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A pressure control scheme of high pressure oil pipe

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ABSTRACT

Referring to the material balance method in oil exploitation, the material balance model of oil supply and oil injection is established. By restricting the error accuracy of the same period (100 Milliseconds, briefly, 100*ms*) of the fuel supply and the fuel injection, it is obtained that, at a fixed injection rate, the opening time of oil pump check valve is 0.298*ms*. Thus, the pressure stability in the high-pressure oil pipe can be precisely controlled. Then, the one-way valve opening strategy is studied, which makes the pressure of high-pressure oil pipe increase from 100 MPa to 150 MPa, and after about 2*s*, 5*s* or 10*s* adjustment respectively, it is stable at 150 MPa.

KEYWORDS: High-pressure common rail system; Non-linear fitting; Data iteration

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I. INTRODUCTION

The high-pressure common rail technology is the basis of many fuel oil engines. The intermittent working process of fuel entering and ejecting can cause pressure changes in the high-pressure fuel pipe. This will cause a deviation in the amount of fuel injected. The high-pressure common rail system is a closed system composed of a high-pressure oil pump, a pressure sensor, and an electronic control unit (ECU) [2]. It separates the generation of injection pressure from the injection process. By [1], the pressure of the high-pressure oil pipe is independent of the engine speed. This shows that the change of fuel supply pressure with engine speed can be greatly reduced.

The working principle of the high-pressure common rail system is shown in Figure 1. Through the high-pressure oil pump, the fuel enters the high-pressure oil pipe from port A, and then ejects from the injection nozzle B.

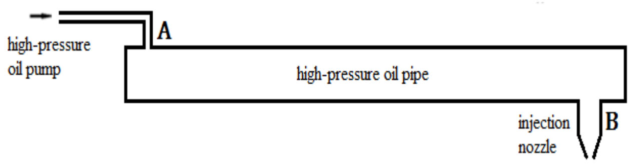

Figure 1. Working diagram of high pressure oil pipe

In the existing research, most of them adopt the algorithm optimization based on PID control (see [3]-[7], for example). According to the difference of pressure deviation, different PID setting coefficients are calculated, and the oil supply time of high pressure oil pump is adjusted to reduce the deviation.

This paper will discuss how to control the pressure in the high pressure oil pipe by using the opening time of one-way valve. so as to make the engine work more efficiently. So the efficiency of the engine will be improved.

II. DISCUSSION ON OPENING TIME OF CHECK VALVE

For the convenience, it is assumed that the check valve of a high-pressure oil pipe will be closed after being opened once. The injector works 10 times per second, and the injection time is 2.4*ms* each time. When the injector is working, the rate of injection from nozzle B to the outside is shown in Figure 2. The pressure provided by high pressure oil pump at inlet A is 160MPa, and the initial pressure in high pressure oil pipe is 100MPa. The following will study how to control the length of oil supply time through the one-way valve switch to make the pressure of high-pressure oil pipe stable.

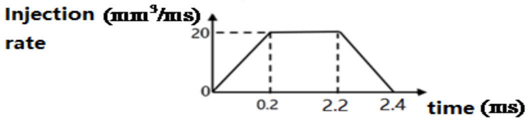

Figure 2. Schematic of injection rate

The relationship between modulus of elasticity and pressure is shown in the table below.

Table 1. Relationship between elastic modulus and pressure

Pressure (MPa)	elastic modulus	Pressure (MPa)	elastic modulus
90	2091.1	125	2396.4
91	2098.9	126	2406.2
92	2106.8	127	2416.1
93	2114.7	128	2426.1
94	2122.6	129	2436.1
95	2130.6	130	2446.2
96	2138.7	131	2456.3
97	2146.8	132	2466.6
98	2155	133	2476.9
99	2163.2	134	2487.3
100	2171.4	135	2497.7
101	2179.7	136	2508.3
102	2188.1	137	2518.9
103	2196.5	138	2529.6
104	2205	139	2540.3
105	2213.5	140	2551.2
106	2222.1	141	2562.1
107	2230.7	142	2573.1
108	2239.4	143	2584.2
109	2248.2	144	2595.4
110	2257	145	2606.7
111	2265.9	146	2618
112	2274.8	147	2629.4
113	2283.8	148	2641
114	2292.8	149	2652.6
115	2301.9	150	2664.3
116	2311.1	151	2676
117	2320.3	152	2687.9
118	2329.6	153	2699.9
119	2339	154	2712
120	2348.4	155	2724.1
121	2357.8	156	2736.4
122	2367.4	157	2748.7
123	2377	158	2761.2
124	2386.7	159	2773.8
125	2396.4	160	2786.4

To keep the pressure in the high-pressure oil pipe stable, it is necessary to make the amount of fuel entering from port A equal to the amount of fuel ejected from port B. According to the knowledge of physics, the density of fuel in the high-pressure oil pipe will change with the change of oil pipe pressure. The pressure change of fuel is directly proportional to the density change, and the ratio coefficient is $\frac{E}{\rho}$, where ρ is the density of fuel, E is the elastic modulus. The relationship between E and pressure is shown in Table 1. When the pressure is 100 MPa, the density of the fuel is 0.850 mg/mm^3. Assumed that the volume of the high-pressure fuel pipe is rigid[8]. The relationship between the fuel density and the corresponding pressure can be finded out. And the change of the pressure inside the high-pressure oil pipe caused by the increase or decrease of fuel can be calculated.

Refer to material balance method used in oil and gas production[8], calculate the quality of oil supply at A and the quality of oil injection at B respectively. Then the corresponding total time of oil supply and injection is obtained. Finally, the opening time of check valve can be adjusted.

III. THE MODELING OF FUEL INJECTION PROCESS FOR HIGH PRESSURE TUBING

Frist, the flow in and out of the high-pressure oil pipe is

$$Q = CA\sqrt{\frac{2\Delta P}{\rho_H}} \qquad \text{............(1)}$$

where Q is the amount of fuel flowing through the small hole per unit time (mm^3/ms), C = 0.85 is the flow coefficient, A is the area of the small hole (mm^2), ΔP is the pressure difference (MPa) on both sides of the small hole, and ρ is Density (mg/mm^3) of high-pressure fuel.

When the fuel enters the high-pressure fuel pipe from A, ΔP is the result of subtracting the pressure at A from the pressure in the high-pressure fuel pipe. Where, the pressure at A is a constant pressure of 160MPa, and the pressure in the high-pressure fuel pipe is a change amount $P(t)$ with time, then

$$\Delta P = P_1 - P(t) \qquad \text{............(2)}$$

And $P(t)$ can be obtained from the pressure $p(t_1)$ at the previous time point t_1 plus the pressure change amount ΔF, that is,

$$P(t) = P(t_1) + \Delta F \qquad \text{............(3)}$$

Since the fuel pressure change ΔF is proportional to the density change $\Delta\rho$, and the proportionality factor is $\frac{E}{P}$,

then, $$\frac{\Delta F}{\Delta\rho} = \frac{E}{\rho} \qquad \text{............(4)}$$

where E is the elastic modulus and ρ is the fuel density.

Since the density changes due to the change in pressure, the density of the above formula can be regarded as the density at the previous time point t_1. According to the relationship between the elastic modulus and the pressure in Table 1, the pressure change is

$$\Delta F = \frac{E(P)}{\rho(t_1)} \Delta\rho \qquad \text{............(5)}$$

During the Δt, the increase of fuel mass in the high-pressure tubing is $Q_1 \rho_1 \Delta t$, so the change in density is

$$\Delta\rho = \frac{Q_1 \rho_1 \Delta t}{V} \qquad \text{............(6)}$$

where V is the volume of fuel in the high-pressure fuel pipe, that is, the volume of the high-pressure fuel pipe.

Thus, oil supply quality m_1 is,

$$m_1 = \sum Q_1 \rho_1 \Delta t \qquad \text{............(7)}$$

The following will calculate the injection quality m_2. By Figure 2, the injection volume flow can be obtained from the rate and the cross-sectional area of the pipeline. The calculation formula is,

$$Q_2 = vt \qquad \text{............(8)}$$

where v is the fuel injection rate and t is the time. Then

$$m_2 = \int_{t_2} Q_2 \rho_2 dt \qquad \text{............(9)}$$

In summary, the model is as follows,

$$\begin{cases} Q(t) = CA\sqrt{\dfrac{2\Delta P}{\rho_H}} \\ \Delta P = P_1 - P(t) \\ P(t) = P_0 + \Delta F \\ \Delta F = \dfrac{E(P)}{\rho(t_1)}\Delta\rho \\ \Delta\rho = \dfrac{Q_1\rho_1\Delta t}{V} \\ m_1 = m_2 \end{cases} \qquad \text{............(10)}$$

where P_1 is constant pressure 160MPa at A, P_0 is 100MPa, and $\rho_{高}$ is high-pressure fuel.

The following will solve the model.

As shown in figure (2), the rate of oil injection outward from nozzle B can be expressed as the following function,

$$Q(t) = \begin{cases} 100t & 0 \le t \le 0.2 \\ 20 & 0.2 < t \le 2.2 \\ 20 - 100(t - 2.2) & 2.2 < t \le 2.4 \end{cases} \qquad \text{........(11)}$$

It can be got that the volume of the injection is

$$\int_0^{2.4} Q(t)dt = 44\,(mm^3)\cdot$$

To obtain the oil supply mass, the fuel density under each pressure should be calculated out first. The data in table 1 shows that the pressure variation ΔF is always 0.5 MPa, and because the density of the fuel is $0.850\ mg/mm^3$ when the pressure is 100 MPa, so this can be used as an initial value to get the fuel density value ρ by iterate forward from 101 MPa to 200 MPa, and get the fuel density value ρ by iterate backward from 0 MPa to 99 MPa. Fitting the data and get the fitting image as shown in the Figure 3.

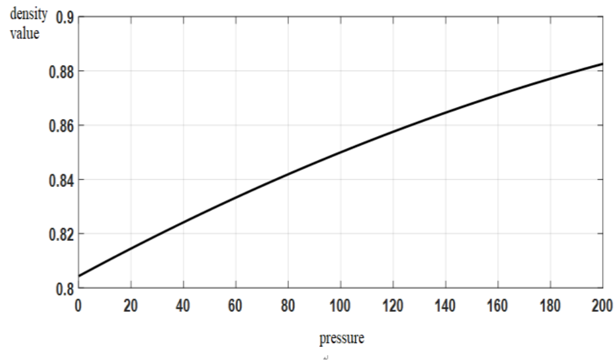

Figure 3. Relationship between fuel pressure and density

It can be seen from Figure 3 that the trend of the data is very similar to image of a exponential function. Therefore, the curve can be fitted by the fitting toolbox of MATLAB. And the function relationship between pressure P and fuel density r is as follow.

$$r(P) = -0.1622\exp(-0.003329P) + 0.9663$$

Where the determination coefficient of the fitting result is R-square = 1, and the variance is SSE = 4.876e-06. The fitting result is better.

From the above functional relationship, the fuel density at any high-pressure fuel pipe pressure can be obtained. Moreover, the fuel quality at this time can be obtained.

Since the corresponding coefficient of P is -0.003329, then the change in the pressure P has small effect on the fuel density. The same conclusion can be obtained from Figure 3. The pressure changes greatly, but the density changes within 0.1. The two results are consistent. This indicating that the fitted curve is reasonable. But if assume that the pressure is constant after injection and after oil supply, the error will be larger.

Here, it should be noted that when the material balance principle is used to calculate the balance between the input and output of high-pressure tubing, the error still exists in the iterative process. So the quality of the fuel supply and the fuel injection are not completely equal. For this reason an error accuracy acc is given. When $\Delta m \leqslant acc$, it is considered that the fuel supply quality is equal to the fuel injection quality.

Based on the above principles, a cyclic algorithm can be used to obtain the total opening time of the one-way valve. The algorithm is shown below:

*step*1 Enter the error accuracy *acc*, unit time Δt, and fuel injection quality m_2. The initial time and initial fuel supply quality are all 0;

*step*2 Calculate the fuel supply flow rate Q in per unit time;

*step*3 Calculate the oil supply quality within a unit time. The oil supply quality will change the pressure of the high-pressure oil pipe. This will affect the calculation of oil supply flow in the next period;

*step*4 Calculate the cumulative fuel supply quality and cumulative time, the formula is as follow.

$$\begin{cases} m_1 = m + \Delta m \\ t = t + \Delta t \end{cases}$$

*step*5 Subtraction of m_1 and m_2. When the difference is greater than the error accuracy *acc*, repeat steps 2 to 5. When the difference is less than or equal to the error accuracy *acc*, the period ends and the time *t* is output.

Through continuous debugging of the program, it is concluded that, when the error accuracy *acc* is 1.13 and the time step of the iteration Δt is 0.001, the running speed is relatively fast and the error of the result is small.

The solution of the problem in II is as follows. The opening time of check valve in 100*ms* is *t* = 2.6830*ms*. Since the check valve needs to be closed for 10*ms* after opening, then the check valve needs to be opened and closed at least 9 times in 100*ms*. Turn on and off one time as a period, so the total opening time *t* is distributed in nine different periods. Thus, it is obtained that a single one-way valve opening time t_0 is $0.2980ms$.

Now, check the opening time of one-way valve every time, and simulate the opening time of one-way valve after even distribution. Generally, the inner nozzle is only opened once in 100*ms*. In order to make the pressure inside the high-pressure oil pipe more stable, the injection process should be interleaved between 9 periods when the check valve is opened. The check valve is opened and closed three times first, then the injection nozzle and check valve are opened at the same time, and then the check valve is opened and closed three times again. Thus, the pressure change diagram of high pressure oil pipe in one second can be drawn as below.

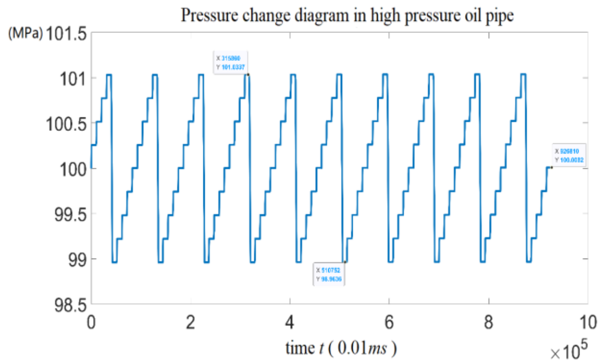

Figure 4. Pressure change of high pressure oil pipe in 1s

It can be seen from the figure that the pressure change in the high-pressure oil pipe is between 98.9636 Mpa and 101.0337 MPa and periodic change. After the end of each period, the pressure in the oil pipe is close to 100MPa. Therefore, the opening time of chack valve can meet the requirements of this problem.

IV. AN EXPAND

When the diesel engine is working, the ECU system can control the pressure change in the high-pressure oil pipe to meet the engine's different injection pressure for different working conditions. The following will use the method above to simulate the problem.

Question: If you want to increase the pressure in the high-pressure oil pipe from 100 MPa to 150 MPa, and stable at 150 MPa after about 2*s*, 5*s* and 10*s* of different adjustment processes respectively, how should the check valve open time be adjusted?

In this case, the internal changes of the fuel system are very complicated. To simplify the model, add a hypothesis that the fuel injection process and the fuel supply process do not occur at the same time. In one period, the check valve opening time can be considered only once. Since the injector works 10 times per second, each time works 2.4*ms*, that is, the duration of each work is very short, then a change process of a period can be regarded as, first injection, then oil supply, and finally neither oil supply nor oil injection, as is shown in the following figure.

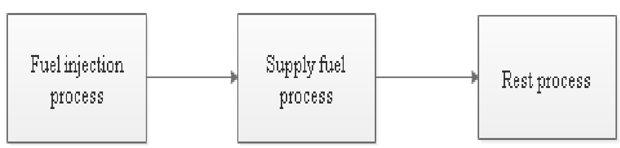

Figure 5. Schematic diagram of fuel change in one period

To increase the pressure in the high-pressure oil pipe, fuel must accumulate in the high-pressure fuel pipe at the end of each period. According to the fuel accumulation quality of each period, the corresponding density change and the corresponding pressure change can be calculated. Then, it can be obtained that how many periods are needed to increase the pressure to 150MPa.

According to the model in this paper, if you want to stabilize the pressure of high-pressure oil pipe at 150MPa, the required opening time of the check valve is about 0.726*s*. Therefore, in order to improve the efficiency of the engine, the process of oil pipe pressure rise in three stages is arranged as follows.

i) Find the fuel supply quality in a period (100*ms*),

$$put\_m = \rho(P)Q(P)t \quad \text{...........(12)}$$

where ρ and Q both change with P, and the values can be obtained by combining formulas (2) and (6).

ii) Find out the injection quality in one period

$$out\_m = \int_0^{2.4} Qdt\,\rho(P) \quad \text{...........(13)}$$

where Q can be obtained according to formula (8), ρ changes with P.

iii) Give the accumulated mass of fuel in each period.

$$\Delta m = put\_m - out\_m \quad \text{...........(14)}$$

To sum up, the model is as follows,

$$\begin{cases} \Delta m = put\_m - out\_m \\ \Delta\rho = \dfrac{\Delta m}{V} \\ \Delta F = \dfrac{E(P)}{\rho(t_1)}\Delta\rho \\ P(t) = P_0 + \Delta F \end{cases} \quad \text{...........(15)}$$

In order to simplify the calculation of the model, assume that, in one period (about 100*ms*), the oil pump starts to supply oil to the high-pressure oil pipe after the injection process of the high-pressure oil pipe is completed. When the area of the small hole is constant, the flow rate of the oil supply is only related to the pressure difference. Before and after injection, the pressure change in the high-pressure oil pipe is less than 4MPa, which has little effect on the flow rate. Then, Even if the injection process and the fuel supply process do not occur at the same time, the error of the final result is smaller.

According to the above model (15), the three-stage check valve opening time

$$t_1 = 0.61ms,\ t_2 = 0.67ms,\ t_3 = 0.682ms$$

is substituted to simulate the pressure inside the high-pressure oil pipe.

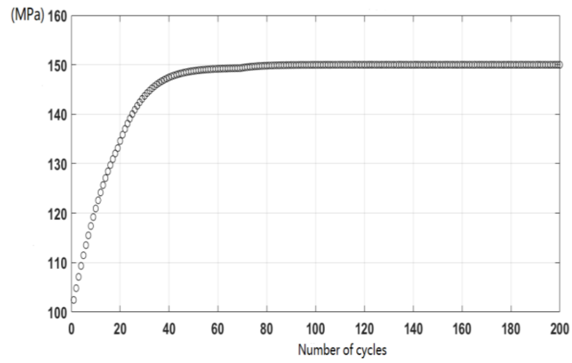

Figure 6. Corrected pressure in high-pressure tubing

From the Figure 6, it can be seen that, in the period of 0~2*s*, the pressure rises rapidly to between 130Mpa and 140MPa. In the period of 2~7*s*, the pressure rises rapidly to about 145MPa, and then slowly to nearly 150MPa. After 7*s*, the pressure of high-pressure oil pipe converged to 150MPa and stabilized at 150MPa.

Under different circumstances, as long as the opening time of the check valve is constant, the pressure in the high-pressure oil pipe will be stable in a certain range. As long as the opening time of chack valve is maintained at 0.682*ms*, the pressure of high-pressure oil pipe will reach 150MPa sooner or later. t_1 and t_2 stages only control the speed of reaching the target pressure. The larger t_1 and t_2, the sooner the target pressure is reached, and vice versa.

V. EVALUATION AND POPULARIZATION OF CHECK VALVE CONTROL MODEL

There are some advantages of the model.

1) The model uses iterative calculation and determines the accuracy according to the step size of iteration. It can simulate and estimate well and approach the actual situation.

2) In the allowable range of error, the model is simplified properly, and the work carried out at the same time is divided into different stages to complete, which reduces the difficulty of calculation.

3) The running time is only related to the number of iterations, so there is no burden on memory space, Which improved iteration efficiency.

While, there are some disadvantages also. For example, when looking for the relationship between pressure and fuel density, due to the small change of fuel density, it is easy to cause the error between the pressure corresponding to the actual fuel density in the high-pressure fuel pipe and the calculated pressure.

With the improvement of fuel economy and emission requirements in recent years, electronic fuel injection technology of diesel engine has gradually become a development trend (see [10]-[13] and others). The pump-tube-nozzle fuel injection model established in this paper is simple and can effectively calculate the opening time of the check valve in the pump. The model can be applied to the injection system of the valve controlled by electromagnetism, so that the user can operate the fuel machinery better and avoid the complex operation. The iterative calculation used in it can also be used in distribution control scheme, heat conduction model calculation, and other cases.

VI. ACKNOWLEDGMENTS

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