Development of High Pressure and Constant Low Flow Test System for Hydraulic Support Safety Valve

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Abstract. The existing test equipment for safety valve with low-flow start and overflow closure characteristics of hydraulic support cannot provide the test conditions stipulated in relevant standards, which affects the accuracy of test results. Aiming at the shortage of the existing test equipment, a test system of high pressure and low flow rate of safety valve with hydraulic support is designed, and a technical solution of using straight line driver to push the plunger cylinder to realize high pressure and low flow rate of liquid supply is put forward. The simulation software AMESim was used to construct the virtual prototype of the test system, and the simulation analysis was carried out to determine the main parameters and the influencing rules of the rigidity of the liquid supply velocity. Based on the simulation study, prototype trial production, flow calibration and field experiment were completed. The experimental results showed that the instantaneous output flow fluctuation of the test system was within the range of $\pm 10\%$ of the rated value of 40ml/min, and the output flow fluctuation range was reduced by 25% compared with the existing way.

1. Introduction

The safety valve is a key hydraulic component which ensures that the hydraulic support achieves the function of supporting the roof and has an overload protection effect on the support structure and its legs [1]. When the pressure on the roof is large, but the roof drops at a low speed (0.005-0.05m/min), the pressure in the cavity of the legs increases relatively slowly. Safety valve Occasionally open the pressure relief and close the pressure holding in time after the pressure drops, which reflects the opening and closing characteristics of the safety valve when the flow of liquid is small [2]. The Chinese National Standard GB2597.3-2010 and the European standard EN 1804-3:2006+A1:2010 stipulate the test methods and performance requirements for the opening and closing characteristics of safety valves under small flow conditions which is 0.04L/min. The environment is particularly affected by the size of the liquid supply flow, so the test device should have a constant flow output characteristic. Existing hydraulic test devices usually use speed control valves for flow adjustment, but the linear adjustment range of conventional high pressure speed control valves cannot reach such a low flow rate, resulting in unstable output flow and unable to provide satisfactory test conditions.

In this work, we developed and verified a high-pressure, constant and small-flow test system, which is used to provide constant and small-flow test conditions in the small-flow opening, overflow and closing characteristics of safety valves for hydraulic supports.
2. Design of the test system

2.1. Hydraulic system

The schematic diagram of the high pressure and constant low flow test system for safety valve is shown in Figure 1. It mainly includes a set of high pressure constant low flow liquid supply device, two one-way valves located in the suction and liquid supply pipelines, and parallel connected to the liquid supply pipeline. Pressure regulator tank, and manual and electric unloading valve, etc. The computer system controls the output pressure and flow rate of the test system by collecting signals from the servo motor encoder and pressure sensor.

![Figure 1. Hydraulic system schematic diagram.](image)

1. High pressure and constant low flow liquid supply device 2. Inlet Pressure Sensor 3. Inlet check valve 4. Outlet check valve 5. Accumulator 6. Manual unloading valve 7. Electromagnetic unloading valve 8. Outlet Pressure Sensor 9. Tested safety valve 10. Filter 11. Liquid tank.

2.2. Design of the high pressure and constant low flow liquid supply device

The core component of the test system is the high pressure and constant low flow liquid supply device; which structure is shown in figure 2. It uses a linear drive mechanism composed of a servo motor, a planetary reducer and a screw nut pair as a power source to push the connected plunger. The plunger of the cylinder is retracted into the cylinder at a uniform speed, thereby increasing the pressure of the liquid inside the cylinder and the connecting pipeline. The liquid will overflow from the tested safety valve when the set pressure is reached. The mechanical transmission of each mechanism inside the liquid supply device is rigid transmission, so it has higher speed rigidity and better speed regulation performance, so that the flow rate of the output liquid is not easily affected by load changes, and the flow rate can be maintained constantly when the liquid is supplied with high pressure and low flow [3].

![Figure 2. High pressure and constant low flow liquid supply device.](image)

1. Servo motor 2. Reducer 3. Servo motor 4. Screw nut linear drive mechanism 5. Plunger cylinder
2.3. Determination of plunger cylinder parameters
The diameter and length of the plunger are restricted by many factors. The rated opening pressure of most safety valves for hydraulic supports is between 45MPa and 50MPa. Considering the pressure fluctuation during overflow, the output pressure of the liquid supply device should reach at least 60MPa. This is a relatively high pressure, appropriately reducing the cross-sectional area of the plunger will help reduce its axial force. Because the test flow required by the safety valve test standard is extremely small, reducing the cross-sectional area is conducive to increasing the speed of the mechanism, which is more conducive to speed control. However, the safety valve test standard also requires a total liquid overflow of 0.12L, which limits the minimum volume of the plunger. Therefore, combining the above factors and the total length of the liquid supply device, the plunger is designed to be slender with a diameter of 15mm and a length of 706mm. In addition, it is also necessary to consider the stroke consumption of the plunger cylinder caused by the liquid compression process. The calculation process is as follows:

Internal volume of plunger cylinder: \( V = Sl = 1.77 \times 10^{-4} \text{m}^3 \),

The volumetric compressibility of 5% concentration emulsion: \( \beta = 55 \times 10^{-11} \text{m}^2/N \),

The amount of liquid volume compression caused by the system pressure increasing from 0MPa to 60MPa: \( \Delta V = V \Delta P \beta = 1.27 \times 10^{-6} \text{m}^3 \),

Supercharge length: \( \Delta l = \frac{\Delta V}{S} = 7.175 \times 10^{-3} \text{m} \),

Therefore, the plunger length is designed as: 713.175mm.

2.4. Stability of plunger cylinder
As the plunger of the plunger cylinder is a slender rod structure, in order to prevent it from bending under pressure, its stability should be checked. The plunger cylinder guide sleeve is located at its end, so it is necessary to check the state that the plunger is fully pulled out and then extended into the cylinder and the maximum pressure is generated [4-6]. Calculate with fixed ends, as shown in figure 3.

\[ F_{cr} = \frac{\pi^2EI}{(0.7l)^2} = \frac{\pi^2 \times 2.2 \times 10^{11} \times \pi \times 0.015^4}{(0.7 \times 706)^2} = 22092.87N \]

Instability critical force: \( F_{cr} \)

Maximum force of plunger: \( F_n = P_n \times S = 10597.5N \)

The calculation shows that the plunger cylinder is not easy to lose stability under non-eccentric load.

3. Virtual prototype construction and simulation of test system

3.1. AMESim hydraulic modelling
Using AMESim's mechanical library, hydraulic component library and basic hydraulic library to compile corresponding simulation modules, and established AMESim model of the test system [7,8], as shown in figure 4.
Figure 4. The modeling of hydraulic system by AMESim.

After creating the system sketch, enter the sub-model mode, build a complete system, and then enter the parameter mode, set the parameters according to the structure and function of each component [9-13]. The parameter settings of the main sub-model are shown in table 1.

Table 1. The main components and parameter settings.

| Parameter                             | Numerical | Unit  |
|---------------------------------------|-----------|-------|
| Plunger diameter                      | 15        | mm    |
| Piston cylinder inner diameter        | 20        | mm    |
| Stroke of linear drive                | 350       | mm    |
| Screw pitch                           | 10.19     | mm/r  |
| Motor power                           | 0.75      | kW    |
| Motor speed                           | 1390      | r/min |
| Motor torque                          | 4.7       | Nm    |
| Speed ratio of reducer                | 59        |       |
| Opening pressure of the tested safety valve | 50       | MPa   |

3.2. Analyse the influence law of parameters through simulation

Under the same given conditions, by changing the main relevant parameters of the virtual prototype of the test system, and analyse the degree of influence of each parameter on the rigidity of the liquid supply speed, to determine which parameters are the main parameters that affect the rigidity of the liquid supply rate, and then analyse the law of its impact.

3.2.1. The influence of pitch and speed on output flow. Figure 5 shows the influence of the coordination of different leads and speeds on the stability of output flow. From the simulation results, it can be seen that changing the lead and speed of the screw does not affect the amplitude and frequency of the output flow fluctuation, but the larger the lead of the screw and a small rotation speed will suddenly reduce the output flow when the safety valve is opened. A small lead screw with a higher rotation speed can make the output flow rate of change during the initial overflow more stable.
3.2.2. The influence of motor speed and reducer speed ratio on the stability of output flow. Figure 6 shows the influence of the coordination of different motor speeds and reducer speed ratios on the output flow stability. From the simulation results, it can be seen that higher motor speeds and larger reduction ratios will increase the output flow fluctuation frequency, but will not affect the fluctuation range, so the motor speed should be reduced as much as possible in the design.

3.2.3. The influence of the volume of the surge tank on the stability of output flow. Figure 7 shows the influence of different surge tank volumes on the stability of output flow. It can be seen from the simulation results that increasing the surge tank volume can effectively reduce the fluctuation range of output flow, but increasing the volume of the surge tank will easily affect the tested safety valve Pressure test data, so the volume of the surge tank should be appropriately reduced when the flow fluctuation range meets the requirements.
4. Test verification

Based on the determination of simulation analysis, the small flow test system of the safety valve for the hydraulic support studied in this paper has completed the prototype trial production, as shown in figure 8, and the system output flow is calibrated by adjusting the motor speed.

Because the system pressure is high and the flow is extremely small, it is difficult to accurately measure the flow through the flow sensor. Therefore, the instantaneous output flow of the test system is calculated by the method of measuring the real-time displacement of the plunger rod by the pull-wire displacement sensor, as shown in figure 9.
Figure 9. The method of flow detection.

Through actual testing of different types of safety valves, the displacement data of the plunger rod was obtained and converted into the instantaneous output flow rate of the system, and the curve of displacement and flow changes with time was drawn, as shown in figure 10.

Figure 10. The Plunger displacement curve and the flow curve.

5. Conclusion
The high pressure and constant low flow test system developed in this paper, the mechanical transmission of each mechanism in the liquid supply device is rigid transmission, so it has better speed regulation performance and higher speed rigidity, so that the flow rate of the output liquid is not easily affected by load changes. The flow can be kept constant when the liquid is supplied in a small amount. The system's instantaneous output flow fluctuation range is 43.68~36.44ml/min, within ±10% of the rated value of 40ml/min, the output flow fluctuation range is 25% smaller than the traditional speed control valve solution, and the instantaneous flow curve of each test has high waveform consistency.
indicates that the output flow of the test system has good repeatability accuracy and can meet the requirements of the test standard.

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