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Analysis and verification of gas content and pressure change rate characteristics in hydraulic system①

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Abstract

Gas content of the hydraulic system directly affects the rate of pressure change of the hydraulic system. The purpose of this paper is to establish a mathematical model of oil gas content, hydraulic system pressure and pressure rise rate, obtain corresponding oil pressure value when the pressure rise rate of different gas content is maximum, and verify the accuracy of this conclusion by the FLUENT simulation software. On this basis, a rapid pressure building device of the hydraulic system is developed and designed. The above oil pressure value is used as the working cut-off pressure of the rapid pressure building device, and then the hydraulic oil pump continues to pressurize to the highest working pressure required by the system. The research content can replace the hydraulic system from the initial low pressure to the rapid pressure build-up of the oil, thus increasing the construction pressure of the hydraulic system. The research results show that the rapid pressure building device effectively reduces the time for the hydraulic system to establish pressure. Through the analysis of theoretical derivation and the collected experimental data, the error is about 5.9%, which verifies the correctness of the theoretical formula.

Key words: hydraulic system, gas content, establishment of pressure rate, rapid pressure building device, pressure building time

0 Introduction

Due to high power density and fast dynamic response of the hydraulic system, the hydraulic system is widely used in various equipments[1-3], so performance of the hydraulic system determines stable operation of the equipment[4-6]. Taking a 12.5 MN fast forging machine as an example, due to the presence of gas in the oil of the hydraulic system, pressure building rate is slow after the slider contacts the work-piece, resulting in certain metal materials with narrow temperature range, low plasticity and easy fracture. Cracks and surface size errors are large after forging, which affects molding rate and work efficiency of the product seriously.

Based on the oil elastic modulus, this paper studies influence of gas content on the pressure rate of hydraulic system to solve practical application problems. In 2015, Yang et al[7] studied influence of oil gas content on the dynamic performance of hydraulic mechanical step-less transmission, and proposed that the larger the gas content of the oil is, the smaller the effective modulus of the oil is. In 2013, Yang et al[8] used pressure to establish mathematical expression of gas content and effective modulus of oil. The study shows that the oil elastic modulus is basically unchanged after the system pressure increases to a certain value. In 2017, Tang et al[9] proposed to establish a theoretical model of the effective volume elastic modulus of gas-containing oil by density. The study shows that gas content is reduced, the effective volume elastic modulus is increased, and the pressure-building time is reduced. People have found that increasing the bulk modulus of the oil can reduce the pressure-building time of the hydraulic system. Therefore, various methods for detecting and improving the effective volume elasticity of the oil are proposed. In 2013, Zhou et al[10] proposed a new method for predicting the dynamic characteristics of air release and absorption in hydraulic oil through CFD simulation and experiment. In

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2011, Hossein et al[11] reviewed various methods for measuring the effective bulk modulus of oil and compared the errors. In 2012, Kim et al[12] used three methods of mass change, volume change and sound velocity method to detect the effective bulk modulus of elasticity in different oil contents. In 2010, Feng et al[13] analyzed the influence of parameters such as gas content and working pressure on the effective bulk modulus of oil in hydraulic system, and designed a vacuuming method to improve the effective volume elastic modulus of oil. However, this method is costly and has a high space occupancy rate. In 2018, David et al[14] designed a filter element to separate bubbles from the oil to reduce the gas content. However, the filter element has a low working pressure and is not suitable for high pressure systems.

This paper establishes a mathematical model of oil gas content, hydraulic system pressure and pressure rise rate. It is found that when gas content increases, the pressure required to stabilize the pressure rise rate increases, but the steady pressure rise rate decreases, and the build time cuts back. Based on the research of mathematical model, a rapid pressure building device for hydraulic system was designed and installed in the hydraulic system of a fast forging machine of a steel plant. Field experiments show that the increase in the rapid pressure build-up device greatly improves the efficiency of the fast forging machine.

1 Building a mathematical model

1.1 Establishing a pressure rise rate model

When gas is pressed in oil, it will change in both dissolution and compression. The gas dissolved in the oil will not affect physical properties of the oil, but the gas in the oil (also known as the gas content) is an important factor affecting the effective bulk modulus of oil. At the same time, the elastic modulus is an important factor affecting rate of the characteristics construction pressure of hydraulic oil. Therefore, the tangential elastic modulus formula is established [15].

$$E = V\frac{dp}{-dV} \tag{1}$$

where, V is the initial oil volume; dp is the oil pressure increase after compression; dV is the oil volume change after compression; E is the effective bulk modulus of the oil.

The effective volume elastic modulus of the oil is mainly composed of a bulk modulus of the oil after the bubble is dissolved, bulk modulus of the undissolved bubble, and bulk modulus of the pipe fittings steel.

The bulk modulus of the pipe fitting steel is the modulus of elasticity generated by wall strain of the pipe after the pressure is established in the pipe, which usually has little effect and is neglected in the calculation process. Because the bubble dissolves into the oil and loses its compressible, the oil is approximately pure, as shown in Fig. 1. The effective volume elastic modulus formula of the oil is

$$\frac{1}{E} = \frac{1-x}{V_l} \times \frac{dV_l}{dp} + \frac{x}{V_g} \times \frac{1}{dp} \tag{2}$$

where V_l is the volume of pure oil; V_g is the volume of undissolved bubbles; x is the gas content after compression.

Effective modulus of modulus is obtained by

$$E = \frac{E_l E_g}{E_g + x(E_l - E_g)} \tag{3}$$

where E_l is the elastic bulk modulus of pure oil, E_l = 1 700 MPa; E_g is the elastic bulk modulus of undissolved bubbles, $E_g = 1.4p$.

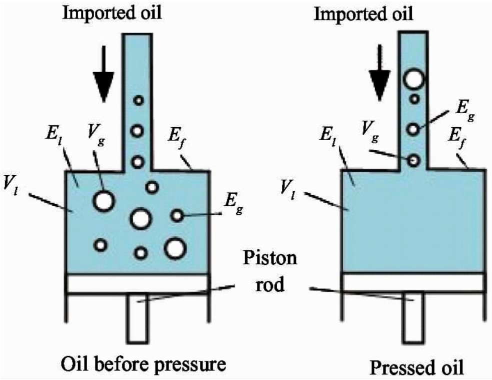

Fig. 1 Simulation process diagram

Since the gas is compressed in the oil and the gas is dissolved and compressed. The gas content equation after the pressure is obtained[16]:

$$x = 1 - \frac{1}{1 + \frac{x_0}{1-x_0} \times \frac{(1 - \frac{\Delta p}{1.4p})}{(1 - \frac{\Delta p}{E_l})}} \tag{4}$$

where x_0 is initial gas content, $x_0 = \frac{V_g}{V}$; $\Delta p = p - p_0$, p_0 is atmospheric pressure, p_0 = 101 325 Pa .

$\frac{dV}{dt}$ is the flow in the pipeline. Therefore, the relationship between the rate of pressure rise and flow can be obtained by Eq. (1).

$$\frac{dp}{dt} = E\frac{q_V}{V} \tag{5}$$

where q_V is the total flow of the hydraulic oil pump.

Mathematical models of gas content, system pressure and pressure rise rate from Eqs(3) – (5) are:

$$\frac{dp}{dt} = \frac{1.4pE_l}{1.4p + \left[\frac{x_0E_l[0.4p + p_0]}{[x_0E_l[0.4p + p_0]] + (1 - x_0)[1.4p(E_l - p + p_0)]}\right] \times (E_l - 1.4p)} \times \frac{q_v}{V} \quad (6)$$

1.2 Establishing an effective oil density model

After the simulation calculation, it is necessary to convert the oil unit kg/s detected in the simulation into m^3/s by the effective oil density, and then draw the mathematical model of the pressure rise rate under different initial gas content, the simulation curve and the gas content change during the simulation curve. The pure oil mass Eq. (7) and the pure gas mass formula Eq. (8) can be obtained from the oil mass formula, respectively.

$$m_l = \rho_l V_l = \rho_l V(1 - x) \quad (7)$$

$$m_g = \rho_g V_g = \rho_l x V \quad (8)$$

where ρ_l is pure oil density, ρ_g is pure gas density.

According to the law of conservation of oil mass, the formula of effective oil density is obtained.

$$\rho = \rho_l(1 - x) + \rho_g x \quad (9)$$

2 Simulation module

2.1 Building a simulation model

In order to verify the accuracy of the mathematical model of gas content, system pressure and pressure rise rate, according to the actual working pressure of the site, the volume and flow of the control simulation model are constant, as shown in Fig. 2. The simulation model of this paper was established using ANSYS 15.0. In order to increase the mesh quality and increase the accuracy of the calculation, the model mesh is divided by the regular hexahedron, and the detected mesh quality is 0.75, which meets the calculation requirements of FLUENT 15.0. According to the actual situation, the compressible oil and gas mixing model is applied in the FLUENT calculation. The specific simulation parameters are shown in Table 1.

2.2 Simulation data analysis

In order to prove the conclusion of the above mathematical model, this paper uses FLUENT for simulation. Figs 2 – 6 are plots of pressure rise rate, gas content change and FLUENT simulated gas content change for system pressures from 0.1 MPa to 26 MPa. The initial gas content of the hydraulic oil is 0.1%, 0.2%, 0.5%, 1% and 2%, respectively.

Table1 Simulation parameter of FLUENT

Equation	Mixture mode
Solver type	Pressure-based
Solver time	Transient
Models-multiphase	Mixture
Oil	889 kg/m^3 (density), 1 700 MPa (elastic modulus)
Air	1.225 kg/m^3 (density), 0.142 MPa (elastic modulus)
Air volume fraction	0.1%, 0.2%, 0.5%, 1%, 2%
Hydraulic cylinder	0.49 m^3
Total inlet flow	30.9373 kg/s
Hydraulic system maximum pressure	26 MPa

Figs 2 – 6 show that errors of the comparative simulation and mathematical model curves after pressure stabilization are all within 8%. As shown in Fig. 3, when the gas content is 0.1%, the pressure rise rate and the gas content curve tend to be stable after the pressure rises to 2.5 MPa, and the pressure rise rate and the gas content are 103.46 and 0.0167%, respectively. The rapid pressure build-up device test of the rapid forging machine found that putting the liquid process of rapid pressure build - up device needs to be completed in 0.12 s and the reduction rate of the built-in pressure is calculated by Eq. (10). The time required to stabilize the pressure rise rate and the pressure rise to 26 MPa by the simulation of the background data is given as follows:

$$\delta = \frac{t_2 - (t_1 + 0.15)}{t_2} \times 100\% \quad (10)$$

where δ is the reduction rate of the built-in time; t_1 is the time required for the rate of pressure rise to stabilize; t_2 is the time when the pressure rises to 26 MPa.

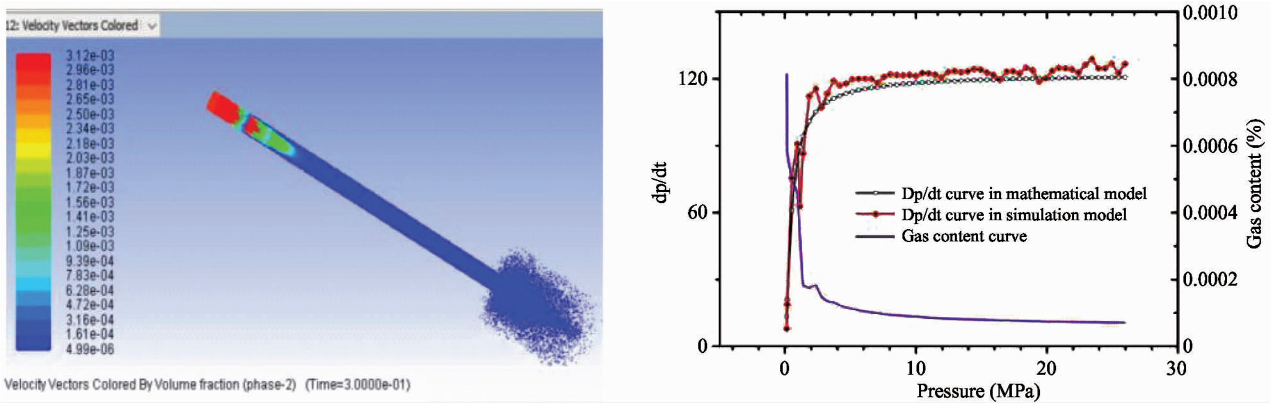

Fig. 2 Curves of pressure rise rate, gas content change and FLUENT simulated gas content change (The initial gas content is 0.1%)

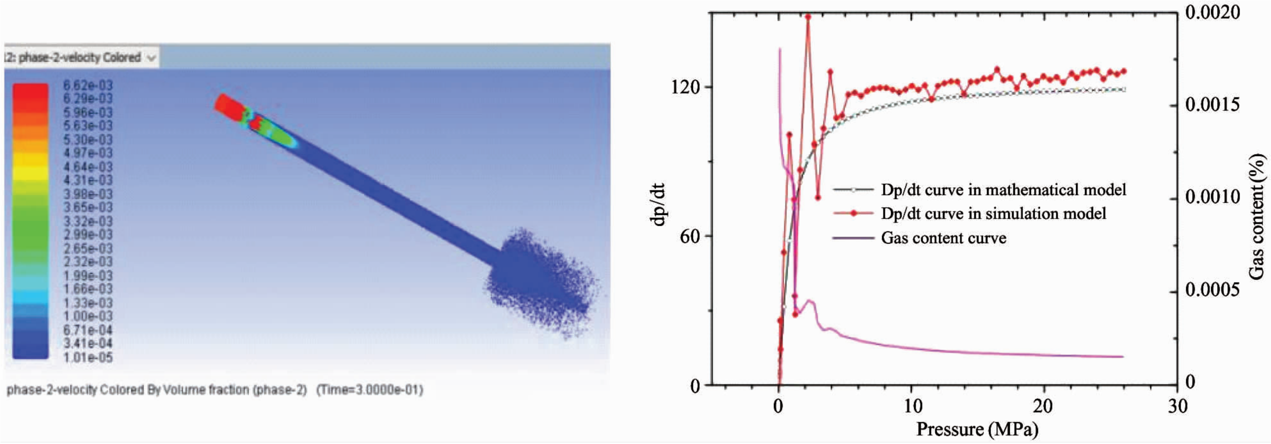

Fig. 3 Curves of pressure rise rate, gas content change and FLUENT simulated gas content change (The initial gas content is 0.2%)

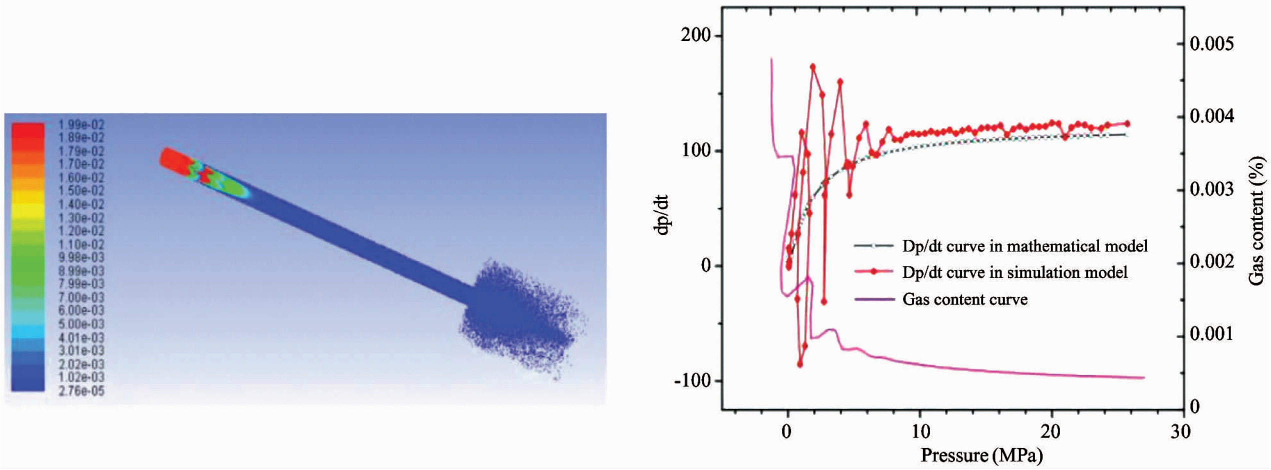

Fig. 4 Curves of pressure rise rate, gas content change and FLUENT simulated gas content change (The initial gas content is 0.5%)

Table 2 shows that as the gas content increases, the pressure value required for the pressure rise rate to stabilize increases, but the rate of pressure rise decreases after stabilization, and the rate of decrease in build-up time increases. Analysis of Table 2 by interpolation method shows that when the initial gas content of the hydraulic oil is greater than 0.438%, the rapid pressure building device will be effective. From the gas content images shown in Figs 2 – 6, it can be seen that when the pressure rises to 26 MPa, the gas content increases as the initial gas content increases, and the gas content mainly accumulates in the pipe inlet.

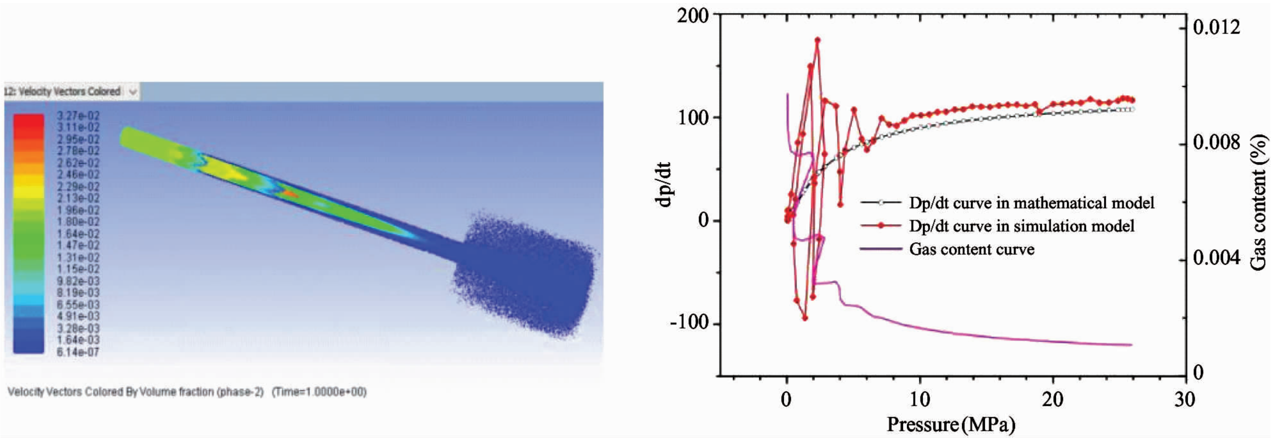

Fig. 5 Curves of pressure rise rate, gas content change and FLUENT simulated gas content change (The initial gas content is 1%)

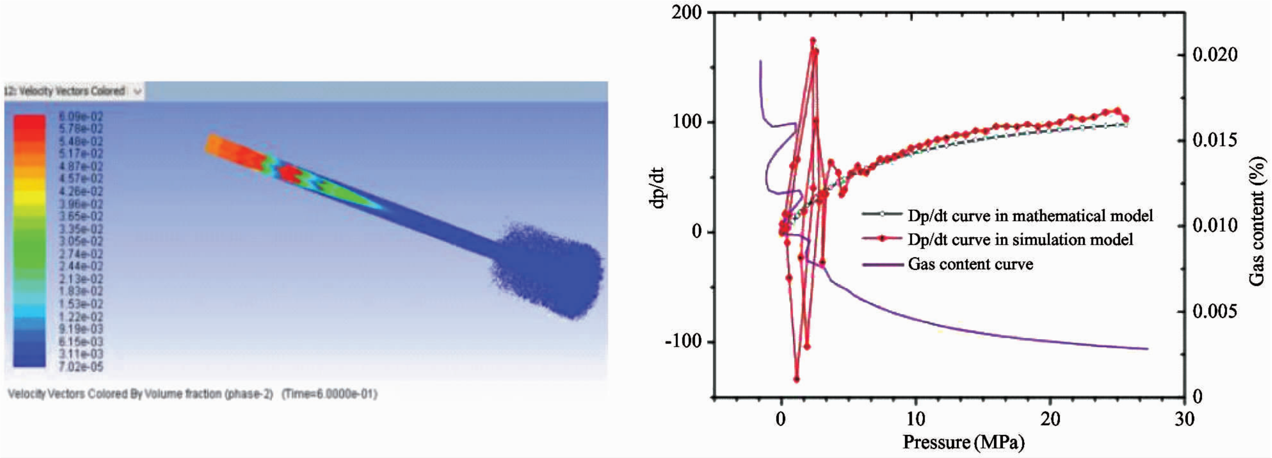

Fig. 6 Curves of pressure rise rate, gas content change and FLUENT simulated gas content change (The initial gas content is 2%)

Table 2 Parameters of system stability under different gas contents

Initial gas content	Stable schedule t_1 (s)	26 MPa time t_2 (s)	Stable pressure (MPa)	Rate of pressure rise	Stable gas content (%)	Pressure reduction time δ (%)
0.1%	0.034	0.224	2.5	103.46	0.0167%	-38.39%
0.2%	0.054	0.238	3.38	101.10	0.0293%	-27.73%
0.5%	0.122	0.28	6.9	99.72	0.0727%	7.143%
1%	0.186	0.351	7.7	93.21	0.1665%	18.80%
2%	0.312	0.472	9.8	77.06	0.458%	40.69%

In summary, the gas content of oil has a great influence on the hydraulic system. In order to increase the pressure building time, the pressure required for the steady rise rate of the pressure is given under different gas content, that is, the optimal pressure starting point of the oil pump under different gas content.

3 Experiment analysis

The above theory is used to transform rapid forging machine of Ma an shan Hengjiu Special Material Co., Ltd., using the accumulator as a rapid pressure-building device to replace the large liquid-filling tank, and install a pressure sensor on the hydraulic cylinder. Collect and record the signal of the sensor with the data acquisition card as shown in Fig. 7, to implement the device signal processing. The schematic diagram of the hydraulic system after the transformation is shown in Fig. 8. The rapid pressure building device consists of the accumulator (Fig. 8, component 9) and the high response servo valve (Fig. 8, components 11.1, 11.2). The rapid pressure building device is turned on and off by the high response servo valve.

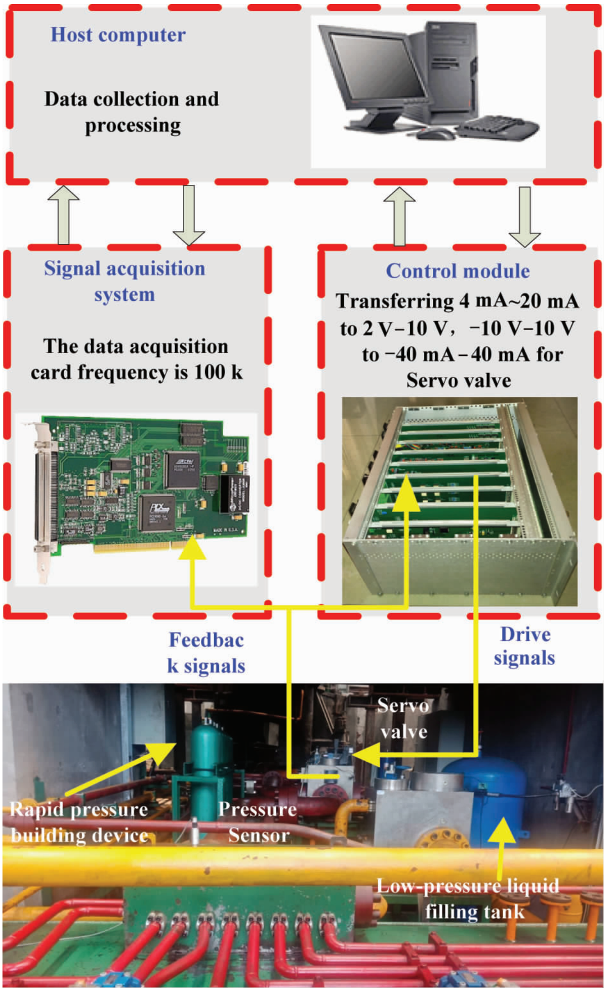

Fig. 7 Rapid pressure building hydraulic structure

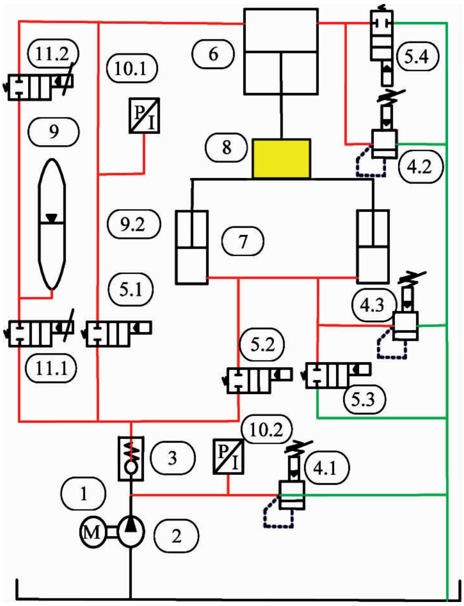

Fig. 8 Rapid forging machine hydraulic system

Before the work-piece is contacted and slider 8 is lowered, directional valves 5.3 and 5.1 are electrically opened. The oil in return cylinder 7 is returned to the tank through directional valve 5.3, and the high pressure oil enters the master cylinder through the proportional directional valve 5.1. When the slider contacts the work-piece, directional valve 5.1 is de-energized and proportional directional valve 11.2 releases liquid to establish high pressure. When slider 8 is raised, the directional valves 5.2 and 5.4 are electrically opened, and high pressure oil enters into return cylinder 7 through directional valve 5.2, and the oil in master cylinder 6 enters into the tank through directional valve 5.4. The slider stops, proportional directional valve 11.1 is energized, and accumulator 9 is refilled. The electromagnetic spill valves 4.2 and 4.3 prevent main hydraulic cylinder 6 and return hydraulic cylinder 7 from being overloaded, respectively.

Due to the relatively high temperature in the area used in the fast forging machine, L-HM68 hydraulic oil is used to ensure the physical properties of the hydraulic oil at high temperatures. And the detected gas content in the oil is 1.32%, and the system pressure is 0.3 MPa when the slider touches the work-piece. The collected data is drawn into the position-pressure curve as shown in Fig. 9. At the same time, the termination pressure of the rapid pressure building device is set to 4.3 MPa, 8.3 MPa and 12.3 MPa respectively, and the position-pressure curves are shown in Fig. 10, 11 and 12, respectively. The termination pressure is set by the rapid pressure building device, and then the hydraulic oil pump continues to supply oil to the system until the system pressure is 26 MPa. During the on-site experiment, it is ensured that the time taken by the slider to contact the work-piece to all the sections outside the built-in pressure of 26 MPa is consistent.

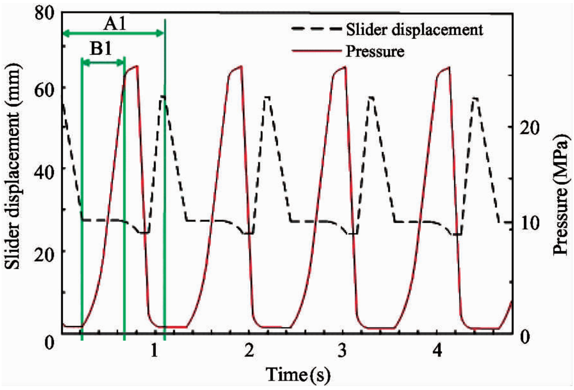

Fig. 9 Displacement-pressure curve with a pressure of 0.3 MPa

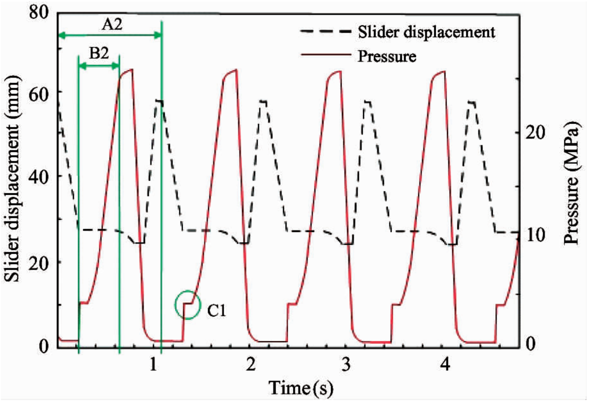

Fig. 10 Displacement-pressure curve with a pressure of 4.3 MPa

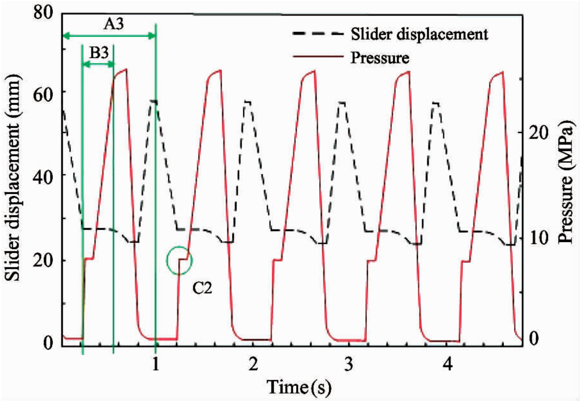

Fig. 11 Displacement-pressure curve with a pressure of 8.3 MPa

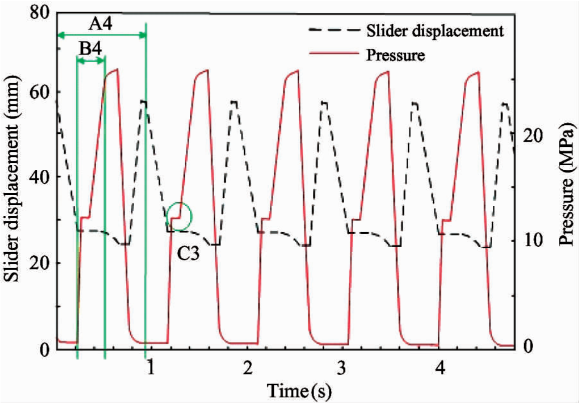

Fig. 12 Displacement-pressure curve with a pressure of 12.3 MPa

When the slider (Fig. 9, component 8) descends, the hydraulic system supplies oil to the master cylinder. When the slider presses the work-piece, the starting time of the hydraulic system is established. The end time is the pressure rises to 26 MPa, as shown in Fig. 10,11,12,13 shown in A and B is the hydraulic system build time, the data are plotted in Table 3 for comparative analysis in the figure. The calculation methods of decompression time reduction rate, total stroke reduction rate and decompression time relative reduction rate are shown in Eqs (11), (12) and (13) respectively.

Table 3 Data of experimental results

The serial number corresponding to A and B_i	Set pressure of rapid pressure building device (MPa)	A_i (t/s)	B_i (t/s)	Establish pressure time reduction rate α	Total trip reduction rate β	Establish a relative reduction in pressure time ε
1	0.3	1.097	0.441	0	0	
2	4.3	1.084	0.428	2.95%	1.18%	2.95%
3	8.3	0.976	0.32	27.43%	11.03%	25.23%
4	12.3	0.921	0.265	39.90%	16.04%	17.19%

$$\alpha_i = \frac{(B_i - B_1)}{B_i} \times 100\% \tag{11}$$

$$\beta_i = \frac{(A_i - A_1)}{A_i} \times 100\% \tag{12}$$

$$\varepsilon_i = \frac{(B_{i-1} - B_i)}{B_{i-1}} \times 100\% \quad (i \geqslant 2) \tag{13}$$

According to Table 3, when the gas content is 1.32%, the higher the end pressure setting of the rapid pressure building device is, the more favorable the rapid building pressure building of the hydraulic system is. However, it can be seen from the relative reduction rate of the build-up time that when the end pressure setting of the rapid pressure-building device is set to 8.3 MPa, the relative reduction rate of the build-up time is the largest, Therefore, 8.3 MPa is the optimal pressure point for the terminal pressure setting of the rapid forging machine, and the reduction rate of pressure setting time is 27.43%. From Table 2, using the interpolation method, pressure is required to stabilize the pressure rise rate when the gas content is 1.32%, that is, the rapid forging machine terminal pressure is 8.3 MPa, and the corresponding reduction time of the build-up time is 25.81%. Comparative simulation and experimental results show that the error is 5.9%. It can be seen that the rapid pressure building device shortens the construction time and total travel time, effectively increasing the working efficiency of the fast forging machine.

Because the FLUENT simulation has a mathematical model of hydraulic oil, FLUENT simulation is an ideal choice for studying the build-up time. However, this model ignores the internal influence of hydraulic oil, such as oil cleanliness, etc., so there is a deviation between control accuracy and simulation results. In the field test, when the temperature of the hydraulic oil is different from that of the pipe elbow, different hydraulic spring stiffness is generated. Therefore, there is a certain gap between the experimental error and the simulation error.

4 Conclusions

(1) A mathematical model of gas content, hydraulic system pressure and pressure rise rate is proposed, and the simulation and mathematical models show that error between the two is less than 8%. At the same time, through the mathematical model, the optimal pressure point under different gas content of the hydraulic system was found, and the slow decompression process of the system was skipped, and the hydraulic system speed of construction pressure was increased. The above theory has certain guiding significance for the study of hydraulic oil characteristics and the design of hydraulic system.

(2) Through conclusion (1) to modify the field equipment, a rapid pressure building device was designed and the stop pressure of the rapid pressure building device was set as the best pressure starting point of the oil pump. The experimental results show that after the pressure-increasing device is increased, the hydraulic system construction time is reduced by 27.43%, which greatly improves the working efficiency of the fast forging machine. Moreover, the rapid pressure building device designed in this paper replaces the liquid filling tank of large flow equipment, which shortens the refilling time and reduces the equipment space occupancy rate.

(3) Under a certain gas content, when the working pressure of the rapid pressure building device exceeds the optimal pressure derived from theory, relative reduction rate of the hydraulic system's pressure building time is reduced, and the reduction time of the pressure building time is not obvious.

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