Design of a high water-based fluid, high-pressure, and large-flow safety valve

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Abstract: Aiming at solving the problem of low unloading sensitivity, bad dynamic performance and poor stability of high-pressure and large-flow relief valve in hydraulic support system, a new differential type of high-pressure, large-flow relief valve, functioned by high water-based hydraulic medium, is designed. Through analysing the influence of spool form, elastic element, and working principle on valve performance, a structural scheme of large-flow and high-pressure safety valve is put forward. The three-dimensional fluid—solid coupling model of differential safety valve is established; through ADINA software, three-dimensional fluid—solid coupling simulation of relief valve’s orifice from shutdown to full opening is carried out to analyse the distribution of internal pressure in the flow field of the safety valve and the pressure change of the structure field. The physical simulation model of safety valve is established by using AMESim software, and the dynamic performance of safety valve is simulated under the given signal of nominal flow and small flow. According to the design structure, the safety valve with the rated flow of 3000 L/min is manufactured and tested. The simulation and experimental results show that the safety valve has good dynamic performance and high sensitivity.

1 Introduction

The safety valve is the key valve which controls the reliable operation of the hydraulic support, can, immediately, release the high-pressure emulsion in the leg of the hydraulic support under the impact load, and therein lies the protection of hydraulic support when overloaded. With the rapid development of the high mining height, the hydraulic support is developing to the high end; therefore, the demand of the safety valve's reliability and durability are more and more urgent. At present, the high-pressure and large-flow relief valve used in the hydraulic support has the problems of not reliable sealing, poor stability, low reliability, low performance of opening and closing and less sensitivity [1]. In view of the above problems, many scholars at home and abroad take the computational fluid dynamics (CFD) theory as the foundation of the safety valve's research [2, 3], not only the structural form is improved, but also the dynamic performance and flow field visualisation as well as other aspects are analysed.

In recent years, in the research on the dynamic performance of high-pressure and large-flow relief valve, Chang Junliang and J. Chang et al. [4, 5] did a joint simulation analysis of high-pressure and large-flow valve using Adams and AMESim, set up the valve's mass—spring system, and researched the valve core's dynamic performance. Wang Baoming [6] analysed the dynamic characteristic of the hydraulic support’s key parts and the hydraulic system, respectively, through the dynamic theory and the power bond graph method combined with the digital simulation software MATLAB/Simulink. W. Marquis Favre [7] and F.D. Dragne [8] made a simulation of high-pressure and large-flow valve in AMESim and deeply studied its dynamic performance.

In addition, some research achievements have been made in the flow field analysis of high-pressure and large-flow valve. For example: Roger Yang [9] simulated the flow field in the slide valve and analysed the hydrodynamic by using CFD and ANSYS/FLOTTRAN. P. Baraman [10] carried out the simulation of the three-dimensional model of large-flow relief valve by Fluent, a software simulation, and obtained the motion law of fluid in the valve. T. Tian et al. and Zhang Qiju [11, 12] carried out the steady-state numerical simulation of the two- and three-dimensional geometric model of safety valve flow field by using Fluent, and conducted the comparison between the two geometric models under different conditions: one is same boundary condition with different opening degree and the other is same opening degree with different boundary condition.

As to imported valves used in high-end hydraulic support, domestic products have the same specification, but the sealing performance, life, corrosion resistance, and the quality of instability cannot be compared with imported valves. So the failure rate of the hydraulic support system is high, thus reducing the safety of coal mining work. Therefore, this paper shows the research about the structure, seal form, valve body's internal flow channel, and so on. Through the simulation of flow field of fluid—solid coupling and dynamic performance, a method to design a high water-based, high-pressure, and large-flow valve will be put forward in the following sections.

2 Design of structure

2.1 Analysis of structure forms

The structural design of relief valve is mainly based on the requirements of good high-pressure and large-flow characteristics, high sensitivity, leakage resistance, and easy processing, so the valve is designed through the comparison and study in spool forms, elastic elements, and working principles.

2.1.1 Spool form: The common form of valve core is the slide valve and the cone valve. The sliding valve is easy to be processed, to control the unloading flow gradient and has good guidance performance; nevertheless, the sealing of slide valve is guaranteed by the overlap structure of the valve port; undoubtedly, there exists dead zone when unloading the pressure. In other words, the valve cannot open immediately. Taper valve's response time is very short, but it is not easy to control the unloading flow gradient. The sealing performance is good; theoretically, there is no leakage, but the requirement of processing technology is high. The matching material of contact area between valve spool and seat needs appropriate hardness, and the requirements are high.

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In the practical application, there are two types: the spring type and the inflatable type. The inflatable safety valve is usually filled with nitrogen, therein lies the relatively good stable performance, but its adjustment pressure is susceptible to external environmental temperature, and the gas is easy to leak. Spring-type structure is simple and mature, so, presently, the main form of safety valve for hydraulic support at home and abroad is spring-type safety valve.

2.1.2 Elastic element: In the practical application, there are two types: the spring type and the inflatable type. The inflatable safety valve is usually filled with nitrogen, wherein lies the relatively good stable performance, but its adjustment pressure is susceptible to external environmental temperature, and the gas is easy to leak. Spring-type structure is simple and mature, so, presently, the main form of safety valve for hydraulic support at home and abroad is spring-type safety valve.

2.1.3 Working principle: It can be designed as direct-acting type, differential or pilot type, in which the differential structure is essentially a direct-acting type.

Considering all the factors mentioned above, direct-acting structure is suitable for the hydraulic support valve. There is a great difference of the structure between high-pressure and large-flow relief valves. In order to satisfy the requirements of high pressure and large flow and other performance index, the valve core is made into a form of non-full-circumference opening but several rows of unloading holes distributed evenly on it, which ensure rapid unloading of the large flow. Its features are high response performance, simple structure, easy processing, and high sensitivity.

However, as to conventional safety valve, under high-pressure and large-flow conditions, the stability and pressure-regulating performance of the direct-acting safety valve become worse, and the common structure is difficult to improve this situation. The reason is, the larger the flow, the larger the inlet diameter and the greater the friction caused by the spool movement, resulting in worse sensitivity of the safety valve. On the other hand, due to the relationship between the setting pressure, spring stiffness, and open size, when the spring stiffness is generally large, the valve's setting accuracy of pressure is more sensitive to the valve opening. That is, the degree of valve opening has a big influence on the setting pressure of valve. So, some measures about the structure need to be taken to reduce the spring stiffness to improve its setting accuracy of pressure. Therefore, the differential structure that can change the force condition of the spool is appropriate. By using the differential area to balance part of the inlet fluid pressure, the hydraulic force on the spring becomes smaller, the spring stiffness and the size of relief valve will be reduced, and thereby the problems caused by the increase of the flow of direct-acting safety valve are solved.

The safety valve's sensitivity of the pilot structure, which is used in the situation of large flow, is lower than that of the direct-acting safety valve, and the pressure-regulating precision is higher than the direct-acting structure. The valve core of the pilot valve is generally conical, and the main valve can be a slide valve or a cone valve. From the hydraulic bridge theory, the main valve and the pilot valve constitute a B-type half bridge, where the main valve's damping orifice is a fixed liquid resistance and the pilot valve's is a variable liquid resistance. The amount of overflow can be controlled through the pressure drop produced by the liquid resistance.

2.2 Structural scheme design

The main technical parameters of high-pressure and large-flow relief valve are as follows: the nominal flow is 4500 l/min, the working pressure is 35–50 MPa, and the working medium is 95% neutral water and 5% emulsion oil. The relief valve's interface is threaded connection. Through the analysis and comparison of the above structural forms, the unloading sensitivity is the most priority index for the high-pressure and large-flow relief valve for hydraulic support, and the differential structure scheme shown in Fig. 1 is designed after comprehensive consideration.

2.2.1 Structural characteristics of differential safety valve: Slide valve spool is the form of the valve core. On the right side of the valve core, there is a balance cavity that can counteract part of the inlet fluid pressure, so such a design can reduce the diameter of the spool and the spring stiffness, as well as improve the valve core sensitivity and pressure accuracy, satisfying large flow requirements.

The requirement of valve core's motion sensitivity is very high for the hydraulic support valve, and the key to improve the sensitivity is to reduce the movement friction of the spool. Under the same condition, the smaller the diameter of the spool, the smaller the friction generated by the seal ring, but the smaller the diameter of the spool, the lower the flow capacity and the structure strength of the valve. Hence, the safety valve adopts the discharge mode of four rows of radial holes on the circumference of the valve core, and the adjacent two rows of small holes are staggered to form a fan structure to increase the structural strength. At the same time, this structural form, when the valve opening completely, allows the flow of the jet direction perpendicular to axial and will not produce axial fluid power. The discharging mode can not only increase the flow capacity of the valve orifices, but also reduce the diameter of the spool to improve the sensitivity.

The material of valve core and valve body is 2Cr13 and the material of spring is 60Si2CrVa, enhancing the safety valve's capability to withstand the chemical corrosion and the corrosion abrasion which is caused by the bad circumstance under the mine. Adopt a sealing method combined dynamic with static. The sealing materials are polyurethane and polytetrafluoroethylene, respectively. The dynamic seal ring has the advantages of high hardness and low compression rate that is good to the sensitivity of valve core.

The spool is easy to be processed and its movement characteristics are good. The trajectory of the spool is affected by the valve seat, valve sleeve, and the spring support, especially the valve seat and valve sleeve, because the precision of their coaxial degree is very strict. In addition, the contact of the spring seat and valve core is designed into arc contact and the purpose is to make the function point of the force from spring seat to the valve core as far as possible in the spool axis, in order to minimise the chance of clamping caused by eccentric load.

2.2.2 Main structural parameters of differential safety valve: In order to meet the requirements of nominal flow 4500 l/min, considering the influence of pressure adjustment deviation, set the benchmark control pressure at 38 MPa. According to the orifice throttle formula:

\[ q = C_d A \sqrt{ \frac{2 \Delta p}{\rho} } \]

where \( C_d \) is the flow coefficient; \( A \) is the valid flow area; \( \Delta p \) is the pressure drop from the import to export; and \( \rho \) is the density of a
high water-based medium. In calculation, let $C_d = 0.73$ and $\rho = 1000 \text{ kg/m}^3$, then got $A = 375 \text{ mm}^2$. Furthermore, the diameter of the spool is calculated as 22 mm, with four rows (72 in all) of small unloading hole whose diameter is 2.6 mm. After strength checking, the structure can meet the requirements.

Using differential structure can reduce the spring stiffness, can not only achieve large flow, but also improve the valve’s performance. The spring stiffness can be derived from the formula about force. Within the prescribed opening range, the displacement of valve core is proportional to the pressure increase and the following expression is obtained:

$$K = \frac{0.9(P_{id} - P_{i})A}{h}$$

where $P_{id}$ is rated pressure; $P_i$ is the close pressure of valve core; $A$ is valid area of action; $h$ is the opening length of the spool; and the coefficient 0.9 is the safety margin when safety valve is full open. The stiffness of the spring is obtained as by calculation.

The size of the lap determines the amount of displacement of the spool before the safety valve is open and is used to guarantee the seal, but the excessive overlap quantity to the valve sensitivity and opening time is unfavourable and will increase the overshoot. Therefore, on the basis of guaranteeing the sealing length, the overlap quantity should be as small as possible. In order to improve the characteristics of opening and closing under small flow condition as well as meet the overlap characteristics of the large-flow relief valve in the process of pressure coming slowly, the overlap volume of valve core with the outlets is designed to be different between the left two rows and right two rows discharging holes, the former is 5.3 mm, and the latter is 7.3 mm, so that the valve can gradually open and the overshoot can be reduced.

3 Three-dimensional fluid–solid coupling simulation analysis of safety valve

Compared with the static analysis of single field in the valve, the fluid–solid coupling analysis of the safety valve can reflect the real flow state of the valve under high-pressure and large-flow conditions. The high-pressure fluid acts on the surface of the inner channel of the valve and causes it to deform or partially move. This deformation or movement also reacts to the fluid, thus changing the distribution and size of the fluid load. Three-dimensional fluid–solid coupling analysis can reflect the actual working condition of high-pressure and large-flow relief valve, verify the rationality of the structure, and provide the basis for the optimisation of the structure.

Before fluid–solid coupling analysis, first, based on the structure of safety valve, a three-dimensional fluid–solid coupling model of safety valve is established in Pro/E software as shown in Fig. 2.

The pressure of hydraulic support’s roof is usually instantaneously established, so set step signal of the import pressure at 60 MPa and the pressure of the export is 0 MPa. The operating pressure of safety valve is 50 MPa. As the safety valve’s structure is symmetrical, in order to reduce the computational load, only 1/4 of the fluid–solid coupling model is created in the simulation, and for this purpose, the boundary processing and grid partitioning are carried out in the 1/4 model of Fig. 2 to perform the simulation analysis.

Fig. 3 gives the pressure picture at different time in the valve cavity, including the pressure change curve in the whole dynamic process of the fluid inlet and the inner valve cavity, the first discharge hole, and the internal balance chamber.

Through the pressure nephogram and the pressure change curve of valve cavity near the first oil discharge hole, it can be seen that the internal pressure of valve chamber elevated from 0 MPa quickly to 60 MPa before the relief valve opening. With the relief valve opening, the internal pressure gradually reduced and the system began to unload pressure. At the same time, because of the turbulence, the pressure changes in the valve cavity are irregular, and the pressure drop near the outlet is relatively faster than the other section. It also can be seen that negative pressure appeared at the outlet in the process of safety valve's movement, where the cavitation and whirlpool are easy to form.

From the pressure change curve of the internal equilibrium chamber, we can see that before the valve opening, the internal pressure of the balance chamber and the pressure of the inner chamber of the valve core are consistent, increased from 0 to 60 MPa. During the spool movement, the volume of balance chamber is compressed, so the pressure in the chamber continues to rise, and the maximum pressure reaches 65 MPa until the relief valve opens. The pressure in the balance chamber decreases transitorily and then begins to increase, and the final pressure fluctuates around 60 MPa. It shows that the balance cavity indeed plays a balance function and reduces the force of spring, so that the spring stiffness does not need to be very large. Therefore, the differential structure is effective for the sensitivity characteristic of the valve.

Fig. 4 shows the pressure cloud picture and the core stress cloud of the central section of the four-row oil discharging hole numbered from the left end of the valve under the full opening state.

The simulation results from Fig. 4 show that:

(i) The trend of axial profile pressure of four-row unloading hole is similar. The closer to the centre of the spool, the higher the pressure is; the closer to the fluid hole, the lower the pressure is; the closer to the equilibrium cavity, the higher the flow pressure inside the spool, and the flow field pressure in the valve core becomes lower as it approaches the 1th row of holes. All the four-row discharging holes appear as negative pressure, whereas forming the cavitation zone.
(ii) It can be seen from the stress cloud that the maximum stress value appears at the four-row discharging holes. Therefore, it is necessary to improve the local structural strength in the design.

The fluid-solid coupling simulation in ADINA is a dynamic process simulation under the interaction of flow field and structure field. Through the simulation results, we can see the state change in the process of opening and moving of the differential large-flow relief valve spool, the conclusions are as follows:

(i) After the release of pressure, all the four-row discharging holes appear as negative pressure, and near the outlet, the pressure drop gradient is big, where the velocity increases fast. On the contrary, in the section that is far from the outlet, the pressure drop gradient is small, where the velocity increases slowly. So it is easy to form cavitation and whirlpool near the discharging holes.

(ii) The closer to the equilibrium cavity, the lower the flow velocity in the spool is, the higher the pressure is, and the higher the stress of the structure is; the closer to the inlet, the higher the flow velocity in the valve core is, the lower the pressure is, and the lower the stress of the structure field is. At the same time, in the adjacent two-row discharging holes, the exit speed of the rear row is higher than the front row. Therefore, it needs to improve the structure strength of the holes near the equilibrium cavity while designing.

(iii) The design of the balance cavity can effectively reduce the force acting on the spring and verify that the differential structure is effective for the sensitivity of the valve.

4 Dynamic characteristic simulation analysis of safety valve

The dynamic characteristic of high water-based, high-pressure, and large-flow relief valve is the opening and closing characteristic, which is the most important performance index to measure whether the safety valve can be opened in time and shut down reliably, including under nominal flow and small flow conditions, which are explained in detail in the safety criterion about coal mining.

Establish the simulation model of differential large-flow relief valve in AMESim software which is consisted of hydraulic element according to the actual structure and parameters of the safety valve, as is shown in Fig. 5.

4.1 Opening and closing characteristics under nominal flow

According to the requirements of coal-mining safety criterion, for safety valve whose nominal flow is larger than 100 l/min, the maximum opening and closing pressure should not be >125% of the working pressure and the minimum value should not be <90% of the work pressure. In order to test the pressure overshoot and the closing pressure value of the safety valve during the opening and overflow under the nominal flow rate, in the simulation, the safety valve working pressure is set to 50 MPa, the nominal flow is 4500 l/min, while the simulation time is 80 ms. Through the simulation, the inlet pressure curve, outlet flow curve, and spool displacement curve of the safety valve are shown in Fig. 6.

As can be seen from Fig. 6, after the safety valve opens, the spool displacement fluctuates for a period, but finally stabilises at a constant value, so does the inlet pressure curve and the flow curve. The maximum pressure is about 58 MPa and the minimum value is

Fig. 3 Pressure diagram of fluid field model in the safety valve

(a) Pressure nephogram at 0.002 ms, (b) Pressure nephogram at 0.104 ms, (c) Pressure nephogram at 0.596 ms, (d) Pressure nephogram at 1.44 ms, (e) Pressure change curve of inlet, (f) Pressure change curve near the first discharge hole inside the valve chamber, (g) Pressure change curve of the balance chamber.
about 49 MPa, which satisfies the requirement of 125–90% in safety criterion. The flow is finally stable at 4500 l/min, reaching the nominal flow rate. The entire transition process, overshoot, and closing pressure values are in line with the requirements.

4.2 Opening and closing characteristics under small flow

According to requirements of safety criterion, the small flow refers to 0.04 l/min while simulating the opening and closing characteristics. The pressure fluctuation range should not be >10% of the working pressure. The maximum pressure fluctuation should not be >110% of the working pressure. The minimum pressure value should not be <90% of the working pressure and the closing pressure should not be <90% of the operating pressure too. The relief valve is set to 50 MPa in the simulation, and the curve shown in Fig. 7 is obtained by simulation.

As can be seen from Fig. 7, the valve core overflows instantaneously when the valve cavity liquid is filled and reaches a certain pressure under the given small flow. As the opening area gradient of valve core is large, overflow quantity is very large, while the given flow is as small as 0.04 l/min, leading to the fact that valve cavity liquid cannot get enough liquid in time. So the import pressure quickly reduced and the valve closed. The spool repeated the open and close loop for several times, forming the pressure curve as shown in Fig. 7. The pressure fluctuation range is always between 45 and 55 MPa which satisfies the requirement between 90 and 110% of the work pressure. From the simulation curve, it can be seen that it is reasonable of the former structure scheme that uses the different overlap amount of the two-row discharging holes to ensure the valve core gradually opens to improve the opening and closing characteristics under small flow to optimise the overflow characteristics of large-flow relief valve in the process of roof pressure established slowly.

Fig. 4 Axial profile of the safety valve’s discharge holes
(a) Pressure nephogram of the holes in first row, (b) Stress nephogram of the holes in first row, (c) Pressure nephogram of the holes in second row, (d) Stress nephogram of the holes in second row, (e) Pressure nephogram of the holes in third row, (f) Stress nephogram of the holes in third row, (g) Pressure nephogram of the holes in fourth row, (h) Stress nephogram of the holes in fourth row

Fig. 5 AMESim simulation model of safety valve
5 Experimental verification

5.1 Testing system of safety valve

The safety valve (Fig. 8) in this design structure is manufactured according to the test equipment capability and the test requirements, whose rated flow is 3000 l/min, and then the performance test is carried on the safety valve testing bench.

Fig. 9 is a comprehensive performance testing system of high-pressure and large-flow valve for hydraulic support, which consists of two parts of test bed and control room. The test system has six test modules, which can be used to test the performance of various valve components in the hydraulic support.

5.2 Test results of safety valve and analysis

The experimental results show that when the overflow is started, the inlet pressure of the safety valve is kept at around 55 MPa, and the closing pressure is about 45 MPa when the relief valve is unloaded. The test results show that the safety valve has stable performance, the opening and closing pressure is in the range of the 90∼125% of working pressure, and the opening and closing characteristics meet the national safety standards. In other words, the structural scheme is feasible.

6 Conclusions

(i) According to the detailed analysis of the advantages and disadvantages of various structural forms of high-pressure and large-flow valve, combined with the actual operating conditions of the hydraulic support system, a design scheme of differential high-pressure and large-flow relief valve is proposed, which effectively reduces the problem of high failure rate of the system.
(ii) Using ADINA software to study the fluid–solid coupling characteristics of the safety valve, through the analysis of the three-dimensional fluid–solid coupling simulation results, the differential structure of the designed safety valve is demonstrated to be rational.
(iii) Using AMESim software to simulate and analyse the opening and closing characteristics of safety valve, and carry on the experiment of the opening and closing performance of safety valve on the experimental platform, the results show that the safety valve has good opening and closing characteristics.
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