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The Pressure Control Strategy Adjustment of High-Pressure Oil Pipe

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Abstract

This paper is based on the background of China Undergraduate Mathematical Contest in Modeling Competition A in 2019. Corresponding analysis based on the data given in this question, calculated changes in pressure in the high-pressure tubing according to the different operating conditions for fuel entry and spewing out, in order to determine some operating parameters of the fuel injection system, so as to improve engine efficiency and economic efficiency. The differential equation is constructed by the mass conservation formula under the corresponding conditions, and using MATLAB to implement Runge-Kutta methods to find the numerical solution of the corresponding differential equation.

Subject Areas

Chemical Engineering & Technology, Fluid Mechanics, Petrochemistry

Keywords

Mass Conservation, Differential Equation, MATLAB, Runge-Kutta Methods

1. Introduction

Since the second industrial revolution, the engine has always been the driving car, aircraft, rockets and a series of large-scale equipment core, so the production and manufacturing technology of engine have been an important indicator of the strength of the manufacturing industry in an industrial modernization country, the study of high efficiency, more stable engine is an important work of national industrial development, which is the most extensive application of fuel engines, the longest development time. Fuel entry and spewing high-pressure tubing are the basis for many fuel engine slots, and the intermittent working process of fuel entry and fuel spewing out can cause changes in pressure in the high-pressure tubing [1], which in turn affects the amount of fuel ejected and thus the efficiency of the engine. Therefore, we will establish a model to stabilize the internal pressure of the high-pressure oil pipe by controlling the mechanism of the injectors, so as to achieve low-cost stability of the injection volume and improve the efficiency of engine efficiency [1].

2. Problem

In the case of a single nozzle, after a series of basic information such as the size of the inner cavity of a certain type of high-pressure oil pipe, the size of the oil supply intake, the operation of the injector, etc., the model is established to make the pressure in the high-pressure oil pipe as stable as possible by reasonably setting the length of each opening of the check valve. 100 MPa Further adjust the opening time of the unidirectional valve to stabilize it from 100 MPa to 150 MPa after the adjustment process of 2 s, 5 s and 10 s respectively (**Figure 1**).

3. Solution to Problem

P_{rail} represents high-pressure oil pump pressure, P_{int} stands for high-pressure tubpressure pressure, P_{back} stands for injection back pressure, A_{pipe} stands for intercept area of high-pressure tubing, L stands for pipe length [1].

Using Matlab to fit the data to the curve, in the case of high fitting degree, the function relationship between elastic modulus E and pressure P, And because the amount of pressure change in the fuel is proportional to the amount of density change, the scale factor is $\frac{E}{\rho}$, and the differential equations are as follows:

$$E = f_e(p) \tag{1}$$

$$\mathrm{d}P = \frac{E}{\rho}\mathrm{d}\rho \tag{2}$$

$$\mathrm{d}P = \frac{f_e(p)}{\rho}\mathrm{d}\rho \tag{3}$$

Numerical solution is obtained by using the fourth-order fifth-order Longer-Kuta method, and then the function relationship between density and pressure P is recorded as curve fitting:

$$\rho = f_\rho(p) \tag{4}$$

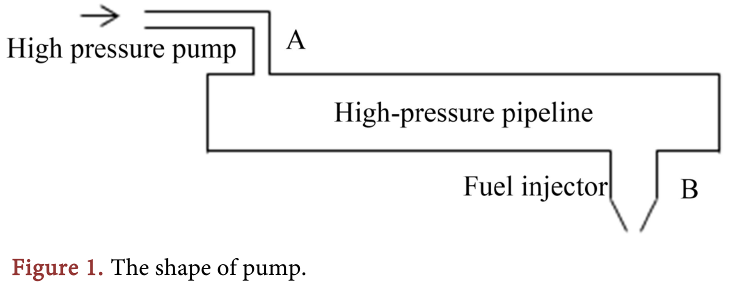

Figure 1. The shape of pump.

The pressure change in the high-pressure tubing is caused by the change in the density of the fuel in the tube, which can be represented by the one-dimensional mass conservation equation as follows:

$$m'_{in} - m'_{out} = V \frac{\mathrm{d}\rho}{\mathrm{d}t} \quad [2] \tag{5}$$

In it, m'_{in} represents the mass flow rate from the high-pressure oil pump to the high-pressure tubing, m'_{out}, indicates the mass flow rate of the pipe from the nozzle [3], V represents the volume of the high-pressure tubing, and the flow from the high-pressure oil pump to the high-pressure tubing is

$$Q = CA\sqrt{\frac{2(160-P)}{\rho_{pumb}}} \quad [4] \tag{6}$$

Among them, Q is the amount of fuel per unit of time that flows through the small hole, $C = 0.85$, A is the area for small hole, ΔP is the pressure difference on both sides of the hole, ρ is the density of fuel on the high-pressure side, $\rho_{pumb} = f_\rho(160) = 0.8708\ \mathrm{mg/mm^3}$:

$$m'_{in} = Q * \rho_{pumb} = CA\sqrt{2(160-P)\rho_{pumb}} \tag{7}$$

$$m'_{out}(t) = \begin{cases} 100\rho t, & 0+100n \le t < 0.2+100n \\ 20\rho, & 0.2+100n \le t < 2.2+100n \\ (240-100t)\rho, & 2.2+100n \le t \le 2.4+100n \end{cases} \tag{8}$$

while $2.4+100n \le t \le 100(n+1)$, $m'_{out}(t) = 0$, add the check valve switch function $f_{in}(t)$

$$f_{in}(t) = \begin{cases} 1, & n(\Delta t+10) \le t < n(\Delta t+10)+10 \\ 0, & n(\Delta t+10)+10 \le t < (n+1)(\Delta t+10) \end{cases} \tag{9}$$

The derivation of the one-dimensional mass conservation equation is as follows

$$m'_{in} f_{in}(t) - m'_{out} = V \frac{\mathrm{d}\rho}{\mathrm{d}t} \tag{10}$$

$$CA\sqrt{2(160-P)\rho_{pumb}}\, f_{in}(t) - m'_{out}(t) = V \frac{\mathrm{d}\rho}{\mathrm{d}t} \tag{11}$$

Bring it into (4), differential equations of pressure and time in high-pressure tubing are established as follows:

$$CA\sqrt{2(160-P) f_\rho(160)}\, f_{in}(t) - m'_{out}(t) = V \frac{\mathrm{d}f_\rho(p)}{\mathrm{d}t} \tag{12}$$

Thus, a model based on the one-dimensional mass conservation equation is established, and the pressure-time curve of the high-pressure oil pipe is obtained under different t-cases by the fourth-order, fifth-order Longer-Kuta method [5].

4. The Solution of the Model

At first, we can get the formula by fitting the given dates, $E = f_e(p)$, the function relationship between elastic modulus E and pressure P (**Figure 2** & **Table 1**)

$$E = f_e(p) = 1489e^{0.00284p} + 48.79e^{0.01376p} \quad (13)$$

Then, the differential equation of P and the p, $dP = \frac{f_e(p)}{\rho} d\rho$ is using the fourth-order fifth-order [5] Longer-Kuta method to obtain a numerical solution (pressure P from 0 to 200, step 0.1, a total of 2001 sets of data, special solution to (0.85, 100)) after the curve fitting to obtain the functional relationship between density and pressure $\rho = f_\rho(p)$ the functional relationship between fuel density and pressure P (**Figure 3** & **Table 2**)

$$\rho = f_\rho(p) = -3.63 + 4.434 * \cos(0.0005415p) + 0.9645 * \sin(0.0005415p) \quad (14)$$

At last, find the best check valve single opening time Δt

1) When the pressure stabilization value is 100 MPa, the check valve is the single opening time Δt [4].

Using the fourth-order, fifth-order Longer-Kula algorithm [2] tries $\Delta t = 0.6$ ms, The P-t curve obtained by using the one-dimensional mass conservation equation is as follows: (**Figure 4**)

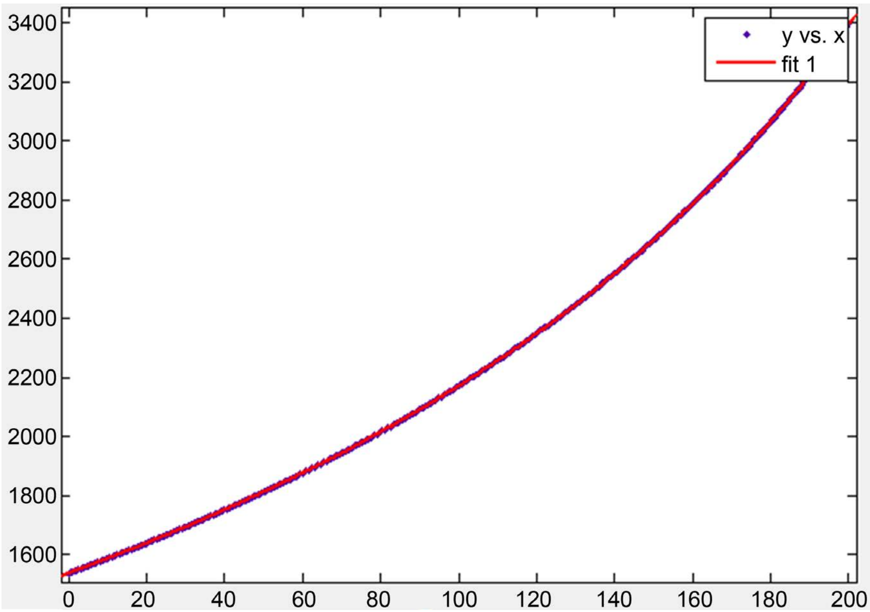

Figure 2. E-P curve.

Table 1. The dates of E-P curve.

SSE	R-square	Adjusted R-square	RMSE
27.82	1	1	0.2647

Table 2. The dates of ρ-P.

SSE	R-square	Adjusted R-square	RMSE
1.423e−008	1	1	2.67e−006

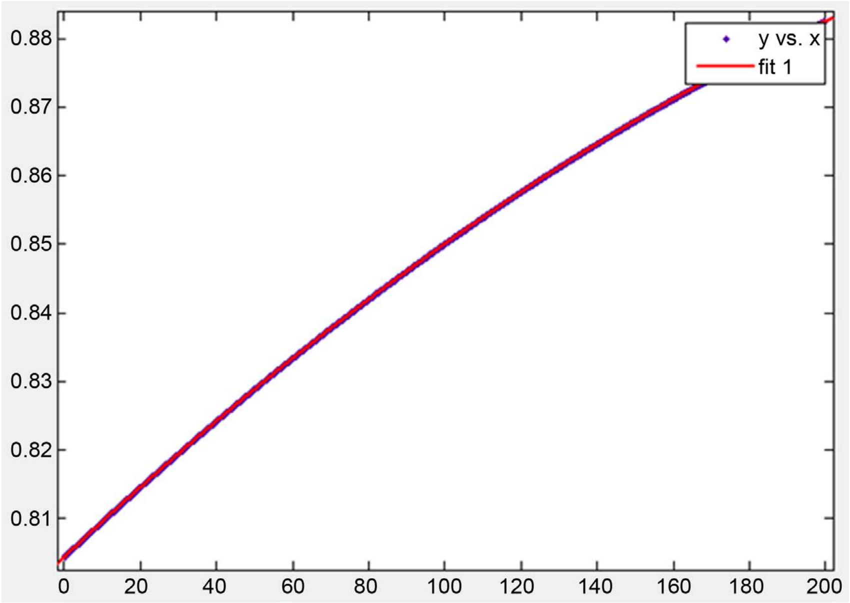

Figure 3. ρ-P curve.

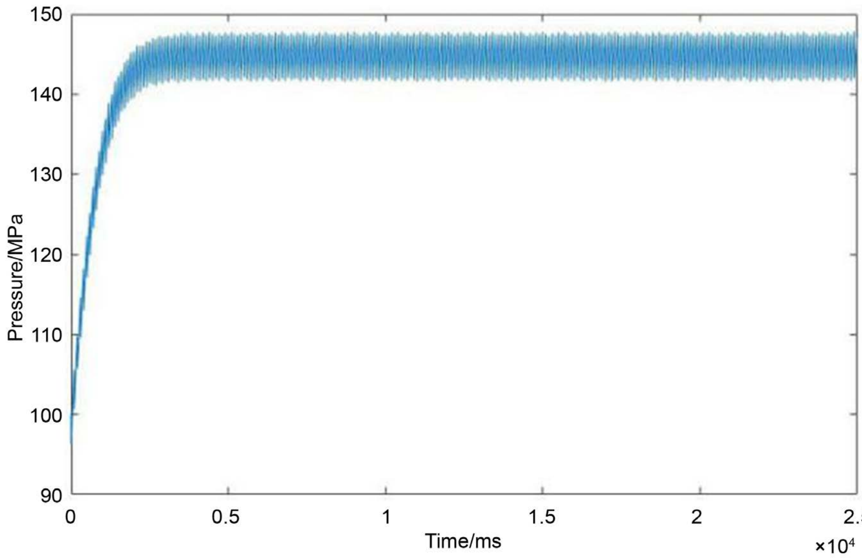

Figure 4. P-t curve.

Analysis of the figure above can be found that when Δt fixed, the high-pressure oil pipe in the fuel pressure P will tend to stabilize, but eventually will still fluctuate around a value, thinking, this is a check valve and nozzle work of the cyclical brought about, cannot be avoided. Therefore, this article defines:

$$\overline{P} = \frac{p_{\min} + P_{\max}}{2} \tag{15}$$

Stable value Δt for pressure in the pipeline in each case, $p_{\min}$ is the minimum value of the fluctuation when the curve tends to stabilize, $P_{\max}$ is the maximum value of the fluctuation when the curve tends to stabilize.

Thus the change curve of $\overline{P}$-t is as follows: (**Figure 5**)

When, $\Delta t = 0.289$ ms, $\overline{P} = 100$ MPa

The corresponding P-t curve is as follows: (**Figure 6**).

2) $\overline{P} = 150$ MPa, the Δt adjustment process corresponds to different situations.

As can be seen from the curve in A, $\Delta t = 0.755$ ms, $\overline{P} = 150$ MPa, make the P-t curve as follows (**Figure 7**).

It can be found in the figure that when the check valve is open at 0.755 ms a single time, the time required to stabilize from 100 MPa to 150 MPa is 4 s.

a) $\overline{t} = 2000$ ms ($\overline{t}$ indicates the time it takes to move P from 100 MPa to 150 MPa).

When the regulation time is 2 s, this paper debugging ideas are as follows: First,

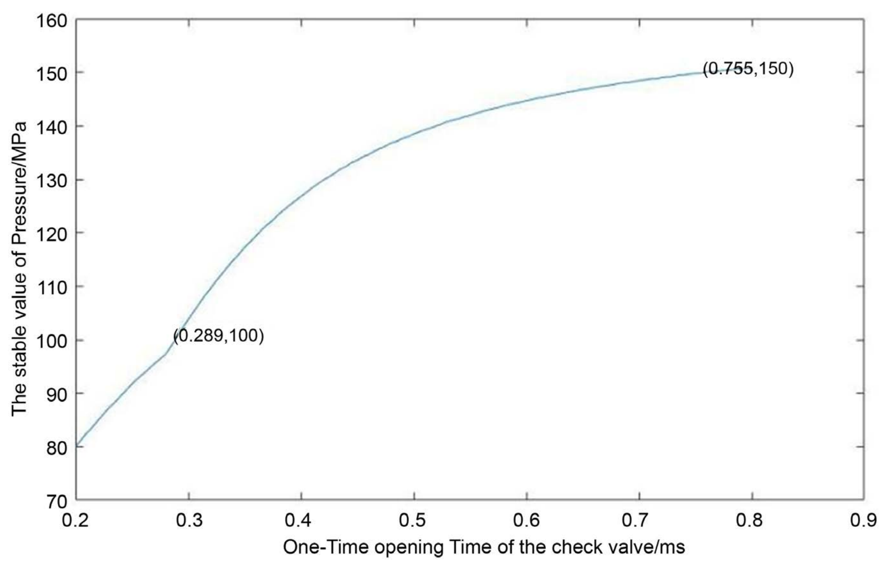

Figure 5. $\overline{P}$-Δt curve.

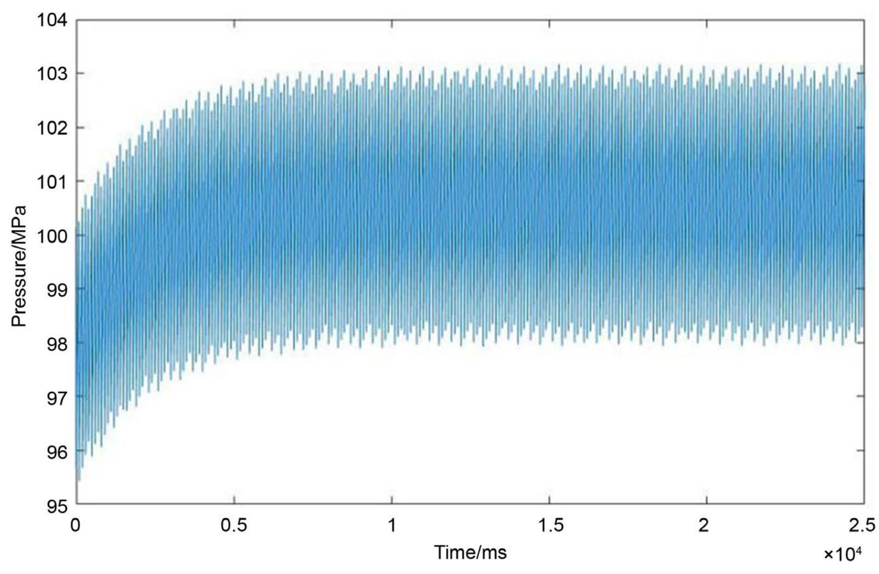

Figure 6. P-t curve ($\Delta t = 0.289$ ms).

find the Δt value that can use 2 s to raise P to 150 MPa, and then switch Δt to 0.755 at 2 s, make 2 s end of each Δt corresponding P-t curve as follows: (Figure 8).

When $\Delta t = 0.88$ ms, you can raise p to 150 MPa at $t = 2$ s, and then switch Δt to 0.755 ms, and make the corresponding P-t graph as follows: (Figure 9).

b) $\bar{t} = 5000$ ms

Since 5 s is longer than the time required for $\Delta t = 0.755$, the following adjustment ideas can be made

$$\Delta t = \begin{cases} 0.289 \text{ ms} \ \left(\bar{P} = 100 \text{ MPa}\right), & 0 < t \le \bar{t} - 4000 \\ 0.755 \text{ ms} \ \left(\bar{P} = 150 \text{ MPa}\right), & \bar{t} - 4000 < t \end{cases}$$

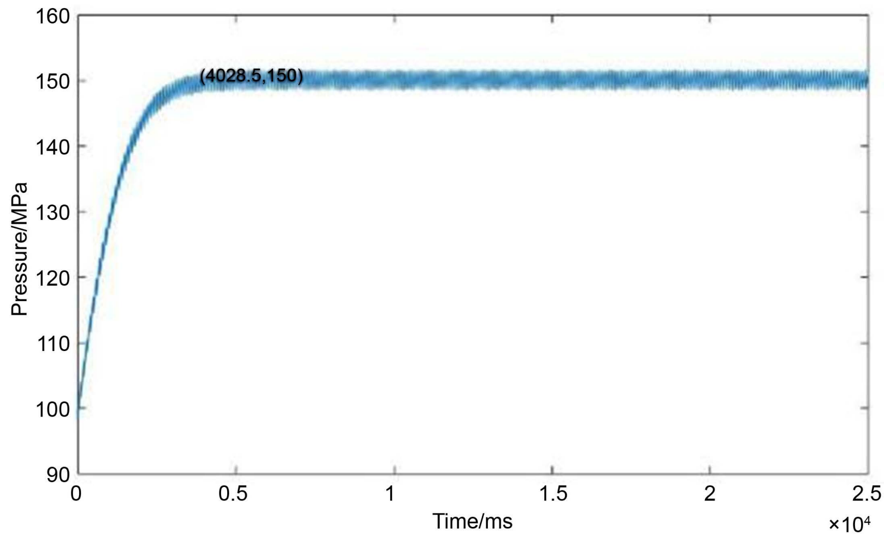

Figure 7. P-t curve ($\Delta t = 0.755$ ms).

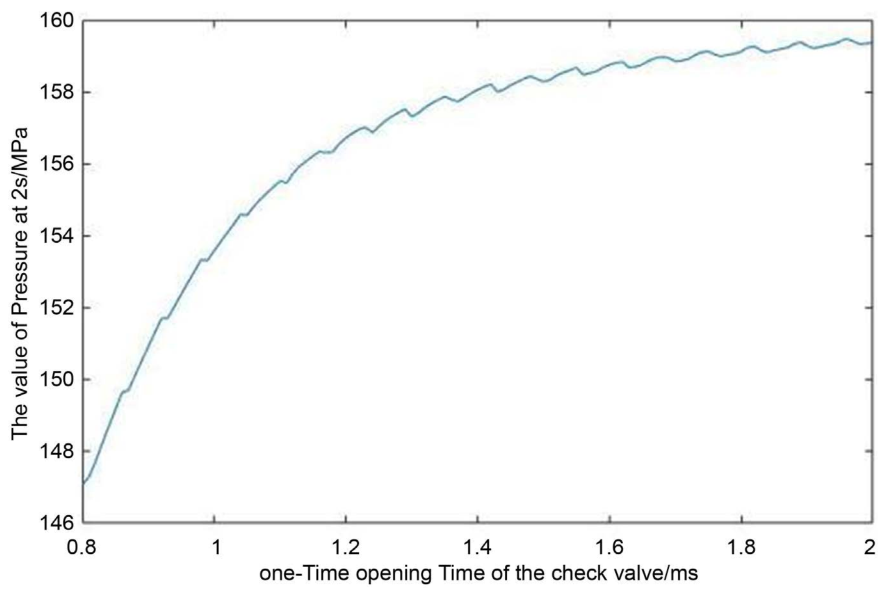

Figure 8. P-Δt curve.

$\overline{t}$ is the time required to stabilize the pressure to 150 MPa.

From 0 to 1000 ms, $\Delta t = 0.289$ ms, stabilize the tubing pressure P in the 100 MPa, Then the $\Delta t = 0.755$ ms can stabilize the P to 150 MPa at the 5th second.

Make the corresponding P-t curve as follows (Figure 10).

c) $\overline{t} = 10000$ ms

As the same as the previous text, the first 6000 ms, the check valve single opening time 0.289 ms, the oil pipe pressure P stabilized at 100 MPa, and then make $\Delta t = 0.755$ ms can be stabilized P in the 10th second to 150 MPa. Make the corresponding P-t curve as follows (Figure 11).

At this point, the problem is solved by the model [1]. The results are as following.

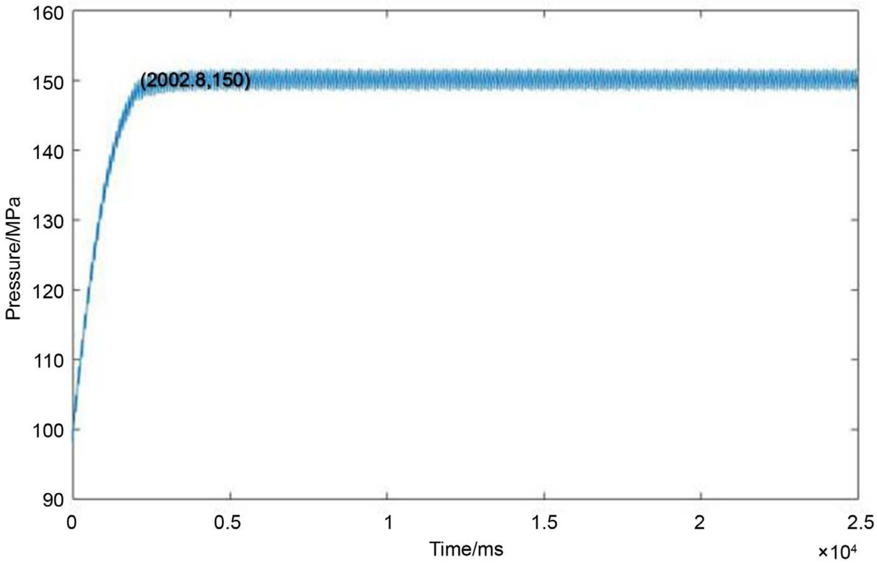

Figure 9. The steady curve at 2 s.

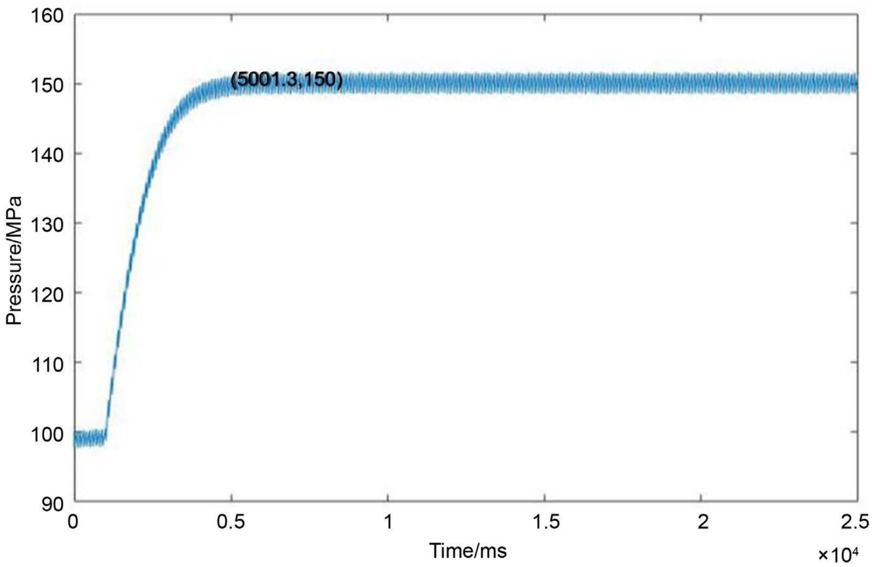

Figure 10. The steady curve at 5 s.

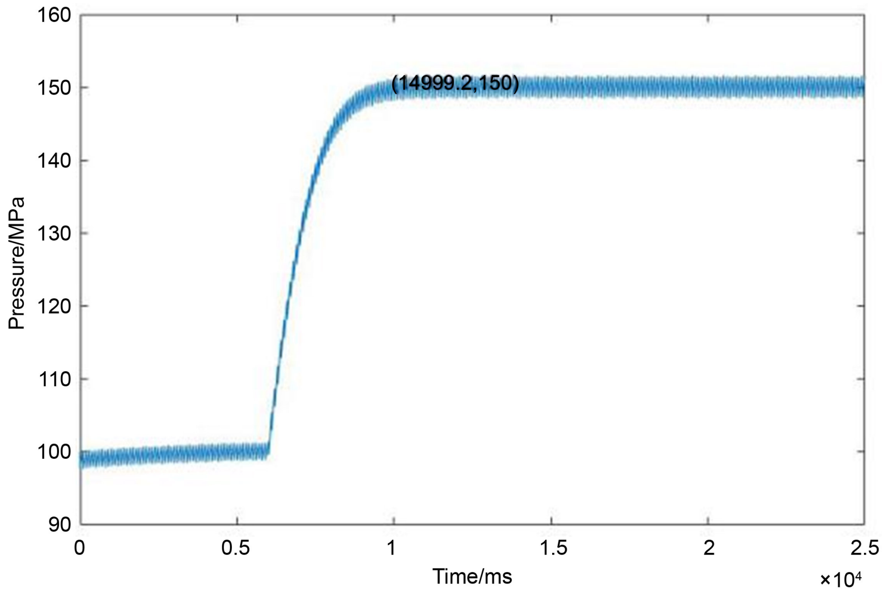

Figure 11. The steady curve at 10 s.

1) Final stabilization, $\overline{P} = 100\ \text{MPa}$, one-time opening time of the check valve $\Delta t = 0.289\ \text{ms}$.

2) Spend 2 s making $\overline{P} = 150\ \text{MPa}$, 0 s - 2 s, $\Delta t = 0.88\ \text{ms}$, 2 s - ∞, $\Delta t = 0.755\ \text{ms}$.

3) Spend 5 s making the $\overline{P} = 150\ \text{MPa}$, 0 s - 1 s, $\Delta t = 0.289\ \text{ms}$, 2 s - ∞, $\Delta t = 0.755\ \text{ms}$.

4) Spend 10 s making $\overline{P} = 150\ \text{MPa}$, 0 s - 6 s, $\Delta t = 0.289\ \text{ms}$, 2 s - ∞, $\Delta t = 0.755\ \text{ms}$.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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