# Research on Pressure Control of High Pressure Oil Pipe Based on Recursive Method

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**Abstract:** The high-pressure fuel pipe fuel system plays an important role in the operation of fuel engines. The size and stability of the fuel injection quantity of the injector has a great impact on the working efficiency of the engine. This paper first combines the binary method and recursive method to program in MATLAB software to determine a sufficiently large check valve opening time range. Take the time point to calculate the pressure difference between this point and the initial state, and select the time point t = 0.2757mm corresponding to the minimum pressure difference within the allowable error range. This point is to stabilize the pressure in the high-pressure oil pipe as about 100 MPa as possible. Then the compound trapezoidal formula is used to integrate and calculate the fuel quantity $Q_1$ discharged from the high-pressure fuel pipe during a period of the needle valve's lifting movement. The cam drives the plunger to move up and down. The data given by the movement gives the fuel quantity $Q_2$ that enters the high-pressure fuel pipe during a cam cycle. Finally, by establishing the total fuel quantity of the high-pressure fuel pipe and the total fuel quantity of the two injectors, the variable relationship between the cam angular velocity and the nozzle operating time is obtained.

## 1. Introduction

The high-pressure fuel pipe fuel system is the core system of many fuel engines. Through this system, a certain amount of fuel is injected to promote the engine's work [1]. Fuel enters the high-pressure fuel pipe through a high-pressure oil pump, and then is injected by the fuel injector to inject fuel. The stability and proper amount of engine will make the engine work more efficiently [2]. Among them, the pressure in the high pressure oil pipe is the core factor to be controlled in this process. If the pressure in the high pressure oil pipe is unstable, it will cause the amount of fuel injected to be unstable. As a result, the engine's working efficiency is not ideal [3].

## 2. Establishment And Solution Of Check Valve Opening Duration Model

First, use the dichotomy method to bisect the estimated time range of the check valve opening, and then bring the diced time point into the matlab program to obtain the pressure difference between the sampled point and the initial state. Use the recursive method to program using matlab software. By comparing the values several times, the time point corresponding to the minimum pressure difference can be obtained, and the length of each check valve opening can be obtained.

After analysis, first make reasonable assumptions, assuming that in the initial state, the fuel supply inlet A and the fuel injector B are in the working initial state, the fuel supply inlet A has a constant flow rate during work and the check valve is closed for only 10ms after each work. Next, analyze and observe the data, determine the length range T of the check valve each time between 0.1mm and 0.5mm, and set $[l_n, r_n]$ as the closed interval of the time range T. $l_0 = 0.1$, $r_0 = 0.5$, bisection point t

$_n = (l_n + r_n) / 2$. This section contains the pressure in the high pressure oil pipe is 100MPa (that is, the initial state $t_n$ at which the check valve should open each time when the pressure difference is 0). Flow at the fuel supply inlet A $Qa = CA\sqrt{\frac{2\Delta P}{\rho}}$ = 15.54mm $^3$ / ms, when the flow rate at the nozzle B is the same as that at A, the internal pressure of the high-pressure oil pipe and the high-pressure oil pipe is the maximum value, and the time point of the maximum pressure value is 0.1554ms. The working time point of nozzle B when the pressure is at the maximum state is $t_b = 0.1554 + 100i$ (i = 1, 2, 3, ..., n). One cycle time $T_a = t_n + 10.x_1 = (\frac{0.1554+100i}{t+10}]$, $x_2 = i$. Under the premise that $t_b - T_a \times x_1 < t_n$, when the n + 1 period $t_n$ is injected in the injector during the time period, the real-time density in the high-pressure tubing is:

$$\rho_1 = 0.85\frac{Q_a t_n x_1 + Q_a(t_b - x_1 \times (t_n + 10)) - 44x_2 - 50(t_b - 100x_2)2] + V}{V}$$

When the n + 1 period $t_n$ is not in the fuel injection period of the injector, the real-time density of the high-pressure fuel pipe is:

$$\rho_2 = 0.85\frac{Q_a \times t_n \times (x_1 + 1) - 44x_2 - 50(t_b - 100x_2)2] + V}{V}$$

The change in the pressure of the fuel is proportional to the change in density, and the proportionality factor is *E/ρ*, among them *ρ* is the density of the fuel, so the error between the current actual pressure difference and the initial pressure difference is:

$\delta = |(|A(k,1)-100)|)-0.85A(k,2)|\rho_m-0.85||$

(A is the data matrix, k = 181,182, ..., 221; m = 1,2)

The pressure index of the smallest error can be obtained.

Let the error reference c = 20000, use matlab software programming to output all k values of $\delta$ <20000. It can be obtained that the pressure $P_k$ corresponding to the output k value and the initial pressure difference is $P_k$ -100.

Satisfying the average pressure difference $\Delta p = \frac{p_k - 100}{n+1}$

Use Matlab to recursively call the dichotomy method into the above steps, and repeatedly calculate the pressure difference corresponding to the point of time $t_n$ at the bisection point, so that the pressure difference is repeatedly calculated under the condition of $r_n - l_n \leq 0.005$. The minimum time point $t_n$ = 0.2757mm. Therefore, it can be concluded that the pressure in the high-pressure oil pipe is stabilized at about 100 MPa, and the check valve is opened for 0.2757mm each time.

Set f ($t_1$) = 2s, f ($t_2$) = 5s, f ($t_3$) = 10s, ($t_c = t_1, t_2, t_3$) bring into the formula:

$$f(t_c) = 0.85\{\frac{1}{V}[\frac{Q_a \times t_n \times t_c}{t_n + 10} + t_c - \frac{t_c + 10}{t_n + 10}(t_n + 10)Q_a - 880] + 1\} - \rho_c$$

Let f ($t_c$) = 0, then $t_1$ = 0.5875ms; $t_2$ = 0.2270ms; $t_3$ = 0.1122ms

If you want to increase the pressure in the high-pressure tubing from 100 MPa to 150 MPa,

After about 2 s adjustment process, it is stable at 150 MPa, and the check valve opening time should be adjusted to 0.5875ms;

After about 2 s adjustment process, it is stable at 150 MPa, and the check valve opening time should be adjusted to 0.2270ms;

After about 10s of adjustment, it is stable at 150 MPa, and the check valve opening time should be adjusted to 0.1122ms.

## 3. Establishment And Solution of Cam Angular Velocity Determination Model

Combined with the data of the needle valve's regular lifting movement to discharge fuel, the compound trapezoidal formula is used to integrate to obtain the fuel quantity $Q_1$ discharged from the high-pressure fuel pipe during one cycle of the needle valve's lifting movement. The cam driven plunger moves up and down and the given data is the fuel quantity $Q_2$ that enters the high-pressure fuel pipe during one cam cycle. Within a certain time range, the number of cycles of the needle valve movement $f_1(\omega)$ and the cam movement are obtained. The number of times of a cycle $f_2(\omega)$. When the total fuel quantity entering the high-pressure fuel pipe is equal to the total fuel quantity leaving the high-pressure fuel pipe, the pressure in the high-pressure fuel pipe is stabilized at about 100 MPa, and the equation $Q_1 f_1(\omega) = Q_2 f_2(\omega)$, solve the equation to get the angular velocity ω of the cam motion.

After analyzing the second problem, first calculate the quantity $Q_1$ of the fuel discharged from the high-pressure fuel pipe during a period of the needle valve lifting movement. When the initial pressure $p_0$ = 100 MPa in the high-pressure fuel pipe, the fuel density $\rho_0$ = 0.85mg / mm $^3$, flow coefficient C = 0.85, needle valve diameter $d_g$ = 2.5mm. At the current time, the fuel injection rate of the fuel injector is:

$$Q(i,1)=\sum_{i=1}^{247} C(B(i,2)\times 9^\circ+\frac{\mathrm{d}^2}{4})\pi\times\sqrt{\frac{\mathrm{d_g}}{\rho_0}}$$

The matlab software repeatedly calls polyfit and polyval to analyze a large amount of discrete data of injection rate and time within a limited number of times, and continuously fits high-order polynomial functions until the actual data is evenly distributed on both sides of the fitting curve, and the error does not exceed the required range (0.05). Finally, the best fitted curve image of injection rate and time is obtained.

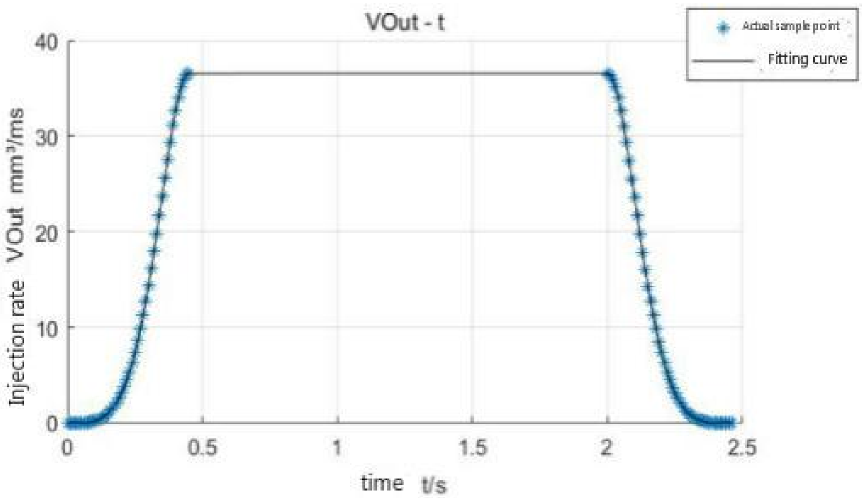


Figure 1. Curve of fuel injection rate and time

The above curve is integrated by the spline interpolation method and the compound trapezoidal formula, and it is found that the fuel quantity $Q_1$ = 66.7167mm $^3$ / ms discharged from the high-pressure fuel pipe during one motion cycle of the needle valve movement.

Next, calculate the fuel quantity $Q_2$ that enters the high-pressure fuel pipe during a cam cycle. Compare the numerical value of the pole diameter in the table of the cam edge curve to obtain the maximum value of the pole diameter $h_{max}$. = 7.239mm, the minimum value of the pole diameter $h_{min}$ = 2.413mm, the inner diameter of the plunger cavity $d_p$ = 5mm, the residual volume of the plunger cavity $V_r$ = 20mm $^3$. Thus the plunger cavity volume

$V_p$ is $V_p=\pi(h_{max}-h_{min})\frac{d_p^2}{4}+V_r$ . Calculate $V_p$ = 114.7583mm $^3$.

By the first formula $f(t_c)=0.85\{\frac{1}{V}[\frac{Q_a\times t_n\times t_c}{t_n+10}+t_c-\frac{t_c+10}{t_n+10}(t_n+10)Q_a-880]+1\}-\rho_c$ , at 0.5 MPa, the density of the fuel ρ 0.5 = 0.8111 mg / mm3

The amount of oil q2 pressed in one cycle of cam movement is $Q_2 = \frac{\rho_{0.5} \times V_p}{\rho_0}$. It is calculated that the fuel quantity entering the high-pressure fuel pipe during a movement period of the cam Q2 = 109.4997mm3 / ms.

Finally, calculate the angular velocity of the cam when the pressure in the high-pressure oil pipe stabilizes at about 100 MPa. Let the angular velocity of the cam rotation be ω period T be a common multiple of the injection and injection time, that is, one cycle of the overall machine work $T = \frac{2\pi \times 100}{\omega}$. Bring the above calculation results into angular velocity $\omega = \frac{2\pi Q_1}{100 Q_2}$. The calculation shows that the angular velocity of the cam ω = 0.0383rad /ms. Therefore, it can be known that when the pressure in the high pressure oil pipe is stabilized at about 100MPa, the angular velocity of the cam is 0.0383rad / ms.

## 4. Establishment And Solution Of Fuel Injection And Fuel Supply Strategy Models

By establishing a balance equation between the total oil injection amount $V_{in}$ of the high-pressure oil pipe and the total injection oil amount $2V_{out}$ of the two injectors at the working time t, the cam angular velocity ω and the nozzle operation are simplified. The variable relationship between the time t. From the rate equation of the oil supply rate.

$\upsilon_{in}$ and the oil output rate $\upsilon_{out}$ of the high-pressure oil pipe, the maximum pressure corresponding to the working time $t_p$ of the injector is obtained. $t_p + 100j$ (j = 1,2, ..., 10) is taken into the expression of the fuel volume difference ΔV (t) in the high pressure oil pipe, and the fuel volume difference ΔV in the high pressure oil pipe is calculated when the maximum pressure is calculated $_{mean}$ (t). Take t in a certain large range and substitute it with the fuel volume difference $\Delta V_{mean}$ (t) in the high-pressure fuel pipe to get the working time of the injector corresponding to $\Delta V_{mean}$ (t) within the allowable error range. The range of t, the range of cam angular velocity ω can be obtained from the ω-t relationship, and the fuel injection and fuel supply adjustment strategy can be obtained. The inequality can be listed from the relationship between the oil input and oil output of the high pressure oil pipe: inlet an oil quantity at the place is ≥ the oil quantity of the two injectors + the oil quantity of the one-way pressure reducing valve, and the value range of ω is obtained.

After analysis, let the total time be $T_a$. First calculate the total fuel injection amount $V_{out}$ of the two injectors. According to the above, we can know that the fuel quantity Q (( TF134) = 66.7167mm $^3$ / ms. Maximum injection quantity per unit time $Q_{max}$ = 36.5484mm $^3$ / ms. The working time of the needle valve in a unit cycle is 2.45ms, and the maximum injection quantity in a unit cycle starts. Time $t_s$ = 0.45ms, the maximum end time of fuel injection amount per unit period is $t_e$ = 2.0ms. $t \subset (0,0.45) \cup (2,2.45)$ Within, the total fuel injection is $S_1 = Q_1 - Q_{max}(t_e - t_s)$ . In $t \subset (0.45,2)$, fuel injection $S_2 = Q_{max}(t_e - t_s)$ . From this we know $t > 0.9$ Total real-time fuel injection $V_{out2} = (t-0.9)Q_{max} + S_1$ when $t <= 0.9$, $V_{out} = \int_0^{\frac{t}{2}} Q dt$.

Secondly, calculate the total oil pressure $V_{in}$ of the high-pressure oil pipe. From the above, we can know that the fuel quantity entering the high-pressure oil pipe $Q_2$ = 109.4997mm $^3$ / ms during one cam cycle oil amount $V_{in} = \frac{T_a}{\frac{2\pi}{\omega}} Q_1$

We can get the relationship between ω-t $\omega = \frac{2\pi V_{out}}{100 Q_2}$.

Then, find the time $t_p$ at which the nozzle works when the maximum pressure in the high-pressure fuel pipe is the maximum.

$\upsilon_{in} = \frac{V_{in}}{\frac{\pi}{\omega}}$ , by $\upsilon_{in} = \upsilon_{out}$ , it can be obtained that the maximum pressure corresponds to the working time $t_p$ of the injector. Bring $t_p$ + 100j (j = 1, 2, ..., 10) into the fuel volume difference in the high-pressure fuel pipe $\Delta V(t) = \frac{tp+100j}{\frac{2\pi}{\omega}} + (tp+100j) - [\frac{tp+100j}{\frac{2\pi}{\omega}}]\frac{Q2}{\frac{\pi}{\omega}}$ , (according to the relationship of ω-t $\omega = \frac{2\pi V_{out}}{100Q_2}$ replace ω with t).

Take a reasonable working time of the injector $t \in [0,3]$, bring in ΔV (t), use matlab software to take the average, and calculate the difference in fuel volume in the high-pressure fuel pipe when the maximum pressure is calculated. And make the picture as follows:

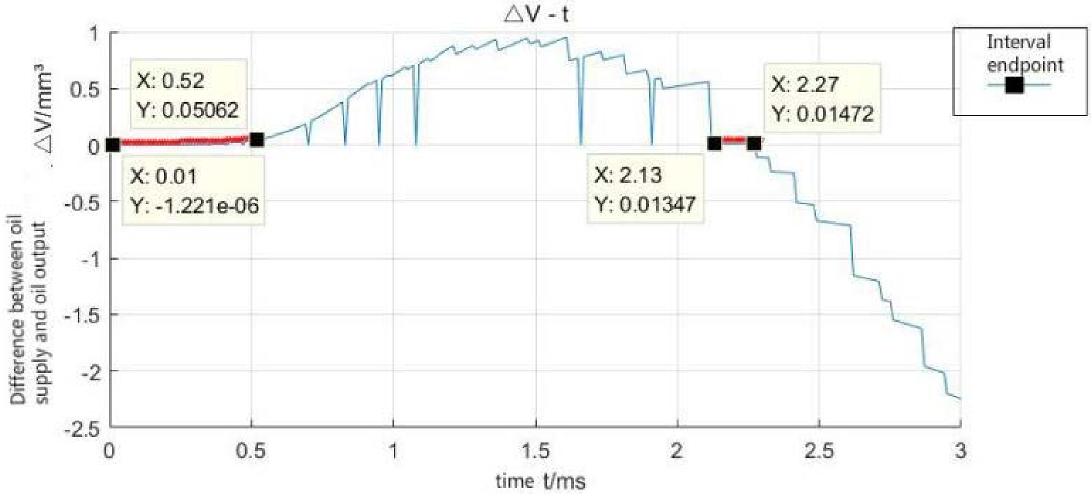


Figure 2. Relationship between the working time of the injector and the average fuel volume difference

Within the allowable error range of less than or equal to 0.05, the reasonable range of the working time of the injector is $t \in [2.13, 2.27]$. (If the working time is too small and the fuel injection is too small, it will affect the efficiency of the engine, so the previous part is discarded.)

According to the relationship of ω-t $\omega = \frac{2\pi V_{out}}{100Q_2}$. Using matlab software to map as follows:

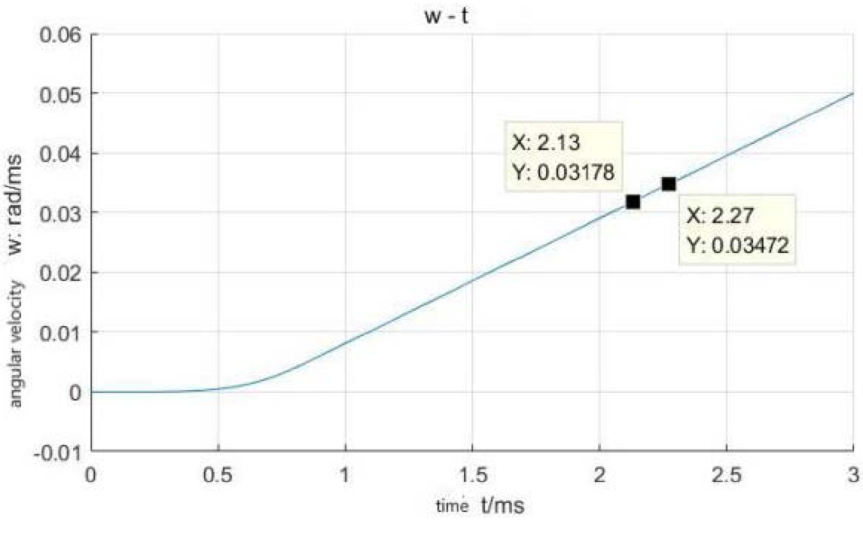


Figure 3. Relationship between the working time of the injector and the cam angular velocity

It can be seen from the figure that the range of the cam angular velocity corresponding to a reasonable range of the working time of the injector is $\omega \in (0.03178, 0.03472)$

Therefore, an additional fuel injector is added, and the fuel injection pattern of each nozzle is the same. The fuel injection and fuel supply strategy is adjusted as follows: the range of the fuel injector working time is controlled $t \in [2.13, 2.27]$ (Unit ms), control the cam angular velocity range at $\omega \in (0.03178, 0.03472)$ (Unit rad / ms).

The difference between the pressure in the high-pressure oil pipe and the pressure in the low-pressure oil circuit $\Delta P_{in\text{-}out} = P_{in} - P_{out} = 99.5$MPa, the time range involved in the calculation $T_d = 200\omega$ flow rate of the pressure reducing valve $Q_d = CA\sqrt{\frac{2\Delta P_{in-out}}{\rho_0}}$, the inequality can be listed by the oil input at the oil inlet a ≥ the oil output of the two injectors + the oil output of the one-way pressure reducing valve $Q_2 \frac{T_d}{\frac{2\pi}{\omega}} \geq \frac{2T_d}{100} V_{out} + Q_d t$. It is found that the angular velocity of the cam is 0.06608rad / ms≤ω≤0.9991rad / ms.

The relationship between the cam angular velocity and the opening time of a single pressure reducing valve $t_d = \frac{\frac{Q_2 T_d}{\frac{2\pi}{k}} - \frac{2T_d V_{out}}{100}}{Q_d}$ ($k \in [\omega_{min}, 1]$ (The step length is 0.01), the relationship between the wheel angular velocity and the opening time of the single pressure reducing valve is as follows:

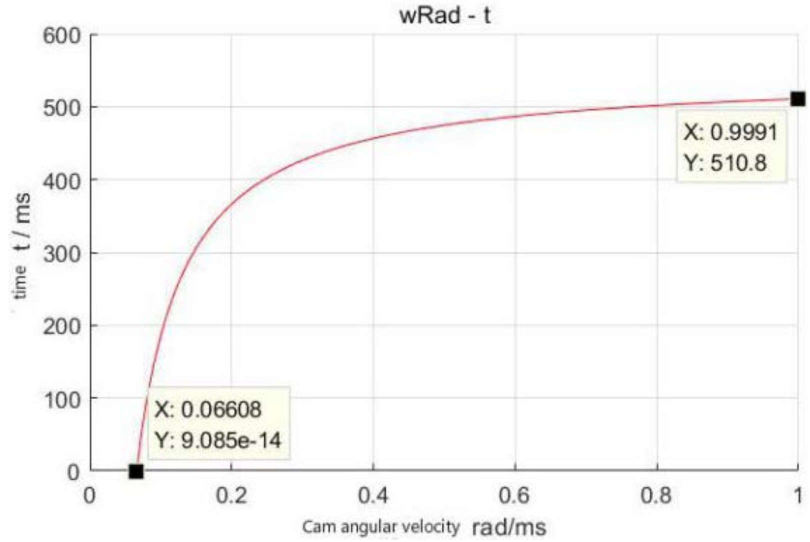


Figure 4. Relationship between cam angular velocity and opening time of single pressure reducing valve

It can be seen from the figure that the opening time range of the one-way pressure reducing valve is $9.085 \times 10^{-14}$ ms ≤ t ≤ 510.8 ms. Therefore, the control scheme of the high-pressure oil pump and the pressure reducing valve after adding a one-way pressure reducing valve is: The angular velocity range of the cam is controlled at 0.06608rad / ms≤ω≤0.9991rad / ms, and the opening time range of the one-way pressure reducing valve is controlled at $9.085 \times 10^{-14}$ ms≤t≤510.8ms.

## 5. Model Error Analysis

1) The assumptions of the model may not be accurately controlled or difficult to achieve in real life. Therefore, the operation results of the model and the actual production results have a certain degree of error.

2) The consideration of the problem is not comprehensive enough, and a certain aspect of the problem has not been taken into consideration, but this aspect of the problem will have a real impact on the production and operation results, which will cause errors.

3) In the process of model establishment, some very small influencing factors are ignored, resulting in deviations between the model operation results and actual operation results.

## 6. Conclusion

Use recursion and other methods to analyze and simplify the problem. The idea of using the model is very clear, concise, and easy to understand and accept. In the analysis process, mat lab software was used to rigorously program and verify the method's operation steps to ensure that the rationality and accuracy of the results. At the same time, in this model, curve fitting and high-order polynomial function fitting are performed on the data given in the question, and the two complement each other to further ensure the applicability of this model to multiple problems. The disadvantage is that when solving the problem, only the initial state is used to establish the model and the algorithm is solved in the standard state. The algorithm solution takes a little longer, and the subsequent analysis can be improved or a more optimized model can be used for solution.

The control of the pressure in the high-pressure tubing has a great impact on the working efficiency of the engine, but in this regard, there is still no algorithm or model that can completely intelligently control the pressure in the high-pressure tubing. So how to more intelligently control the pressure stability in the high-pressure tubing to control the fuel injection amount of the injector has become the main direction of our research. The model established in this article needs to be further improved and optimized, so that the model can incorporate more realistic factors and initial state considerations for many different situations. Using more subsequent models can be improved or optimized to analyze and solve. The model is further optimized and improved, and the model can be considered to be applied to other areas.

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