The Pressure Control of High-pressure Tubing

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Abstract. This article mainly studies the pressure control of high-pressure tubing. Based on the theoretical basis of the pressure formula, a pressure variation model based on the pressure formula is established and solved by the enumeration method within the range. In the process of solving the model of the open time of the one-way valve in the problem, first, establish a model of the pressure change of the inlet and outlet oil. Using integral thinking, we get the oil density under each pressure. Based on the tubing pressure requirements in the corresponding time period together with the relationship between the net mass of the inlet and outlet oil per unit time, the relationship between the opening time of the inlet valve and the pressure is obtained by using the principle of the inlet valve opening time to control the inlet mass. The results of the corresponding pressure requirements are obtained through the enumeration method within the range.

Keywords: Integral thinking, recursive algorithm, range enumeration, high-pressure tubing, time research unit.

1. Introduction

This article is the research results of some problems of high-pressure tubing. It analyzes and discusses the high-pressure tubing pressure controlling questions 1 of the 2019 National College Student Mathematical Modeling Contest A in detail, and gives feasible solutions. The intermittent working process of fuel entering and spraying will cause changes in the pressure in the high-pressure fuel pipe, causing deviations in the mass of fuel sprayed, thereby affecting the working efficiency of the engine.

In the modeling problem, fuel enters the fuel pipe from A and exits the fuel pipe from B. The question requires the oil pipe to stabilize at 100MPa and then rise to 150MPa within the specified time.

2. Analyses and resolution of the problem

2.1. Problem restatement and analysis

2.1.1. Problem restatement. Fuel entering and ejecting from high-pressure fuel pipes is the basis of working for many fuel engines. Figure 1 shows the working principle of a high-pressure fuel system. Fuel enters the high-pressure fuel pipe from A through a high-pressure fuel pump, and then is ejected from nozzle B. The intermittent working process of fuel entering and spraying will cause changes in
the pressure in the high-pressure fuel pipe, causing deviations in the amount of fuel sprayed, thereby affecting the working efficiency of the engine.

Figure 1. Schematic diagram of high pressure tubing.

Therefore, we hope to make the pressure in the pipe more stable by controlling and improving the device to improve the working efficiency of the engine.

2.1.2. Problem analysis. To solve the problem, we hope to establish a gas pressure changing model based on the gas pressure equation, and determine the relationship between the pressure change in the tubing and the opening time of the inlet valve within a cycle after the time research unit considered.

The task following is to simplify the problem. We think that during one time research unit the pressure change in the inner tubing is not considered due to the accuracy of the problem data. Moreover there is an in-depth understanding of the problem. Because the pressure change is proportional to the density change, and the coefficient is \( E/\rho \), the density corresponding to each pressure can be obtained by using the integral idea. The recursive algorithm can be used to obtain the pressure after the corresponding time.

Finally, by using the range enumeration method, we could obtain the time \( \Delta t \) of the opening of the inlet valve.

2.2. Model assumptions
In the question, during the assumed time research unit \( t_1 \), the pressure in the tubing remains almost unchanged.

2.3. Symbol Description

| Symbol | Meaning                                      | Dimension |
|--------|----------------------------------------------|-----------|
| \( L \) | Inner cavity length of high pressure tubing | mm        |
| \( D \) | Inner diameter of high pressure tubing       | mm        |
| \( d_A \) | Diameter of small hole at oil supply inlet A | mm        |
| \( t \) | Open time of one-way valve                   | ms        |
| \( t_1 \) | One time research unit                       | ms        |
| \( t_3 \) | The opening time of one-way valve during one time research unit | ms |
| \( t_0 \) | The closing time of one-way valve during one time research unit | ms |
| \( T \) | The duty cycle of the check valve            | ms        |
| \( 0 \) | Density of fuel at pressure of 100Mpa        | mg/mm\(^3\) |
| 1     | Density of fuel at 160Mpa pressure           | mg/mm\(^3\) |
| 2     | Density of fuel at 0.5MPa pressure           | mg/mm\(^3\) |
| high  | High fuel density on high pressure side      | mg/mm\(^3\) |
| \( l \) | The amount of fuel density change in the high-pressure fuel pipe for one fuel inlet and one fuel outlet pipe | mg/mm\(^3\) |
| \( A \) | The area of small hole in Flow Formula       | mm\(^2\)  |
| \( C \) | Flow Coefficient                             |           |
| \( E \) | Elastic Modulus                              |           |
| \( Q \) | The volume of fuel flowing through the small hole per unit time | mm\(^3\)/ms |
| \( P \) | Fuel pressure in high-pressure oil pipe      | MPa       |
| \( p \) | The pressure difference on both sides of the inlet valve orifice | MPa |
| \( V_0 \) | Internal cavity volume of high-pressure tubing | mm\(^3\) |
| \( V_1 \) | The volume of oil discharged by the injector during one cycle | mm\(^3\) |
| \( m_2 \) | The mass of fuel injected by the fuel injector during one cycle | mg |
| \( m_1 \) | Inlet oil mass within one-way valve during one cycle | mg |
2.4. Model building and solving

2.4.1. Maintain the pressure in the high-pressure tubing at about 100MPa.

(I) Find the oil density corresponding to the pressure from 0 to 160MPa

The pressure change scale value is 0.5MPa, and the relationship between the pressure change and the density change is directly proportional:

\[ \Delta p = \frac{E}{\rho} \Delta \rho \]  \hspace{1cm} (1)

Taking the density of 0.85mg/mm\(^3\) at 100MPa as the known point, the imaginary pressure changes up and down by 0.5MPa. We make use of C++ to get the corresponding oil density at each pressure through the cycle algorithm. The calculation results are as follows:

![Figure 2. Correspondence between pressure and density.](image)

In the first question, we take the density 1 when the pressure is 160MPa, and its value is 0.87102mg/mm\(^3\).

(II) Calculate the oil intake mass once the one-way valve is opened

The area of the small hole:

\[ A = \pi \left( \frac{d_A}{2} \right)^2 \]  \hspace{1cm} (2)

The pressure difference on both sides of the small hole is 160-100=60Mpa.

The amount of fuel flowing into the cavity per time research unit:

\[ Q = CA \sqrt{\frac{E \Delta p}{\rho_1}} \]  \hspace{1cm} (3)

The oil intake mass of the one-way valve during one cycle:

\[ m_1 = Q \Delta t \rho_{\text{high}} \]  \hspace{1cm} (4)

(III) Calculate the fuel injection mass \( m_2 \) of the fuel injection nozzle for one cycle (100ms)
According to the area of the fuel injection rate diagram, find the fuel injection volume at one time:

\[
\text{oil injection rate (mm}^3/\text{ms)}
\]

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

The mass of the oil during one injection:

\[ m_2 = V_0 \rho_0 \]  

(5)

(IV) Calculate the inner cavity volume of the high-pressure tubing:

\[ V_0 = \pi \left( \frac{D}{2} \right)^2 L \]  

(6)

(V) Calculate the change of fuel density in the high-pressure fuel pipe for one fuel inlet and fuel outlet

The fuel injector works 10 times per second, and the fuel injector working cycle:

\[ t_1 = \frac{10^3}{10} = 100 \text{ms} \]  

(7)

Combining equations (1) (2) (3) (4) (5) (7) to find the increase in fuel mass in the high-pressure fuel pipe during one time research unit:

\[ \Delta m = m_1 * \frac{\tau_1}{\Delta t + \tau_0} - m_2 \]  

(8)

The amount of fuel density change in the high-pressure fuel pipe for one fuel inlet and one fuel outlet pipe:

\[ \Delta \rho = \frac{\Delta m}{V_0} \]  

(9)

Let equation (9) be zero, then the opening time \( \Delta t \) of the one-way valve can be solved when the pressure in the cavity is maintained at 100MPa.

Finally, \( \Delta t = 0.2496135 \text{ms} \). Considering the effective value of the accuracy of this problem, take \( \Delta t \) as 0.25ms.

2.4.2. After about 2s of adjustment process, the pressure is stabilized at 150MPa. We still take the hypothetical time research unit of the previous question as the basic unit considered, that is, the 2-second process of the problem is divided into 20 changing processes, each of which is a working time unit. By default, the pressure in the high-pressure tubing within a working time unit remains unchanged, and the pressure changes once every time research unit passes.

Therefore, when the pressure changes, equation (3) will become the following equation:
Therefore, combining equations (2) and 1 and equations (10) obtained in picture 2, under the premise that the opening time $\Delta t$ of the inlet valve is given in one cycle, it only takes one procedure to study the initial pressure $p$ of the unit, and then we can get the mass of oil entering the tubing after a time research unit. It can be expressed by the following formula:

$$m_1 = CA\sqrt{2(160-p)} \times \rho_{\text{high}} \Delta t$$  \hspace{1cm} (11)$$

Next, we consider the oil mass of the oil pipe after a time research unit. It can be seen from picture 2 that the volume of oil sprayed by the fuel injector after a research unit of time is a constant value $V_0$. Therefore, to get the oil mass, only the density $\rho$ of the oil in the tubing needs to be considered.

Therefore, when asked about the pressure change in the tubing, combined with picture 2, we can see that the density of the tubing changes, then the equation (5) becomes the following equation:

$$m_2 = \rho V_0$$  \hspace{1cm} (12)$$

Therefore, only the initial density $\rho$ is required for the value of the fuel injection nozzle after a time unit.

So far, under the premise of a given $\Delta t$, the amount of change in the oil mass in the tubing after a time research unit can be determined by the initial value ($\rho$, $p$). From picture 2, it can be seen that the oil density $\rho$ and the pressure $p$ have a one-to-one correspondence. So whenever the initial value $p$ of the pressure is known, the amount of change in the oil mass in the tubing after a time research unit can be obtained.

It can be seen from equation (9) that the change in oil density $\Delta \rho$ is directly proportional to the change in oil mass $\Delta m$. Combining equations (8), (9), (11) and (12), the change in oil density $\Delta \rho$ can be obtained:

$$\Delta \rho = \frac{-\rho V_0 + \frac{1}{\Delta t+\Delta t_0} \times C A \Delta t \sqrt{2(160-p)} \times \rho_{\text{high}}}{V_0}$$  \hspace{1cm} (13)$$

Therefore, under the premise that the opening time $\Delta t$ of the one-way valve is given in one week, the 2s process is divided into twenty time research units. The density after each time research unit is used as the new initial density of the next time research unit. We make use of C++ programming loop recursive algorithm to obtain the pressure after two seconds.

The above operation is actually obtained when the one-way opening time $\Delta t$ of the one-way valve is given, but $\Delta t$ is actually the quantity to be determined. At this time, you need to use the enumeration method within the range, try to give some possible values, determine the smaller range of $\Delta t$, and then enumerate further to get the final answer.

After entering the enumerated value in the C++ program through the "cin" method, it is finally determined that the pressure in the tubing reaches 150MPa in 2s and the $\Delta t$ needs to be set to 0.84s.

2.4.3. After about 5s and 10s adjustment process, the pressure is stabilized at 150Mpa. To solve this question, we actually only need to change the number of program cycles at 2s to 50 and 100 respectively which means dividing it into 50 and 100 time research units for research. Debug the program and use the enumeration method within the range to get: when it is required to reach 150MPa in 5s, $\Delta t$ needs to be set to 0.75s, and when it is required to reach 150MPa in 10s, it needs to be set to 0.72s.
In order to study the process of pressure rise in more detail and verify the correctness of our result, we consider the case where the pressure rises to 150MPa in 2s, and plot the node pressure values of twenty time research units:

![Pressure changing process.](image)

**Figure 4.** Pressure changing process.

It can be seen from the image that after 2s, the pressure in the high-pressure tubing just reached the required 150MPa, which meets the requirements of the problem. So this scheme is feasible.

### 3. Conclusions

Using the time research unit method to study problems is essentially a micro-element thinking, with good model effects and clear model interpretation. We have made use of this kind of thinking to solve the problem, offering a feasible solution to maintain the stability of the pressure in the high-pressure tubing. In this way, the working efficiency of the engine will be maintained at a high level.

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