The Pressure Control of High Pressure Tubing Together with Problems about Carbon Deposit

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Abstract. In this article, we solve the controlling problems raised by the problem for the part A of the 2019 Chinese University Students Mathematical Modeling Competition----Pressure Control of High Pressure Tubing. Also we have considered the actual problems that may arise, and give a feasible controlling plan. This article is based on fluid mechanics model and micro-element thinking. With the help of software tools such as Excel, Microsoft Visual Studio, and C++ language for programming calculations and simulations, we finally give a feasible solution to stabilizing the pressure in the high-pressure oil pipe, which provides a reference to improve engine efficiency.

Keywords: C++, carbon deposit, high-pressure tubing, time research unit, oil injection, micro-element thinking.

1. Introduction
One of the basic tasks of the engine is to inject fuel into the high-pressure fuel pipe and eject fuel through the fuel injection nozzle to burn to provide the engine power of corresponding level. However, in order to ensure the efficiency of the engine, it is necessary to control the oil output of the fuel injector. This requires the pressure in the high-pressure oil pipe to be kept in a relatively stable state. However it is difficult to control the oil output. This article is concentrated on such problems.

2. Analyses and resolution of the problem
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. we need to try different programs to stable the pressure in the tubing.

Figure 1. Schematic diagram of high pressure tubing.
2.1. Model assumptions
In the problem, during the assumed time research unit $t_1$, the pressure in the tubing almost does not change.

2.2. Symbol Description

| symbol | meaning | dimension |
|--------|---------|-----------|
| $t_1$  | One time research unit | ms        |
| $T$    | The working cycle of the check valve | ms        |
| $0$    | Density of fuel oil at pressure of 100MPa | mg/mm³    |
| $2$    | Density of fuel at 0.5MPa pressure | mg/mm³    |
| $C$    | Flow Coefficient |           |
| $Q$    | The volume of fuel flowing through the small hole per unit time | mm³/ms    |
| $P$    | Fuel pressure in high-pressure oil pipe | MPa       |
| $m_2$  | 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        |
| $V_{up}$ | The volume when the plunger moves to the top dead line in the high pressure oil pump | mm³       |
| $V_{down}$ | The volume when the plunger in the high pressure oil pump moves to the bottom dead line | mm³       |
| $l_0$  | Maximum length of plunger moving up and down | mm        |
| $D_1$  | The inner diameter of the plunger cavity | mm        |
| $R$    | The radius of the circle obtained by cutting the nozzle at the bottom of the needle valve | mm        |
| $r$    | The radius of the needle valve | mm        |
| $m_{2\text{micro}}$ | The mass of oil sprayed by the injector every 0.01ms (as a function of time) | mg        |
| $\omega$ | Cam angular velocity | rad/s  |

2.3. Model building and solving

2.3.1. Determine the angular velocity of the cam so that the pressure in the high pressure tubing is stabilized at about 100MPa as stable as possible.

(I) It is known that the rotation of the cam drives the plunger to squeeze the oil into high-pressure oil. A small change in density can cause a large change in pressure. Therefore, it is said that pressure responds strongly to changes in density.

From the problem, when the plunger moves to the top dead center, the remaining volume of the high-pressure oil pump is 20mm³, so:

$$V_{up} = 20\text{mm}^3$$  \hspace{1cm} (1)

The following picture can be obtained from the EXCEL data of the cam edge curve attached to the problem:
It can be seen from Figure 2 that the maximum length of plunger movement in the high-pressure oil pump is:

$$l_0 = 4.826\text{mm}$$  \hspace{1cm} (2)

Therefore, when the plunger reaches the low dead line of the oil pump, the volume of plunger is:

$$V_{\text{down}} = V_{\text{up}} + l_0 \times \pi \times \left(\frac{D_1}{2}\right)^2$$  \hspace{1cm} (3)

Through calculation, the value is 114.758mm$^3$.

Thus, the oil density changes as much as five times, and the one-way valve is already opened when the plunger is compressed, so pressurization and oil intake are simultaneous processes. Therefore, when the plunger reaches the top dead center, the one-way valve oil intake process just ends, and the oil pressure in the plunger cavity is 100MPa.

(II) Consider the mass of the oil input by the oil inlet valve after a time research unit.

Obtain the oil intake mass of the one-way valve after a time research unit from the initial and final state of the plunger chamber:

$$m_1 = \frac{t_1}{T} \times \left\{\left(\frac{D_1}{2}\right)^2 \times \pi \times l_0 + V_{\text{up}}\right\} \times \rho_2 - V_{\text{up}} \times \rho_0$$  \hspace{1cm} (4)

The calculated value is 7532.5/Tmg.

(III) Then consider the structure of the injector in detail.

Here is the image of the injector:

Figure 3. The enlarged schematic diagram of the injector nozzle.
Because the needle valve and the fuel injection nozzle are symmetrical in the three-dimensional space, we consider the cross-section conditions and draw the following cross-sectional analysis Figure 4:

![Figure 4. Cross-sectional analysis diagram of needle valve.](image)

In Figure 4, the red line segment d is the distance from the initial position of the needle valve at any time, r is the needle valve radius, and the blue line segment R is the radius of the circular surface obtained by cutting the nozzle at the lower end of the needle valve at any time.

(IV) Then quantitatively consider the mass of the oil released by the injector after a time research unit.

The position of the needle valve in the fuel injector is a function of time, and the corresponding relationship of the value of this function is given in the file attached to the problem "Needle Valve Movement Curve". To better imply the relationship between the position of the needle valve and the time without showing the file, we draw Figure 5 with the help of MATLAB:

![Figure 5. The relationship between the position and time of the needle valve in a cycle.](image)

From the problem:

\[ r = 1.25 \text{mm} \]  \hspace{1cm} (5)

Then we can get:

\[ Q = C \times \pi \times (R^2 - r^2) \times \frac{2 \times \rho}{\sqrt{p_0}} \]  \hspace{1cm} (6)

In equation (6), only R is a time-related variable, so its changing law of the flowing rate is known and fixed.
The minimum unit of data 0.01ms is used as the division value to study the mass of the oil released by the fuel injector in one time research unit. Since the accuracy of the data provided by the problem is 0.01ms, it is reasonable to believe that the position of the needle valve will not change within 0.01ms.

Therefore, divide a cycle of needle valve movement at 0.01ms intervals, and obtain the mass of the oil output from each 0.01ms injector in turn:

$$m_{\text{2micro}} = Q \times 0.01 \times \rho_0$$  \hspace{1cm} (7)

Putting equation (6) into equation (7), we get:

$$m_{\text{2micro}} = 0.01 \times C \times \pi \times (R^2 - r^2) \times \sqrt{2\rho_0}$$  \hspace{1cm} (8)

Taking the data provided by the problem, choosing 0.01ms as a unit, using C++ programming method to perform cyclic calculations, we could obtain the mass of oil sprayed by the injector after one time research unit:

$$m_2 = \sum_{t=0\text{ms}}^{100\text{ms}} m_{2(\text{micro})}$$  \hspace{1cm} (9)

Through the program loop calculation, we can get $m_2=56.7119\text{mg}$. That is, after each time research unit, the mass of oil output from the fuel injector is 56.7119mg.

In order to get results that are easy to compare, we consider 1s to achieve the purpose of changing unit. Thus we can get the angular velocity expression of the cam:

$$\omega = 2\pi \times \frac{m_2\times 1\times 10^{-3}}{m_1}$$  \hspace{1cm} (10)

Substitute the data to get: The value of $\omega$ is 47.3059rad/s.

2.3.2. Analyze the rationality of the angular velocity of the cam. Converting the angular velocity value obtained in the previous question, we can get the equivalent velocity of the cam: 7.5 revolutions per second. Considering the actual situation in conjunction with reference [1], the actual cam can indeed reach a speed of 7.5 revolutions per second, which is in line with the actual situation and does not require special manufacturing.

2.3.3. Solve the fuel supplying strategy of adding a fuel injector.

(1) Background introduction

The formation of "carbon deposits" in the fuel injector: In the actual working situation of the high-pressure fuel pipe, when the fuel flows through the fuel injection nozzle, due to the influence of pressure on the fuel density, the impurities in the fuel will solidify and adhere to the fuel injection nozzle surface. Then "carbon deposit" forms and it will affect the working efficiency of the fuel injection nozzle.

After studying the substance "carbon deposit", it is found that "carbon deposit" has the characteristics of small mass and large volume, so it can be removed naturally by washing if processed in time. That is to say, changing the flowing rate $Q$ of the fuel injector can effectively solve the "carbon deposit" problem.

However the flow rate $Q$ of the fuel injection nozzle can not change significantly directly. We choose to add a fuel injection nozzle on this basis to significantly change the fuel injection nozzle flowing rate $Q$.

The following picture shows the formation of "carbon deposit" at the fuel injector:
Figure 6. Schematic diagram of carbon deposit formation at the fuel injector.

(2) The supplying strategy
(I) Comparison of fuel injection strategy and fuel supplying strategy

From the problem solved above, the angular velocity $\omega$ of the cam is about 47.3 rad/s.

The working accuracy of the cam determines that it should work in a low speed and a small flow situation. If the cam speed goes up blindly, it will increase the wear of the cam. Thus, we can not just speed up the cam to solve the "carbon deposit" problem. Therefore, after weighing the pros and cons, we decide to solve the above problems by using two injectors alternately.

The figure below is an illustration of the program:

Figure 7. Schematic diagram of dual injectors.

(II) Cooperative work of two injectors

It can be seen from picture 5 that the fuel injection nozzle works 10 times per second, and the fuel injecting time is 2.4 ms each cycle.

When injector B is working, a large amount of fuel will accumulate in the nozzle hole of injector C. After injector B stops working, injector C starts to work, and the flow is formed in an instant $Q$ sweeping away the "carbon deposits" attached to the inner surface of injector C. And vice versa.

Therefore, through adjusting the current core of the fuel injector, we make it work 5 times per second, and its working time each cycle is still 2.4 ms. The another fuel injector starts working 100 ms later than the former one.

As shown in Figure 7 below, the alternate working conditions of two injectors are given:

Figure 8. Schematic diagram of two fuel injectors working alternately.
3. Conclusions
So far, we have given solutions for various situations. By adding a fuel injector, we have achieved the goal of stabilizing the pressure of the high-pressure tubing in various situations. At the same time, we also considered the actual "carbon deposit" problem and solved it in time through the alternate controlling scheme of two injectors.

Of course, our plan also has some flaws. For example, towards the setting of time research unit, we believe that the time research unit is short enough that transients cannot occur in this process. This may cause some deviations. To solve this problem, on the one hand, we can further reduce the time research unit, on the other hand, we can use MATLAB for process fitting.

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