Numerical Simulation of Pressure Control in High Pressure Pipe

Mei Xiong, Longwei Chen* and Yang Sun
College of Statistics and Mathematics, Yunnan University of Finance and Economics Kunming, Yunnan, 650221, P.R. China

*Corresponding author

Abstract. When the injector works, how to control the fuel inlet valve so that the fuel pressure in the high-pressure fuel pipe is kept at a constant value. The method of calculation and numerical simulation is presented.

Keywords: High pressure pump; Pressure control; Modeling; Numerical simulation.

1. Introduction

![Injection speed graph](image)

**Figure 1.** Injection speed in a period.

The length of the inner cavity of a certain type of high-pressure oil pipe is 500mm, the inner diameter is 10mm. The diameter of the hole at A of the oil supply inlet is 1.4mm. The oil supply time is controlled by the one-way valve switch. The one-way valve should be closed for 10ms after each opening. The fuel injector operates 10 times per second, with a fuel injection time of 2.4ms[1]. The rate of injection from nozzle B (Fig.1) is as shown in Figure 1. The pressure provided by the high-pressure fuel pump at inlet A is $160 \text{ MPa}$, and the initial pressure in the high-pressure oil pipe is $100 \text{ MPa}$. How to set the duration of each opening of the check valve if you want to stabilize the pressure in the high-pressure fuel pipe at about $100 \text{ MPa}$ as much as possible.

The intermittent working process of fuel entering and expelling will cause the change of pressure inside the high-pressure tubing, making the fuel volume at the inlet and outlet not equal, thus achieving the purpose of affecting the working efficiency of the engine. This paper explores the control strategy of high pressure tubing based on numerical simulation.

2. Control Strategy for Stabilizing High Pressure Tubing Pressure

The fuel at high pressure pipe A comes from high pressure oil pump, and the needle valve controls nozzle B. Fig.2 shows the oil pressing process of a high-pressure oil pump. The cam drives the plunger up and down, and the relationship between the cam edge curve and the twist is attached. The fuel in the plunger chamber is compressed as the plunger moves upward[2]. When the pressure in the plunger chamber is greater than that in the high-pressure tubing, the one-way valve connecting the plunger...
chamber and the high-pressure tubing opens and the fuel enters the high-pressure tubing. The internal diameter of the plunger cavity is 5mm. When the plunger moves to the top stop, the residual volume of the plunger cavity is 20mm$^3$. When the plunger moves to the bottom stop, the low pressure fuel fills the entire plunger chamber (including the remaining volume) at a pressure of 0.5MPa.

**Figure 2.** The structure of high pressure pipe.

### 2.1. Oil Pump Ressure
Knowing the relationship between the polar angle and the polar diameter of the left camshaft in Figure 3, when the polar angle is extremely, \( \theta = 0 \) or \( 2\pi \), the pole diameter reaches the maximum (top dead center) \( r_{\text{max}} = 7.239 \text{ mm} \). When it is extremely, \( \theta = \pi \), bottom dead center \( r_{\text{min}} = 2.413 \text{ mm} \). This establishes a functional relationship between the polar diameter \( r \) and the polar angle \( \theta \), \( r = r(\theta) \), and also establishes a functional relationship between the volume of the high pressure pump and the pole[3]. The diameter of the high-pressure fuel pump is \( d = 5/2 \text{ mm} \), that is, the difference between the poles of the top dead center and the bottom dead center, \( L_0 = r_{\text{max}} - r_{\text{min}} = 4.826 \), and the maximum height at which the piston can be compressed. Let the stroke of the piston move upwards as \( h \in [0, L_0] \), piston void volume (fuel volume)

\[
V(h) = \pi d^2 (L_0 - h)
\]

among \( h = h(\theta) = r_{\text{max}} - r(\theta) \). Under normal pressure \( P_0 = 0.5\text{MPa} \), when \( \rho_0 = 0.8 \text{mg/mm}^3 \), Maximum amount of fuel that can be inhaled is \( m_0 = V_{\text{max}} \cdot \rho_0 = 76.65 \text{mg} \).

The density in piston cavity is

\[
\rho_b = \frac{\Delta m}{(V(h)+V_{\text{oo}})}
\]

Where \( V_{\text{oo}} = 20 \text{mm}^3 \) is the residual volume of fuel pump.

The relationship between pressure and density is as follows:

\[
P_k = P_{k-1} + \frac{E_{k-1}}{\rho_{k-1}} \cdot (\rho_k - \rho_{k-1})
\]

### 2.2. Injection Speed of Injector
The nozzle structure is shown in Fig.3. The diameter of the needle valve is 2.5 mm, seal seat for one and a half Angle for 9° taper, minimum nozzle diameter of 1.4 mm. Under the working times of the injector, the size of the high-pressure fuel pipe and the initial pressure given in section 1, determine the angular velocity of the cam, so that the pressure in the high-pressure fuel pipe is as stable as possible at about 100 MPa [4].

It is known that the relationship between needle valve lift \( y \) and time is \( y = y(t) \), and the numerical simulation diagram is shown in Figure 4.
Establish the relationship between orifice flow $Q_j = Q_j(h) = Q_j(y(t))$. The effective flow area formula of needle valve opening is

$$S = S(t) = S_2 - S_1 = \pi(d_2^2 - d_1^2).$$

(4)

Where $d_2 = d_1 + y(t)\tan \alpha_0$ is the radius of the plane circle at the bottom of the needle valve, $d_1 = 2.5/2 \text{ mm}$ is the radius at the bottom of the needle valve, $\alpha_0$ is the top angle of the half cone. Therefore, the orifice flow is

$$Q_j = C \cdot S(t) \sqrt{2(P_j - P_0)/\rho_j}$$

(5)

Where coefficient $C = 0.85$, $P_j$ is the pressure in the high pressure oil pipe, $P_0$ is the atmospheric pressure in the cylinder. The density is $\rho_j = \Delta m_j/V_0$ in the high-pressure oil pipe, $\Delta m_j$ is the quality of fuel in the high pressure fuel line[5].

In a period of time $2.4 \text{ ms}$, the mass of fuel injected within $100 \text{ MPa}$ is $m_0 = 79.56 \text{ mg}$. The theoretical value of fuel injection is $m_0 = 79.56 \text{ mg}$ at a constant pressure of $P_j = 100 \text{ MPa}$, which is close to that of $m_i = 76.65 \text{ mg}$. Therefore, a fuel injection corresponding to a reciprocating motion of the oil pump is considered. For high-pressure fuel lines, fuel mass must be conserved, i.e $\Delta m_{in} = \Delta m_{jet}$.

---

**Figure 3.** Needle valve and spray hole.

**Figure 4.** Relation between time and needle valve lift.
2.3. The Angular Velocity and Injection Quantity of Camshaft

2.3.1. Fuel density and pressure in the pump. We suppose the camshaft angular speed as $\omega / \text{arc ms}$, when $t \in [0, 2.4] \text{ ms}$ the polar diameter is $r = r(\omega \cdot t + \pi)$, then calculate the volume, density and pressure of the fuel pump.

$$V(h) = \pi d^2 (L_0 - h), \quad \rho_b = \Delta m_b / (V(h) + V_0), \quad P_k = P_{k-1} + \frac{E_k}{\rho_{k-1}} \cdot (\rho_k - \rho_{k-1})$$

2.3.2. Mass of fuel from the pump into the high pressure pipeline. When the pressure reaches 160 MPa, the fuel control valve opens and the fuel mass per time unit flows is

$$\Delta m_F = Q_k \cdot \rho_{lk} = C \cdot A \sqrt{2 \left( P_{lk} - P_{2k} \right) / \rho_{lk}} \cdot \rho_{lk} = C \cdot A \sqrt{2 \left( P_{lk} - P_{2k} \right) / \rho_{lk}}.$$ 

In the upper form, $C = 0.85, A = \pi d^2, d = 0.7 \text{ mm}, P_{lk}$ is the oil pump pressure of time step $k$, $P_{2k}$ is the pressure of high pressure fuel pipe in time step $k$; $\rho_{lk}$ is the fuel density of step $k$ oil pump.

2.3.3. Fuel density and pressure changes in high pressure fuel lines. The quality of fuel in the high-pressure oil pipe is

$$\Delta m = \Delta m_F + m_0 - \Delta m_{jet}.$$ 

Where $\Delta m_F$ is the inflow, $\Delta m_{jet}$ is the injection, and $m_0$ the mass of fuel in the oil pipe. Because the volume formula of high-pressure fuel pipe is $V_o = L \cdot \pi \cdot d^2$ ($L = 500 \text{ mm}, d = 5 \text{ mm}$), Its density formula is $\rho_k = \Delta m_k / V_o$. The pressure is calculated according to the following formula:

$$P_k = P_{k-1} + \frac{E_k}{\rho_{k-1}} \cdot (\rho_k - \rho_{k-1})$$

Among them, the elastic modulus is basically kept at 100 MPa due to the pressure of high-pressure pipe, approximate modulus value $E(100) = 2171.4$ at this moment.

3. Conclusion

It is difficult to solve the angular velocity directly. $\Delta t = 0.01 \text{ ms}$ is the time step for discrete calculation. In the same time step, all variables are calculated as constant. Range of estimated angular velocity $\omega \in [0.05, 2] \text{ arc / ms}$, Through the numerical simulation method, using the ergodic method to get $\omega = 1.308 \text{ arc / ms}$. Assuming that the camshaft starts at the shortest polar position, the pressure of the high-pressure pump does not change in a cycle $T_o = 2.4 \text{ ms}$; The fuel pressure in the high-p is as shown in the figure 5.
At the initial stage when the time is less than 0.4 ms and the pressure in the fuel pump does not reach 100 MPa, the high-pressure oil pipe has started to inject oil, causing the pressure of the high-pressure oil pipe to be slightly less than 100 MPa. When the time exceeds 0.4 ms, the oil inlet valve A is opened, and the fuel pressure in the high-pressure oil pipe rises rapidly, reaching the maximum value and keeping above 100 MPa. When the time is more than 2 ms, the pressure of the high-pressure pump drops, and a local maximum value is formed due to the decrease of the injection quantity of the high-pressure pipe. The fuel quality from the high-pressure pump to the high-pressure oil pipe is $m_{total} = 75.5 mg$. The quality of fuel pressure oil pipe ejected from the high-pressure oil pipe is $m_{2_{total}} = 66.36 mg$. The total surplus fuel oil is $\Delta m_\delta = 9.14 mg$, and the pressure reducing valve must be opened to allow it to return to the fuel pipeline. In order to keep the pressure in the high-pressure oil pipe at 100 MPa, open the pressure relief valve near the pressure front value of the high-pressure oil pipe. Set the opening time as $t_o ms$, then,

$$\Delta m_\delta = Q_\delta \cdot \rho_\delta \cdot t_\delta = C \cdot A \cdot t_r \sqrt{2(P_{r_1} - P_{r_2}) \cdot \rho_r}.$$  \hspace{1cm} (8)

$C = 0.85$, $A = \pi \times 0.7^2 = 1.5386 \text{ mm}^2$, $P_{r_1} = 100 \text{ MPa}$, $P_{r_2} = 0.5 \text{ MPa}$, $\rho_r = 0.85 \text{ mg/mm}^3$, get the solution $t_r = 0.0055 \text{ ms}$.  

Figure 5. The pressure in oil pump in a work period (MPa).

Figure 6. The pressure in oil pipeline in a work period (MPa).
Acknowledgement
The author sincerely thanks Yunnan Tobacco Company for the support of the science and technology project "Research on Data Resource Mining Based on Multi-objective Decision Making".

Reference
[1] Ouyang G, An S, Liu Z, et al. Common rail fuel injection technology in diesel engines[J]. 2019.
[2] LIU Guanlin, MIAO Yuanyuan, Gong Jinke, Design of High Pressure Fuel Pump Control System for GDI Engine, Journal of Hunan University(Natural Sciences), Vol. 45, No.4 Apr.2018:57-64.
[3] AN Shi-jie, Zhou Lei, YANG Kun etc., Simulation analysis on dynamic characteristics of high pressure fuel pump based on fuel metering valve, SHIP SCIENCE AND TECHNOLOGY, Vol.39,No.10 Oct., 2017:97-103.
[4] WANG Huimin, XIANG Jianhua, WANG Chuan, Simulation of Micro Motion of Common Rail High-pressure Fuel Pump Plunger, Chinese Internal Combustion Engine Engineering, Vol. 40 No.3 June. 2019:65-72.
[5] Kang J, Hu H. Vibration detection & diagnosis for high-pressure fuel pipe of diesel engine[C]//International Conference on Information Acquisition, 2004. Proceedings. IEEE, 2004: 127-129.