$$

As in equation (10), $\rho_{\text{ejection}}$ represents the fuel density of the fuel injection high-pressure fuel pipe at time $n$; $p_{\text{ejection}_n}$ represents the pressure of fuel injection high-pressure fuel pipe at time $n$; $m_{\text{ejection}_n+1}$ represents the mass of fuel in the high-pressure fuel pipe.

4. Experimental results

If the length of the inner cavity of a certain type of high pressure tubing is 500mm, the inner diameter is 10mm, the diameter of the small hole at the oil inlet A is 1.4mm, the length of the oil supply time is
controlled by the check valve switch, after the check valve is opened once, it will be shut down for 10ms. The fuel injector works 10 times per second, and the fuel injection time for each job is 2.4ms. The high-pressure oil pump provides a constant pressure of 160MPa at the inlet A, and the initial pressure in the high-pressure oil pipe is 100MPa.

4.1. Fuel enters first and then ejects

As the fuel injection quantity is:

\[ M_1 = \rho \int_0^{2.4} V_{\text{ejection}} \, dt \]  

As in equation (11), \( M_1 \) is a certain value, and according to the selected data, \( M_1 = 44.43 \)mg can be calculated iteratively by the constructed model. In each cycle, when the total fuel intake is approximately equal to \( M_1 \), the pressure is stable at 100MPa. Through the above iterative model, when the total fuel intake is greater than or equal to \( M_1 \), the iteration is stopped, and the time \( t \) is calculated. \( t \) is recorded as the length of time the check valve is opened when the high-pressure fuel pipe is maintained at 100MPa when the fuel enters first and then is ejected.

The calculation results of line 1-5 and line 335-339, the selected data of the calculation results of the check valve opening time when the fuel enters first and then ejects are as follows:

| Time / ms | Pressure    | Injection quality every 0.1ms | Total          |
|----------|-------------|------------------------------|----------------|
| 0.01     | 100.0085019 | 0.153594495                  | 0.133811524    |
| 0.02     | 100.0170035 | 0.153583613                  | 0.267613567    |
| 0.03     | 100.0255048 | 0.15357273                   | 0.40140613     |
| 0.04     | 100.0340057 | 0.153561847                  | 0.53518921     |
| ...      |             |                              |                |
| 3.34     | 102.8206954 | 0.149951671                  | 44.16397449    |
| 3.35     | 102.8290826 | 0.149940674                  | 44.29460281    |
| 3.36     | 102.8374695 | 0.149929677                  | 44.42522154    |
| 3.37     | 102.845856  | 0.14991868                   | 44.55583069    |

Final result 3.37

It can be seen from Table 1 that when the fuel enters first and then ejects, the pressure in the high-pressure fuel pipe continues to rise, which makes the fuel injection rate of the high-pressure pump gradually decrease, so in this case the check valve has the longest opening time and the maximum time \( t \) is 3.37ms.

4.2. Fuel is injected after entering

It can be seen from the situation (1) that when the fuel is first injected

\[ m_0 = \rho_{\text{low}} V' - M_1 \]  

When the total amount of entry reaches \( M_1 \), the pressure is restored to 100MPa, and \( M_1 = 36.65 \)mg is iteratively calculated according to the selected data through the model constructed above, and the \( m_0 \) in the above formula is brought into the discharge model, and iterate to stop the condition when the total amount of entry reaches \( M_1 \), calculate the time \( t \), \( t \) is recorded as the length of time that the check valve is maintained at 100MPa when the fuel is first injected and then enters.

The calculation results of line 1-5 and line 269-273, the selected data of the calculation results of the check valve opening time when fuel is injected first and then enter are as follows:
Table 2. Calculation result of check valve opening time when fuel is injected first and then entered.

| Time / ms | Pressure        | Injection quality every 0.1ms | Total            |
|----------|-----------------|-------------------------------|-----------------|
| 0.01     | 97.97988844     | 0.156169542                   | -36.5139451     |
| 0.02     | 97.98846843     | 0.15615874                    | -36.3778996     |
| 0.03     | 97.9970481      | 0.156147938                   | -36.24186352    |
| 0.04     | 98.00562745     | 0.156137136                   | -36.10583684    |
|          |                 |                               |                 |
| 2.68     | 100.2590745     | 0.153273425                   | -0.524910254    |
| 2.69     | 100.2675662     | 0.153262533                   | -0.391387935    |
| 2.7      | 100.2760576     | 0.15325164                    | -0.257875107    |
| 2.71     | 100.2845486     | 0.153240747                   | -0.124371768    |

Final result: 2.72

It can be obtained from Table 2 that when the fuel is first injected and then entered, the initial pressure in the high-pressure fuel pipe is lower than 100MPa, which makes the injection rate of the high-pressure fuel pump higher than that in other cases, so the check valve has the shortest opening time, the shortest time \( t \) is 2.72 ms.

4.3. Fuel enters into injection at the same time

From the analysis in Tables 1 and 2 and above, it can be seen that the opening time of the single valve which maintains the pressure of 100MPa in the high-pressure fuel pipe is between 2.84ms and 2.9ms, while the fuel entering and exiting simultaneously is between the two, the interval between complicated and valve opening is more precise.

5. Conclusion

The above three situations can be obtained, the check valve opening time is between 2.72ms and 3.37ms. The huge pressure fluctuation of high-pressure fuel will also cause greater elastic deformation of the high-pressure fuel pipe. Under such deformation, the pressure will change accordingly. Therefore, it is necessary to adjust the running law of the check valve in the high pressure oil pipe so that the pressure is relatively stable at a certain value, the working process of the engine is more reasonable, and the engine loss is reduced. In this paper, the improved Euler method is used to optimize the recursive formula for solving, which can make the results more accurate. If the problem is further analyzed, the finite element method can be used to build a more accurate model of the high-pressure oil pipe and oil pump.

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