Fuel system control design based on mass conservation

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Abstract. Fuel entering and ejecting high-pressure fuel pipe is the basis of fuel engine operation. The intermittent operation of high-pressure oil pump and injector will lead to the change of pressure in high-pressure oil pipe. This paper studies the influence of the opening and closing of one-way value and the speed of cam angle on the pressure in high-pressure oil pipe. Because the fuel flow is unstable in the high-pressure fuel pipe, it is necessary to determine the influence of pressure change on fuel density, and then calculate the mass of fuel supply and fuel injection in unit time. Considering the principle of mass conservation, the problem can be transformed into the length of single opening time of one-way valve when the mass of fuel entering and leaving the high-pressure oil pipe is equal in unit time interval. At the same time, by deducing the influence of the single opening time of the one-way valve on the pressure in the high-pressure oil pipe, the single opening time of the one-way valve when the pressure of the high-pressure oil pipe reaches equilibrium after 2s, 5s and 10s is 0.610895 ms, 0.425998 ms and 0.373376 ms respectively. Consider the working principle of the fuel system on the basis of the above considerations. Fit the function relationship between the needle lift and working time, deduce the change rule of flow volume of injector with time, and calculate the volume and mass of fuel injected by the injector in the working cycle. The results show that the high-pressure oil pump supplies oil 94 times in a working cycle of the injector, and the time required for the cam to rotate for one circle is 1.064 ms, and the angular velocity of the cam is 5.906 rad/ms. In this paper, based on the theory of unsteady liquid motion, mass conservation and energy conservation of fluid mechanics, many elements involved in the problem stem are analysed and related, and the control model of one-way valve switch and cam angular velocity is given.

1. Introduction

The fuel system is mainly composed of fuel pump, fuel filter, fuel pulsation damper, fuel pressure regulator, fuel injector, oil inlet pipe and oil return pipe [1,2]. The high-pressure oil pump built in the fuel tank of the fuel engine generates oil pressure when it rotates. The fuel flows through the one-way valve at the outlet of the oil pump to the fuel filter, which filters out the dust in the fuel. After the pressure is stabilized by the pulsation damper, the fuel enters the high-pressure oil pipe to supply oil to the fuel injector. The fuel pressure regulator regulates the return oil quantity of the return pipe according to the negative pressure value of the intake pipe, and returns the excess fuel to the tank through the return pipe [3,4,5].

Fuel entering and ejecting high-pressure fuel pipe is the basis of many fuel engines. The intermittent working process of fuel entering and ejecting will lead to the change of pressure in the high-pressure fuel pipe, which makes the amount of fuel ejected deviate, thus affecting the working efficiency of the engine. Many scholars have studied the law of fuel pressure fluctuation in high-pressure oil pipe. Bianchi G M. et al. (2002) proposed that multiple injection fuel volume fluctuations are caused by fuel pressure drop in the pipeline caused by injection; Henein N A. et al. (2002) found that pressure fluctuations in the common rail system will affect the movement of injector needle valve and fuel injection; there are other literatures that show that the fluctuation of fuel pressure in the high-pressure oil pipeline caused...
by pre-injection will affect the opening and closing of the injector \cite{6}; the size of the high-pressure fuel pipeline will affect the fuel pressure fluctuation; Li Pimao et al. established a one-dimensional pipeline model with constant pressure inflow and orifice outflow as boundary conditions, considering fuel viscosity, and solved it with MacCormack and TVD finite difference method. They found that the fluctuation amplitude of fuel pressure in high-pressure oil pipe showed a periodic change law with the increase of injection pulse width \cite{7}; Yin Zijia tested the transmission speed of the fuel pressure wave in the high-pressure oil pipe under the condition of high-pressure injection. He found that the fuel in the high-pressure oil pipe has two-phase characteristics, and its pressure wave speed is significantly lower than that in the single-phase liquid \cite{8}.

In order to study the influence of different adjustment schemes of various structures in the fuel engine on the internal pressure of the high-pressure oil pipe, the length of the internal cavity of the high-pressure oil pipe is set as 500\,mm, the internal diameter is 10\,mm, the diameter of the small hole at the oil supply inlet is 1.4\,mm, the length of the oil supply time is controlled by the one-way valve switch, and the injector and the one-way valve work independently: each time the one-way value is opened, it will be closed for 10\,ms; the injector will work 10 times per second, and the injection time is 2.4\,ms each time. When the injector is working, the rate of injection from the nozzle to the outside is fixed. The pressure provided by the high-pressure oil pump at the inlet is 160\,MPa, and the initial pressure in the high-pressure oil pipe is 100\,MPa. Try to determine the opening time of the one-way valve and the angular speed of the cam each time, and stabilize the pressure in the high-pressure oil pipe at a fixed value as much as possible, in order to reduce the deviation of the amount of fuel injected, so as to improve the working efficiency of the engine.

2. Method

2.1. One-dimensional unsteady flow equation (continuity equation based on mass conservation)

In this paper, it is assumed that the area of the cut-off surface is \( A \), \( x \) is the length of the fuel flowing through the control body, \( v \) is the flow rate of the fuel in the control body. The fuel density \( \rho \) changes with time \( t \), that is: \( \rho = \rho(x,t) \). The control body is shown in figure 1:

According to the law of mass conservation, the sum of the mass difference between the inflow and outflow control body (high-pressure oil pipe) in the shortest time interval \( dt \) and the mass changes in the volume in the same time period shall be equal to 0 \cite{9}. In this paper, by calculating the mass difference between the inflow and outflow control bodies and the mass increased with the change of density, the one-dimensional unsteady flow equation \cite{10} is obtained according to the law of mass conservation. The specific calculation steps are as follows:

**Step 1:** Measure the mass of fuel \( m_A \) flowing into the high-pressure oil pipe from the inlet through the one-way value in the time period, as shown in formula (1):

\[
 m_A = \rho vAdt \tag{1}
\]

Among them, \( vdt \) is approximately regarded as the length of fuel flowing through the high-pressure oil pipe in the time period \( dt \), \( vAdt \) is regarded as the volume of fuel covering the oil pipe in the time period \( dt \), then the mass at the inlet is calculated according to the physical formula \( m = \rho V \).

**Step 2:** Measure the mass \( m_B \) of the high-pressure oil pipe flowing out of the injector in the time period \( dt \), as shown in formula (2):

\[
 \rho vAdt + \frac{\partial}{\partial x} (\rho vAdt)dx
\]
Step 3: Measure the difference between outflow and inflow, that is net inflow \( \Delta m \), as shown in formula (3):

\[
\Delta m = \left[ \rho vAdt + \frac{\partial}{\partial x} (\rho vAdt) dx \right] - \rho vAdt = \frac{\partial}{\partial x} (\rho vAdt) dx
\]

Step 4: Measure the mass increased due to the change of fluid density (caused by the change of air pressure) in time period \( dt \), that is, the fuel mass increased \( \Delta m \) in high-pressure oil pipe in time period \( dt \), as shown in formula (4):

\[
\Delta m = \frac{\partial}{\partial t} (\rho Adx) dt
\]

Among them, \( \rho Adx \) is the mass of fuel in the original high-pressure oil pipe, so the mass of fuel in the high-pressure oil pipe after time period \( dt \) is \( \rho Adx + \frac{\partial}{\partial t} (\rho Adx) dt \).

Step 5: According to the law of mass conservation, the sum of the mass difference between the inflow and outflow control body (high-pressure oil pipe) and the mass change in the volume in the same time period should be equal to 0, that is, \( \Delta m = \Delta m' \):

\[
\frac{\partial}{\partial x} (\rho vAdt) dx + \frac{\partial}{\partial t} (\rho Adx) dt = 0
\]

The general form of the continuity equation of one-dimensional unsteady flow can be obtained by simplification:

\[
\frac{\partial}{\partial x} (\rho vA) + \frac{\partial}{\partial t} (\rho A0) = 0
\]

3. Result and Discussion

3.1 Model assumptions
1. Consider the compressibility of fuel oil that when the pressure of fuel oil changes, the density also changes;
2. Assume that the whole high-pressure oil pipe space will be filled continuously when the fuel flows without any gap;
3. Assume that the high-pressure oil pipe will not deform under the pressure change, that is, the area and volume of the vessel cut-off surface remain unchanged before and after;
4. Assume that the plunger contacts the cam when it moves up and down, and the effect of friction is ignored;

3.2 Symbol description

| Symbol | Symbol description | Unit |
|--------|--------------------|------|
| \( m_A(i) \) | A mass of the \( i \)th injection of high-pressure oil pipe | mg |
| \( m_B(i) \) | B mass of the \( i \)th injection of high-pressure oil pipe | mg |
| \( m_0 \) | Initial fuel mass \( m_0 \) in high-pressure fuel pipe | mg |
| \( \rho_A \) | Fuel density at \( A \) | mg/mm\(^3\) |
| \( \rho_0 \) | Fuel density at initial pressure in fuel pipe | mg/mm\(^3\) |
| \( \Delta \rho \) | Fuel density difference | mg/mm\(^3\) |
| \( t_s \) | Opening time of one-way valve | ms |
| \( V_{A(i)} \) | A volume of the \( i \)th injection of oil pipe | mm\(^3\) |
| \( V_B \) | B volume of fuel injected in unit time | mm\(^3\) |
| \( \Delta \rho \) | Pressure difference on both sides of the small hole | MPa |
3.3 Solution procedure

Figure 2 shows the working principle of a high-pressure fuel system. The fuel enters the high-pressure oil pipe from A through the high-pressure oil pump, and then ejects from nozzle B.

![Fig.2 Schematic diagram of high-pressure oil pipe](image)

The one-way valve switch controls the length of oil supply time, thus affecting the pressure value in the high-pressure oil pipe. In this paper, it is assumed that the length and inner diameter of high-pressure oil pipe and the diameter of the small hole in the oil supply pipe have been determined, and it is known that the pressure provided by the high-pressure oil pump at inlet a is constant 160 MPa, and the initial pressure in the high-pressure oil pipe is 100 MPa. There are three aspects to consider when solving this problem:

First, considering the independent working characteristics of the one-way valve and the injector, a model of the opening time of the one-way valve and the pressure in the high-pressure oil pipe is established based on the principle of conservation of fluid mass \([11]\). In order to realize the one-way valve to control the pressure in the high-pressure oil pipe \([8]\). Second, considering the relationship between the mass and density of the fuel liquid, the pressure in the fuel pipe changes when the fuel enters the fuel pipe, and the fuel density changes accordingly. Third, considering the compressibility of the fuel, the fuel flow is unstable in the high-pressure fuel pipe, so it is necessary to make clear the different fuel density before and after the pressure change. After a certain period of time, the pressure in the high-pressure oil pipe is maintained at a stable value, so it is necessary to keep the mass difference of fuel entering and leaving the high-pressure oil pipe as constant as possible.

In this paper, a single opening time model of one-way valve is established to adjust the single opening time of one-way valve so as to maintain the pressure in high-pressure oil pipe at a certain stable value. For this problem, this paper solves it from the following three steps:

**Step 1:** Measure the mass \(m_{Ai}\), density \(\rho_{Ai}\) and volume \(V_{Ai}\) of oil supply in a certain period of time at A.

The mass \(m_{Ai}\) of the oil supply in the time interval at A is shown in formula (7):

\[
\sum_{i=1}^{T} m_{Ai(i)} = \sum_{i=1}^{T} \rho_{Ai(i)} V_{Ai(i)}
\]
Among them, $m_{A(i)}$ is the fuel mass of each time the one-way valve is supplied, $\rho_{A(i)}$ is the fuel density of the $i$th time of supply, $V_{A(i)}$ is the fuel volume of the $i$th time of supply, and $T = \frac{t}{t_a + 10}$ is the working times of the one-way valve in the time period.

$\rho_{A(i)}$ can be obtained from Formula \( \Delta P = \frac{E}{\rho} \Delta \rho \), as shown in formula (8):

\[
\rho_{A(i)} = \rho_a + \Delta \rho = \rho_a + \frac{\Delta P}{E} \rho_0
\]  

(8)

Substitute $\rho_{A(i)}$ into Formula \( Q = CA \sqrt{\frac{2 \Delta P}{\rho}} \) to get $V_{A(i)}$, as shown in formula (9):

\[
V_{A(i)} = t_A Q = CA \sqrt{\frac{2 \Delta P}{\rho_{A(i)}}}
\]  

(9)

Step 2: Measure the mass $m_B$, density $\rho_B$ and volume $V_B$ of oil supply in a certain period of time at B.

The mass $m_B$ of the oil supply in time interval at B is shown in formula (10):

\[
\sum_{j=1}^{n} m_{B(j)} = \sum_{j=1}^{n} \rho_{B(j)} V_{B(j)}
\]  

(10)

Among them, $m_{B(j)}$ is the fuel mass of the one-way valve each time it supplies fuel, $\rho_{B(j)}$ is the fuel density at the $j$th injection, $V_{B(j)}$ is the fuel volume at the $j$th injection, and $T' = \frac{t}{100}$ is the working times of the injector in the time period.

In this paper, it is assumed that the injection rate of the injector at B is as shown in figure 3, and the volume $V_{B(j)} = 44\text{mm}^3$ of fuel injected by the injector for 2.4ms each time can be obtained.

![Fig.3 Schematic diagram of injection rate](image)

Step 3: Calculate the initial fuel mass $m_0$ in the high-pressure oil pipe

\[
m_0 = \rho_0 V
\]  

(11)

Among them, when the pressure is 100MPa, the fuel mass is $\rho_0 = 0.850\text{mg/mm}^3$, and the volume of high-pressure oil pipe is $V = SL = \left(\frac{D}{2}\right)^2 \pi L = 12500\pi\text{mm}^3$.

According to formula (6) ~ (9), it can be obtained by using MATLAB software to solve the equations. When the single opening time of one-way valve is $t_A = 0.288865\text{ms}$, the pressure in the high-pressure oil pipe can be stabilized at about 100MPa as much as possible. Take $t=2s$, $t=5s$, $t=10s$ into the equations respectively. The results show that when the single opening time of the one-way valve is $t_A = 0.610895\text{ms}$, the pressure in the high-pressure oil pipe can be stabilized at 150MPa after about 2s of adjustment. When the single opening time of one-way valve is $t_A = 0.425998\text{ms}$, the pressure in the high-pressure oil pipe after 5s adjustment can be stabilized at 150MPa; when the single opening time of one-way valve is $t_A = 0.373376\text{ms}$, the pressure in the high-pressure oil pipe after 10s adjustment can be stabilized at 150MPa.
In order to better show the distribution of the pressure value when the high-pressure oil pipe is stable in different opening time of the one-way valve, the following three-dimensional space stereogram is drawn, and the effect is shown in figure 4.

![Fig.4 Time distribution of pressure value in steady state](image)

It can be seen from the above figure that the longer the opening time of the one-way valve is, the shorter the time for the pressure in the high-pressure oil pipe to reach the specified pressure value is. This is because the switch of the one-way valve controls the length of the oil supply time. The longer the single opening time is, the larger the oil supply quantity is. Under the condition that the working efficiency of the injector is stable and unchanged, the faster the pressure in the high-pressure oil pipe increases.

On the basis of the above research, this paper further considers the working mechanism of the fuel system in the actual working process: the plunger of the high-pressure oil pump at the oil inlet moves up and down driven by the cam. When the plunger moves up, it compresses the fuel in the plunger cavity, resulting in the increase of the pressure in the cavity. When the pressure is greater than the pressure in the high-pressure oil pipe, the one-way valve connecting the plunger cavity and the high-pressure oil pipe is opened, and the fuel enters the high-pressure oil pipe; the injection position is controlled by the needle valve of the injection nozzle. When the needle valve lift is 0, the needle valve is closed; when the needle valve lift is greater than 0, the needle valve is opened, and the fuel flows to the injection hole and is ejected through the injection hole. We require the pressure in the high-pressure oil pipe to be stabilized at the initial pressure of about 100MPa. According to the principle of mass conservation, the expression of fuel density and volume of high-pressure oil pump and fuel injector is obtained, and the multi-element cam angular velocity model is constructed, which integrates cam angular velocity, needle valve lift, diameter, volume and other factors.

The oil pressure process of the high-pressure oil pump plunger is shown in figure 5. Considering the working principle of oil inlet and injection, the density and volume of fuel at the inlet of high-pressure oil pipe and injector are calculated by \( m = \rho V \), and then the relationship between cam angular velocity and pressure is established, and the equation is established according to the principle of mass conservation. To solve this problem, this article will follow the steps below:
Step 1: Measure the mass $m_B$, density $\rho_B$ and volume $V_B$ of fuel injected at B.

The fuel mass $m_B$ injected in a working cycle at B is as shown in formula (12):

$$m_B = \rho_B V_B$$  \hspace{1cm} (12)

For the injected fuel volume $V$, since the needle valve rises and falls once every time the injector works, the moving distance of the needle valve in one working cycle is $2h$. In this paper, the unit working time (2.45 ms) is divided into several time intervals $dt$ as small as possible. At this time, the lift in each $dt$ is negligible, that is, the volume of fuel injected from B in $dt$ can be approximately regarded as the difference between the cross-sectional area of the injector nozzle and the cross-sectional area of the needle valve in $dt$, that is, the ring area $S$. Starting from the needle valve closed state ($h=0$), with the change of $dt$, $S$ will change, and $S$ will gradually increase due to the rise of the needle valve, that is, the volume of fuel flowing out will continue to increase. Until $S=S_{\text{Nozzle}}$, the area of the ring at $dt$, i.e. the volume of fuel injected, just reaches the maximum allowable flow through the orifice, i.e. $S_{\text{max}}$. After that, $h$ continues to increase and $S$ remains unchanged. When the needle valve lift $h$ reaches the maximum value in one lifting, i.e. $h=H_{\text{max}}$, $h$ gradually decreases after this time. When $h=H_2$, $S$ starts to decrease because the fuel ejected from the ejector is blocked due to the needle valve lowering, until the lift $h=0$, i.e. the needle valve returns to the closed state, at this time $S=0$, so far, the needle valve completes one working cycle [12].

According to the relation between needle valve lift and time in an injection cycle, the function relation between them is fitted by MATLAB, and the result is shown in formula (13):

$$h = 15.397t^2 - 1.9309t + 0.026$$ \hspace{1cm} (13)

According to the above analysis, the cross-sectional area of the nozzle is $S_{\text{Nozzle}}=0.49\pi mm^2$, so when $S=0.49\pi mm^2$, the cross-sectional area of the nozzle in $dt$ is equal to the sum of the cross-sectional area of the nozzle and the cross-sectional area of the needle valve, which is $6.74\pi mm^2$, so the cross-sectional radius $AO=1.433 mm$, then $AB=AO-BO=0.183 mm$, and then the lift $h = \frac{AB}{\tan 9^\circ} = 1.155 mm$. When the
needle valve lift is at the maximum value, the corresponding increase in lift is $t_1=0.33\, ms$ during needle valve rise, and the decrease in lift is $t_2=2.12\, ms$ during needle valve fall. Therefore, the relationship between $S$ and $h$ can be obtained, as shown in equations (14):

\[
S = \begin{cases} 
\left(\tan 9^\circ \right) h^2 \pi + \tan 9^\circ hD\pi, & h \in (0,1.155] \\
\left(\frac{d}{2}\right)^2 \pi, & 1.155 < h \leq h_{\text{max}} 
\end{cases}
\]  

(14)

The gravitational potential energy at the injector is converted into kinetic energy, so the fuel flow velocity $v = \sqrt{2gh}$ can be obtained by using the law of energy conservation $\frac{1}{2}mv^2 = mgh$.

According to Formula $Q=Sv$ and formula $v = \sqrt{2gh}$, the fuel volume $Q$ flowing through the small hole in unit time can be obtained, and the fuel volume $V = Qt = Svt = S\sqrt{2gh}t$ ejected after a certain period of time $t$ can be obtained. Therefore, the fuel volume $V_b$ ejected in one working time of the injector can be obtained from formula (15):

\[
V_b = 2 \int_0^{0.33} Vdt + V_{(r=0.33)}(t_2 - t_1)
\]  

(15)

Density $\rho_b$ is shown in formula (16):

\[
\rho_b = \frac{\sum m_{h(i)} + m_0}{V_0}
\]  

(16)

**Step 2:** Measure the initial mass $m_0$, density $\rho_0$ and volume $V_0$ of fuel in high-pressure oil pump.

Because the plunger in the high-pressure oil pump is driven up and down by the cam, which causes the pressure change in the cavity, and the fuel density also varies with the pressure change, it is necessary to determine the mass $m_0$, density $\rho_0$ and initial capacity $V_0$ of the high-pressure oil pump plunger before the first oil pressure.

The initial density can be calculated according to Formula $\Delta P = \frac{E}{\rho} \Delta \rho$, as shown in formula (17):

\[
\rho_0 = \rho - \Delta \rho = \rho - \frac{\rho \Delta P}{E}
\]  

(17)

Where $\rho$ is the fuel density under the pressure of 100 MPa.

According to the polar angle and polar diameter values, the distance $d$ between the plunger movement to the top dead center position and the bottom dead center position can be calculated, that is, the maximum range of plunger movement in a working cycle, as shown in figure (7). At the same time, when the plunger moves to the top dead center position, the residual volume of the plunger cavity is $20\, mm^3$, and the diameter of the plunger cavity has been given in the title, so the residual space height of the plunger cavity is calculated as $h$. Then the height of the high-pressure oil pump $l$ is the sum of the polar difference $d$ and the residual space height of the plunger cavity $h$, and then the initial capacity of the high-pressure oil pump $V_0$ can be obtained.

Fig. 7 Schematic diagram of the height of the piston in the oil pump at the top dead center and bottom dead center of the plunger
Step 3: Measure the fuel mass \( m_A \), density \( \rho_A \) and volume \( V_A \) of the high-pressure oil pump flowing into the high-pressure oil pipe.

In this paper, the working cycle time of the injector (100 ms) is taken as an arbitrary time period to investigate the actual working situation of the high-pressure oil pipe in the fuel system, and it is assumed that in 100 ms, the one-way valve first carries out multiple oil feeding operations, and the last 2.4 ms is the working time of the injector.

Due to the irregularity of the cam, the polar diameter difference in the adjacent polar angle is different, as shown in figure 8. Therefore, the increase (or decrease) distance of the plunger after each unit polar angle of the cam is the product of the cross-sectional area of the plunger cavity, which is the fuel volume \( \Delta V \) in the plunger cavity compressed (or expanded) when the plunger moves due to this rotation, as shown in formula (18):

\[
\Delta V_j = S_{\text{Plunger}} d_j d_{j+1} (d_j - d_{j+1})
\]

Fig.8 Schematic diagram of plunger height change value \( \Delta d \) after cam rotation angle \( \theta \)

Since the pressure oil is a continuous process, this paper takes the pressure in the high-pressure oil pipe such as the pressure in the plunger cavity every time, that is, before the one-way valve connecting the plunger cavity and the high-pressure oil pipe is opened, the volume of the high-pressure oil pump decreases to \( V - \Delta V \), the pressure increases gradually, and the density increases. Assuming that the fuel density does not change at this time, then \( \rho_j \) can be obtained from formula (19), we can get:

\[
\rho_j = \frac{m}{V - \Delta V}
\]

The fuel mass \( m_A \) flowing into the high-pressure oil pipe by the high-pressure oil pump is calculated, as shown in formula (20):

\[
m_A = \sum_{i=1}^{z} m_{A(i)} = \sum_{i=1}^{z} \sum_{j=1}^{t} 2\Delta V_j \rho_j
\]

Step 4: According to the principle of mass conservation, let \( m_A = m_B \), calculate the number of times \( n \) that the one-way valve opens or the fuel is supplied in one working cycle of the injector, that is, the cam turns \( n \) turns in this period. In this paper, it is assumed that the working time is extracted and the cam moves in a uniform circle, then the time \( t' \) required for the cam to rotate for one circle can be calculated.

According to the formula \( \omega = \frac{2\pi}{t} \) of angular velocity, the angular velocity which can meet the requirement of \( n \) times of cam rotation in a given time can be obtained.

According to formula (12) ~ (20), \( n=94 \), that is to say, the high-pressure oil pump supplies oil 94 times in a working cycle of the injector, and calculates the time \( t' = 1.064 \text{ms} \) required for the cam to rotate for a circle, at this time, the angular velocity of the cam is \( \omega = 5.906 \text{rad}/\text{ms} \).

4. Conclusion

The model is based on the principle of mass conservation in the one-dimensional unsteady flow equation. The method is simple and easy to understand, and has been applied in real life. Secondly, the density change before and after the injection at the injection nozzle B is considered, and the fuel mass discharged from the injection nozzle is solved more accurately.

On the basis of correct and clear analysis of the question, this paper selects several important factors to establish the angular velocity analysis model of the cam, which is convenient for the inspectors to roughly solve the motion state of the cam in their daily life, and uses the definite integral to solve the
volume of nozzle B ejected in any period of time (in the question, take the working cycle length of the nozzle as an example), with good accuracy. At the same time, considering the up and down movement of the piston in the high-pressure oil pump will lead to the density change of the fuel in the container, this paper discretizes the relationship between the density and volume of the fuel, which is helpful to better understand the mass change of the fuel flowing out of the high-pressure oil pump.

However, in this paper, too few factors are taken into account when establishing the model, such as neglecting the material properties of high-pressure tubing and the resistance of fuel flow in high-pressure tubing, which may cause some errors to the experimental results. What remains to be improved in this model is that the specific movement of fuel in the high-pressure oil pipe is transmitted by the pressure wave, and the change of the specific position pressure in the high-pressure oil pipe is discussed.

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