2019 3rd International Conference on Mechanical and Electronics Engineering (ICMEE 2019)

Pressure Control Model for High Pressure Fuel Pipe of Diesel Engine

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Keywords: stability, stability, Pressure image

Abstract: As an important fuel supply component of the engine, the stability of the fuel provided by the engine can be improved by adjusting its parameters reasonably. Through the establishment of high-pressure oil pump model, high-pressure oil pipe model and fuel spray nozzle model, as well as fluid continuity theorem, the difference equation of fuel balance in high-pressure oil pipe is established. Then the optimal solution is obtained by repeated iteration using genetic algorithm. Furthermore, the scheme to improve the stability of high-pressure tubing is put forward. The pressure images of the fuel pipe before and after adjustment are drawn with Matlab, which verifies the practicability of the model. This provides a theoretical basis for calculating and studying the internal pressure of high-pressure tubing and improving its working stability.

1. Introduction

At present, diesel engines play an increasingly important role in people's daily production and life, ensuring the fuel supply stability of diesel engines is the basis and premise for the normal and stable operation of the engine power system. Once the fuel supply of the diesel engine fluctuates, it directly affects the smooth operation of the entire diesel engine. [1] Among them, the fuel system of the diesel engine plays a very important role in the whole operation process. How to coordinate the relationship among high pressure oil pump, high pressure oil pipe and injection nozzle, and to ensure the stability of fuel pressure in high pressure oil pipe have become an important research topic in the stability of fuel system. In this paper, we first analyze the structure and principle of high-pressure tubing, abstract the mathematical model from it, and give the solution method of the model. Finally, we propose an optimization scheme to improve the stability of high-pressure tubing.

2. Structure and Principle of Fuel System

The high-pressure fuel system is mainly composed of a high-pressure oil pump, a high-pressure oil pipe and a fuel injection nozzle. The working principle is that the fuel enters the high-pressure oil pipe through the high-pressure oil pump, and then is sprayed out by the fuel injection nozzle. During this process, the non-continuous working process of the high pressure oil pipe inlet and the fuel injection of the fuel injector will cause the pressure in the high pressure oil pipe to change, so that the amount of fuel injected per time deviates from the ideal situation, thereby affecting the working efficiency of the engine.

The high-pressure oil pump is mainly composed of a plug of a cam and a cam-driven column. The cam drives the

Plunger to move up and down. After the cam angular velocity is given, according to the curve and angle relationship of different cam edges, the reciprocating motion of the plunger can be obtained. When the pressure in the plunger

Chamberis greater than the pressure in the high-pressure oil pipe, the one-way valve connected to the high pressure oil pipe of the plunger chamber is opened, and the fuel enters the high-pressure oil pipe.

In the high-pressure fuel pipe, when the fuel system is working, the fuel passes through the high-pressure oil

Pump and enters the high-pressure oil pipe. The high pressure oil pipe delivers the fuel to the injector at a certain

Pressure and speed through the pressure wave, and finally is ejected by the fuel injection nozzle.

In this paper we study the nozzles controlled by mechanical needle valves. The injector is mainly controlled by a needle valve. The up and down reciprocating motion of the needle valve changes the effective area of the fuel

Injection. The intermittent operation of the injector will affect the internal and external pressure of the high-pressure fuel pipe. When the operating frequency of the control needle valve is changed, the oil discharge rate is indirectly affected.

In the course of this research, according to the relationship between cam edge curve and angle, the relationship

Between plunger's movement distance and time in plunger cavity at different speeds is obtained. According to the

Fluid continuity theorem, the fuel flow balance equation in the plunger cavity is listed. Calculate the flow expression of the high-pressure oil pipe flowing from the plunger cavity; determine the flow expression of the fuel injection of

The injector according to the mass balance relationship and the movement law of the needle valve; according to the relationship between the pressure and the elastic model, by iterating from the initial state. The relationship between

Fuel density and pressure is fitted by least squares based on the iterated data. Then, using the continuity equation of

The fluid, the constraints of pressure, fuel density and flow rate in the high-pressure fuel pipe are listed, and the

Corresponding mathematical model is established and the solution method is given.

3. Model establishment and solution.

3.1 Model establishment.

(1) Analysis of oil injection process of high-pressure oil pump

During the pressure oiling process of the high-pressure oil pump plunger, the cam drives the plunger to move up and down, and the lift curve of the high-pressure oil pump plunger is drawn according to the relationship between the cam edge curve and the angle. By conversion, we can get an image of $h_z - t$. The relationship between the fuel flows in the high-pressure fuel pipe satisfies the following relationship:

$$Q_z = Q_{ys} + Q_a (1), \quad Q_z = S_z \frac{dh_z}{dt} (2), \quad Q_{ys} = \frac{V_z}{E} \frac{dP_z}{dt} \tag{1}$$

The pressure inside the high-pressure oil pipe is P_g, then the fuel that flows from the plunger chamber to the high-pressure oil pipe through the oil discharge valve is:

$$Q_a = \varepsilon CA \sqrt{\frac{2}{\rho}(P_Z - P_g)}, \varepsilon = \begin{cases} 1 & P_Z > P_g \\ 0 & P_Z \le P_g \end{cases} \tag{2}$$

Substitute Equations 2, 3, and 4 into Equation 1:

$$S_z \frac{dh_z}{dt} = \frac{V_z}{E} \frac{dP_z}{dt} + \varepsilon CA \sqrt{\frac{2}{\rho}(P_z - P_g)} \Rightarrow \frac{dP_z}{dt} = \frac{E}{V_z}(S_z \frac{dh_z}{dt} - \varepsilon CA \sqrt{\frac{2}{\rho}(P_z - P_g)}) \tag{3}$$

Each time the high-pressure oil pipe enters the oil, the mass of the fuel in the plunger chamber changes, the volume of the plunger chamber changes, and the density of the fuel in the plunger chamber changes. Through the mutual connection between the variables, Q_a can be determined as:

$$Q_a = \varepsilon CA\sqrt{\frac{2}{\rho}(P_Z - P_g)}, \varepsilon = \begin{cases} 1 & P_Z > P_g \\ 0 & P_Z \le P_g \end{cases} \tag{4}$$

(2) Injector analysis of injector

Study the injection quantity of the needle valve, set the pressure between the bottom of the needle valve and the injection hole to P_i, the volume is V_i, the mass of the retained fuel is M_i, and the density of the fuel is ρ_i. When the needle lift is 0, the needle valve is closed; when the needle lift is greater than 0, the needle valve is opened, and the fuel flows to the nozzle hole and is ejected through the nozzle hole. The pressure outside the orifice is P_c. Then, when the needle valve rises to a certain height, the injector is analyzed by the principle of continuity similar to the hydrodynamics in Problem 1, and the following difference equation is obtained:

$$M_i(t+\Delta t) = M_\mathrm{i}(t) + \Delta t S_i\sqrt{\frac{2(\mathrm{P}_g - \mathrm{P}_i)}{\rho_g}}\rho_i - \Delta t S_c\sqrt{\frac{2(\mathrm{P}_i - \mathrm{P}_c)}{\rho_i}}\rho_c (S_i = \pi(H(t)\tan\theta + r_2)^2 - \pi r_2{}^2)$$

Further, the following relationship is obtained:

$$\begin{cases} M_i(t+\Delta t) = M_\mathrm{i}(t) + \Delta t S_i\sqrt{\dfrac{2(\mathrm{P}_g - \mathrm{P}_i)}{\rho_g}}\rho_i - \Delta t S_c\sqrt{\dfrac{2(\mathrm{P}_i - \mathrm{P}_c)}{\rho_i}}\rho_c \\ \rho(\mathrm{t}) = \dfrac{M_i(\mathrm{t})}{V_i} \quad P_i = f(\rho_i)(\text{drawn by model one}) \end{cases} \tag{5}$$

Based on the iteration of the quality relationship from the initial moment, under the constraint of Equation 7, Q_b can be determined as:

$$Q_b = \Delta t S_i\sqrt{\frac{2(P_g - P_i)}{\rho_z}} \tag{6}$$

(3) High pressure oil pipe analysis.

Step 1: Determining the relationship between P and ρ

The pressure change of the fuel is proportional to the change in density. The proportional coefficient is $\frac{E}{\rho}$, then:

$$\Delta P = \frac{E(p)}{\rho}\Delta\rho \Rightarrow P(i) - P(i-1) = \frac{E[P(i-1)]}{\rho(i-1)}[\rho(i) - \rho(i-1)] \tag{7}$$

We use a quadratic function to fit the relationship between them. The fitted relationship between ρ and P is expressed as shown in Equation 10.

$$\rho = -6.607203573830587\times 10^{-7}P^2 + 5.236080567161428\times 10^{-4}P + 0.804238543868881 \qquad (8).$$

Step 2: Continuity equation of fluid mechanics

By the law of conservation of mass—the sum of the differences in the mass of the fluid flowing out of the closed surface in a unit of time is equal to the mass that is reduced by the density change in the closed surface, that is:

$$[\frac{\partial(\rho u_x)}{\partial x} + \frac{\partial(\rho u_y)}{\partial y} + \frac{\partial(\rho u_z)}{\partial z}]\mathrm{dxdydz} = -\frac{\partial\rho}{\partial t}dxdydz(\text{Where u is the flow rate})$$

In this paper, the object studied is high-pressure tubing, that is, the research object is one-dimensional, and then the fluid differential equation can be reduced to:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}=0 \tag{9}$$

Step 3: Derivation of the relationship between pressure P and time t

In this paper, the flow rate of fuel is u, the flow rate per unit time of fuel is Q, and the cross-sectional area of high-pressure fuel pipe is S, the volume is v, and the mass of fuel in high-pressure fuel pipe is M, then:

$$\mathrm{M}=\rho \mathrm{v}, \mathrm{Q}=\mathrm{uS} \tag{10}$$

According to the continuity differential equation of the fluid Equation 11 and Equation 12, the following derivation is performed:

$$\frac{dM}{vdt}+\frac{d(\rho u)}{dx}=0, \frac{dM}{dt}+\rho u S=0$$

Integrate t on both sides, obtain the following difference equation:

$$M(t+\Delta t)=M(t)+Q_a \Delta t \rho_{160}-Q_b \Delta t \rho(t) \tag{11}$$

Where $M(0)=\rho_{100} v$, taking $\Delta t=0.001 ms$, substitute $M(0)$ into Equation 13 to obtain the quality of the fuel at each corresponding moment, then:

$$\rho(t)=\frac{M(t)}{v} \tag{12}$$

According to the function fitted by ρ and P, that is Equation 10 and Equations 13, 14, the pressure P at the corresponding time point can be obtained.

(4) Establishment of single target optimization model

Here we introduce the fluctuation coefficient k to measure the gap between the existing state and the steady state sought. Its specific definition is as follows:

$$k=\frac{1}{n} \sum_{i=1}^{n}(\mathrm{P}-\mathrm{P}_0)^2$$

Where P is the pressure at each time point i in the existing state, and P_0 is the steady state pressure. The problem we want to solve is transformed into the following single-objective optimization model:

$$\text{Objective function} : \operatorname{mink}=\min \frac{1}{n} \sum_{j=1}^{n}(\mathrm{P}-\mathrm{P}_0)^2$$

$$s.t.\begin{cases} Q_a=\varepsilon C A \sqrt{\frac{2}{\rho_z}(\mathrm{P}_z-\mathrm{P}_g)}, \varepsilon=\begin{cases}1 & P_z>P_g \\ 0 & P_z \leq P_g\end{cases} \\ Q_b=\Delta t S_i \sqrt{\frac{2(\mathrm{P}_g-\mathrm{P}_i)}{\rho_g}} \quad \rho(\mathrm{t})=\frac{M(\mathrm{t})}{v} \\ \rho=-6.607203573830587 \times 10^{-7} P^2+5.236080567161428 \times 10^{-4} P+\ 0.804238543868881 \\ M(\mathrm{t}+\Delta \mathrm{t})=\mathrm{M}(\mathrm{t})+\mathrm{Q}_a\ \Delta t \rho_z-\mathrm{Q}_b\ \Delta t \rho(\mathrm{t}) \end{cases}$$

4. Model Solution.

Given the number of injector operations, high-pressure tubing size and initial pressure, we need to determine the angular velocity of the cam so that the pressure in the high-pressure oil pump is as stable as possible at around 100 *MPa*. Under the constraints in the single-objective optimization model, the angular velocity ω of the cam is adjusted so that the objective function k takes a minimum value.

It can be seen from Figure 1 that when ω = 0.02 rad/ms, the image is inclined downward, the high-pressure pipeline is too small, and the angular velocity ω of the cam is small; when ω = 0.03 rad/ms, the image is tilted upward, indicating the high-pressure pipeline If the amount of oil is too much, the angular velocity ω of the cam is too large.

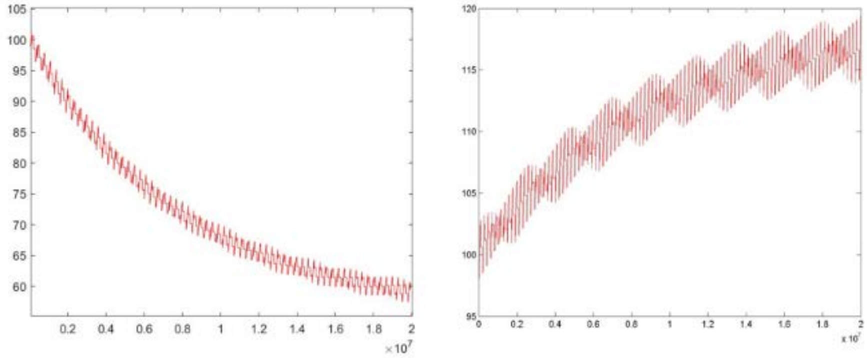

Figure 1. Stability of pressure at *ω = 0.02 rad/ms*

(Left) and stability at *ω = 0.03 rad/ms* (right)

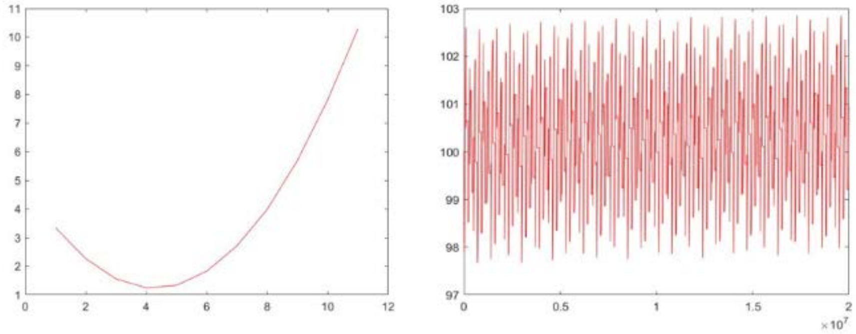

Figure 2. The relationship between the fluctuation coefficient k and the angular velocity *ω* of the cam (left) and the pressure stability of ω = 0.0274 *rad/ ms* (right) we further narrow the range to 0.02 *rad / ms* ~0.03 *rad / ms* and continue to solve the optimal solution of the objective function. The relationship between the fluctuation coefficient *k* and the angular velocity *ω* of the cam can be found in Figure 2 (left). In the end, we can get the pressure in the high-pressure fuel pipe to be around 100 *MPa* when *ω* = 0.0274 *rad / ms* . The specific pressure stability is shown in Figure 2 (right).

5. Mode Model Optimization

On the basis of the above research questions, an injection nozzle is added, and the fuel injection rules of each injector are the same, and the fuel injection and oil supply strategies are adjusted. In addition, to more effectively control the pressure of the high-pressure fuel line, install a one-way pressure reducing valve at D (Fig. 3). The one-way pressure reducing valve outlet is a circle with a diameter of 1.4 mm. When opened, the fuel in the high-pressure pipeline can be returned to the external low-pressure oil circuit under pressure, so that the pressure of the fuel in the high-pressure pipeline is reduced. The control schemes for the high-pressure pipeline and the pressure reducing valve are given below.

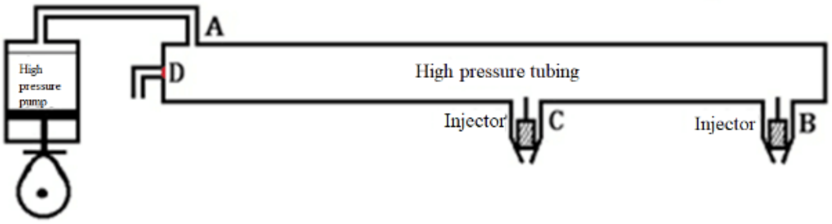

Figure 3. Schematic diagram of optimized high-pressure oil pipe

When a new injector is added, the injection law of each injector is kept the same. Since the rotation period of the cam is inconsistent with the working period of the injector, in order to simplify the problem, the plunger is moved to the bottom dead center as a starting point. At this time, the injector B starts to work. Determine the starting injection time of injector C and the angular velocity of the high-pressure pump cam to achieve the minimum value of the objective function. When studying the angular velocity of a single variable, the complexity of the problem is already high, and the complexity of the problem increases exponentially due to the introduction of a new time variable injector C opening time *t*, which is difficult to solve with the traditional optimization method. Therefore, we use modern heuristic algorithm - genetic algorithm to solve. When a one-way pressure reducing valve is installed at D, keep the fuel injection strategies of the injectors B and C unchanged, adjust the angular velocity of the cam ω and the opening threshold of the one-way pressure reducing valve, and use the genetic algorithm to solve the problem. From then on, the optimal high-pressure pipeline and pressure reducing valve control scheme is obtained.

(1) The first improved genetic algorithm to solve

In the genetic algorithm, the angular velocity ω of the cam and the opening time *t* of the injection valve C is encoded using a binary coding strategy. A binary code is randomly generated as the initial population. The fluctuation coefficient *k* reflects the stability of the high-pressure fuel pipe, so the fluctuation coefficient can be used as the fitness function:

$$k = \frac{1}{n}\sum_{i=1}^{n}(\mathrm{P} - \mathrm{P}_0)^2$$

According to the model before the improvement, the nozzle C is added on the basis of the same, and the regularity is the same as that of the injector B, except that the time t' is delayed in the opening period, so the changes of the model before the improvement are:

$$\begin{cases} \mathrm{Q}_c = \Delta \mathrm{t} S_i (t - t^{'}) \sqrt{\dfrac{2(P_g - P_i)}{\rho_g}} (t^{'}\text{is the delay time}) \\ M(t + \Delta t) = M(t) + Q_a \Delta t \rho_z - Q_b \Delta t \rho(t) - Q_c \Delta t \rho(t - t^{'}) \end{cases} \tag{13}$$

By calculation, the minimum value of the fluctuation coefficient is obtained at ω = 0.0735ms and $t^{'}$ = 13.93*ms*, and the minimum value is 1.2308. At this time, the pressure inside the high-pressure pipeline is the most stable. The fluctuation coefficient *k* is reduced by 11.45% compared with the improved single injector injection. It can be considered that the stability of the high-pressure fuel pipe is improved after adding a nozzle. The stability of the air pressure under the specific optimal solution is shown in Figure 4.

(2) The second improved genetic algorithm is solved.

Since a new one-way pressure reducing valve is installed at D, the fuel flow it discharges is:

$$Q_{\mathrm{d}} = \lambda CA \sqrt{\frac{2（P_g - P_{\mathrm{c}}）}{\rho_z}}, \lambda = \begin{cases} 1 & P_z > P_{z0} \\ 0 & P_z \le P_{z0} \end{cases}$$

Its objective function is still:

$$\min k = \min \frac{1}{n}\sum_{j=1}^{n}(P - P_0)^2$$

The constraints are relative to the changes in the pre-improvement model:

$$\begin{cases} \mathrm{Q}_c = \Delta \mathrm{t} S_i (t - t^{'}) \sqrt{\dfrac{2(P_g - P_i)}{\rho_g}} (t^{'}\text{is the delay time}) \\ M(t + \Delta t) = M(t) + Q_a \Delta t \rho_z - Q_b \Delta t \rho(t) - Q_c \Delta t \rho(t - t^{'}) - Q_d \Delta t \rho(t) \end{cases} \tag{14}$$

For the first improved solution process, in the second improvement, the delay time of the injector C relative to the injector B is assumed to be constant, and after the pressure reducing valve is added, the initial population becomes the one-way pressure reducing valve opening threshold P_{z0} and the cam angular velocity ω, the open threshold and the angular velocity are randomly generated to generate a binary code, and the rest of the solution process is the same. Through the genetic algorithm, the angular velocity of the cam is ω = 0.2518*ms*. When the one-way pressure reducing valve is critically opened, the pressure difference between the inside and the outside of the high-pressure pipeline is P_z = 99.9510*MPa*, that is, the opening threshold of the one-way pressure reducing valve P_{z0} = (99.9510 − 0.5) *MPa* = 99.4510 *MPa*, and the obtained pressure in the high-pressure pipeline changes with time as shown in Figure 5. At this time, the fluctuation coefficient is 0.5332, which is 56.68% higher than that of the first improved high-pressure oil pump.

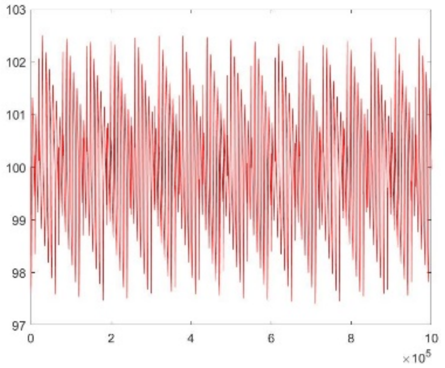

Figure 4. Optimal solution of high pressure oil pipe pressure stability (double injection port)

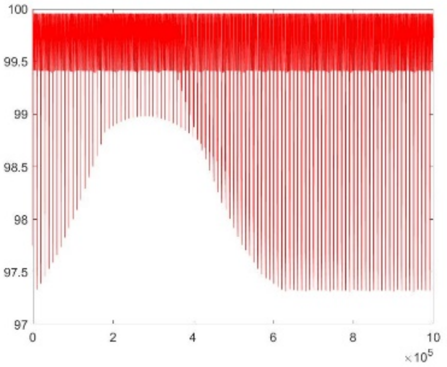

Figure 5. Image of pressure in high pressure tubing as a function of time (increased pressure reducing valve

Table 1. Three Scheme comparing.

Evaluation index	**one nozzle**	**Add a nozzle**	**Add a pressure reducing valve**
Volatility coefficient *k*	1.3899	1.2308	0.5332
Stability improvement rate	/	11.45%	56.68%

6. Conclusion

In this paper, Matlab is used to solve the mathematical model of diesel engine, and the stability process is iteratively calculated by the difference equation. By drawing the curve of the pressure in the high-voltage voltage regulator, it can be seen that the pressure in the high-pressure fuel pipe converges to the target pressure quickly and stably, indicating that the model has strong practicability. Compared with the experiment, Matlab simulation has the advantages of convenient statistics, fast calculation speed, transparent data and low cost. The model is solved by Matlab and the mathematical model established in this paper is suitable for the calculation of diesel engine.

The genetic algorithm is used to simulate the effect of the key parameters such as the speed of the protruding shaft, the opening period of the injector and the opening threshold of the pressure reducing valve to maintain the pressure of the Zener tube. The solution process of these key parameters is given. This method optimizes the parameters of the diesel engine. It is of great significance to improve the efficiency of diesel engine use and prolong the life of the engine. It has certain reference value for the structural design of high-pressure diesel engine.

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