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The Design and Analysis of Novel High-Flow Filling Valve based on Multi-Stage Hydraulic Resistance and Compound Flow Channels

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Abstract

The filling valve and relief valve are core components to ensure the rapid filling of fluid and the stable pressure unloading in the large press. To further improve the filling speed of the filling valve with the function of pressure relief, a novel high-flow filling valve based on compound flow channels and multi-stage hydraulic resistance was designed. The mathematical model and simulation model of the structure of multi-stage hydraulic resistance based on AMESim were established, the influence rules of the critical parameters of the annular hydraulic resistance on pressure relief characteristics were analyzed. The multi-stage annular structure can achieve multi-stage pressure relief. The numerical analysis model of the filling valve with detailed structures based on Fluent was built. The curves of multi-stage pressure unloading based on the pressure contours and velocity contours show that the designed valve has good multi-stage relief characteristics, and the filling rapidity and unloading stability can also be balanced well. Comparing to the traditional single-channel filling valve, the valve with compound flow channels can significantly improve the filling rate according to the numerical analysis in Fluent. The novel designed hydraulic component for filling has the function of high-flow filling and steady pressure unloading. Therefore, it has good engineering application value.

Keywords: *filling valve, multi-stage hydraulic resistance, compound flow channels, AMESim, Fluent*

1. Introduction

Hydraulic press is an important equipment in the mechanical industry and widely applied in aerospace, automotive, chemical industry, electricity and construction industry and so on [1, 2]. In order to improve the performance and efficiency of the product pressing, the higher requirements of the rapidity and stability of hydraulic press are proposed. In the working process of the hydraulic press, the basic movements of the master cylinder conclude several processes of fast-forward, pressing, pressure maintaining, pressure relief, backhaul and so on, while the filling valve takes part in most processes. The properties of the filling valve have a directly impact on improving performance of the hydraulic press [3]. So the filling valve has become one of the core elements to ensure high efficient pressing of the hydraulic press.

The main functions of the filling valve include the charging/discharging under the low pressure condition and the pressure relief under the high pressure condition. The current research on the filling valve mainly involves in two aspects that enhancing the stability and

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rapidity. In terms of enhancing the stability, Yin Z. S. [4] designed a pilot-operated filling valve, which can achieve functions of fluid charging/discharging and smooth pressure relief with the pilot valve. In addition, Lin M. Y. [5] considered the stable design variables and the uncontrollable factors of the filling valve, and improved the stability performance through robust design for the filling valve based on the established mathematical and simulation models. In terms of enhancing rapidity, LAEIS Company added a diversion element in the traditional filling valve, which diversion channels of streamlined curves were constituted between its appearance of the valve and the upper beam. The structure can significantly reduce hydraulic resistance and increase filling rate substantially [6, 7]. Nassetti Company connected the spool of filling valve with control cylinder piston fixedly, and the structure without return spring can drive the filling spool directly and improve the opening/closing speed of the filling valve [7].

In spite of the greatly development of the research on rapidity and stability of the filling valve, there are still insufficient as follows:

A. Lacking stability of pressure release under the high-pressure condition

In order to avoid the strong impact of high-pressure oil release in the opening moment, the filling valve can’t open until the pressure in main cylinder bellow a safety value through a series of external unload components. These unload components in this way increases the cost and the system is complex. Meanwhile if the filling device is open under the high pressure condition due to the electronic control failure, it will cause serious damages. The way of adding the pilot valve with damping orifice in the filling device will also have some disadvantages, such as the poor control performance of unloading pressure, the lack stability of pressure relief and so on.

B. Improving filling rapidity of the valve faces a bottleneck

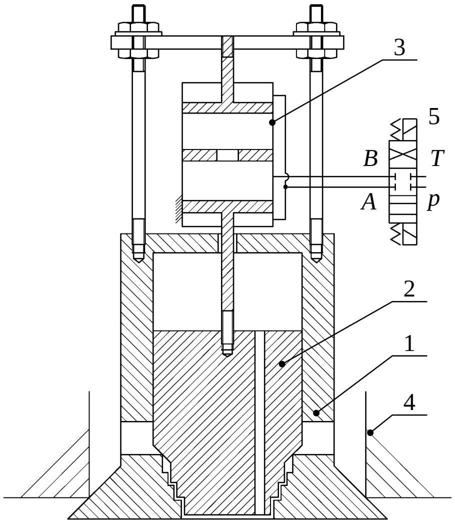
In the current researches, the filling rate is improved by optimizing outer contour of the filling spool, such as the structure of mushroom cone-shaped spool and the designed spool surface for diverting flow channels. These ways can’t improve the filling rate significantly. In the field of high-flow hydraulic press, the size of filling spool often increases as the flow rate rising. Furthermore, the large size of the valve has some adverse effect for improving the filling speed, which is a bottleneck to further enhance the filling speed under high pressure conditions.

Aiming at the above problems，a novel high-flow multi-stage pressure relief filling valve based on compound channels was designed to realize high filling rate and stable pressure relief by the structures of multi-stage annual gap resistance and compound fluid channels. Based on AMESim and Fluent, the performance of the multi-stage resistance and compound channels was analyzed to obtain the influence rules of the key parameters on the characteristics of pressure relief and filling rate. This paper offers a new structure and method for improving rapidity and stability of the filling valve used in the large press, which can be applied in engineering conveniently.

2. The Design of the Novel High-Flow Filling Valve

The high pressure chamber in the master cylinder can be directly unloaded through the filling valve in the large press with an inlay pressure relief device or relief structure. Due to the booster link of the large press, the pressure in the master cylinder can reach 42MPa after pressure amplification. The way of conventional single-stage pressure relief, in which plenty of high-pressure oil in the main cylinder returns to the tank directly, could result in large pressure impact and easily cause damages on the frame structure and control elements. However, the way of multi-level pressure relief can not only ensure that high pressure oil is released smoothly, but also improve the rate of pressure relief through the rational design of multi-stage pressure relief structure, thereby this way takes the stability and rapidity into account at the same time.

The main principle of multi-level pressure relief is to apply multi-stage hydraulic resistance or networks of hydraulic resistance to achieve pressure unloading. On the basis of considering the structure of the high-flow filling valve, the relief structure based on multi-level annual gaps was designed. Meanwhile, the compound flow channels structure of the main and auxiliary valve ports is designed to further enhance flow capacity of the filling valve. The novel high-flow filling valve with multi-stage pressure relief based on compound flow channels structure is shown in Figure 1, mainly including the main spool 1, auxiliary spool 2, compound cylinder 3, valve body 4, and two position four-way directional valve 5.

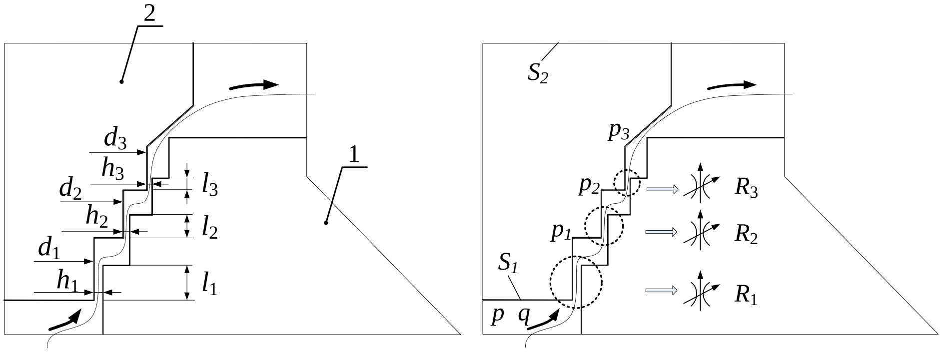


1 main spool, 2 auxiliary spool, 3 compound cylinder, 4 valve body, 5 two position four-way directional valve

Figure 1. The Schematic Diagram of the Novel High-Flow Filling Valve with Multi-Stage Pressure Relief and Compound Flow Channels

2.1. The Structure of Multi-Stage Pressure Relief

The multi-stage pressure relief structure is constituted by the main spool 1 and the auxiliary spool 2 in the high-flow filling valve shown in Figure 1, which is enlarged as shown in Figure 2. As we can see, the throttling orifice is constituted between the inside of the auxiliary spool 2 and the outside of the main spool 1. Several annular gaps can be formed by setting stepped structures. Each gap has an effect of hydraulic resistance, and the filling valve has three annular gaps as shown in Figure 2, namely three hydraulic resistances. Furthermore, through reasonable deign of the axial length l of annular gaps, we can make every annular hydraulic resistance open in sequence with the upward movement of the auxiliary spool 2. The working conditions of hydraulic resistances of the designed filling valve in this paper are shown in Figure 3 when the auxiliary spool 2 is moving upward. Obviously, each annular hydraulic resistance opens from top to bottom in sequence in the course of the auxiliary spool 2 moving upward, and eventually the filling valve is full open. In order to ensure the sequence of hydraulic resistance opening, the effective axial length of the annular gaps is designed to meet the equation $l_1 > l_2 > l_3$.



1 main spool, 2 auxiliary spool

Figure 2. The Partial Enlarged Drawing of the Multi-Stage Pressure Relief Structure

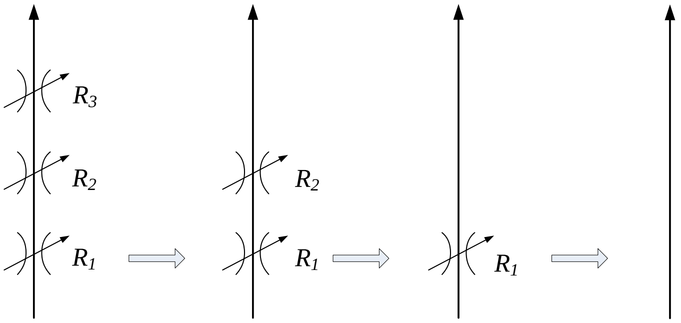
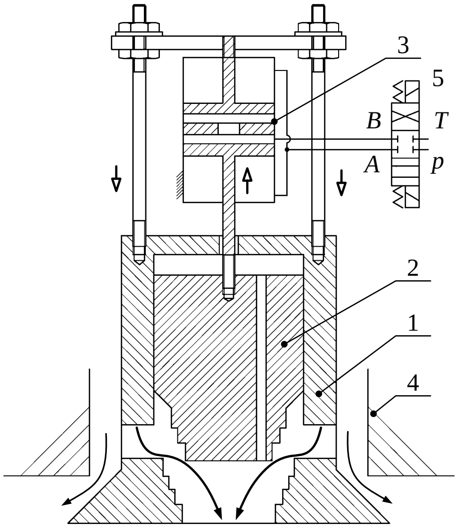


Figure 3. Working Conditions of Hydraulic Resistances of Annular Gaps when the Auxiliary Spool 2 Moving Upward

2.2. The Compound Flow Channels

In Figure 1, the orifices of the multi-stage pressure relief valve are constituted between the inside of the auxiliary spool 2 and the outside of the main spool 1. To further enhance flow capacity of the filling valve, the outside of the main spool 1 is designed as inverted cone structure for forming a cone seal port of main valve with the valve body 4. Through the compound controlling of the main valve port and the auxiliary port, the flow capacity of the filling valve can be significantly improved. In order to realize multi-stage pressure relief and compound flow through the coordination of the main orifice and auxiliary orifice, the actuator and control component should be added, namely the compound cylinder 3.

Firstly, we analyze the state of the valve in the filling working condition. In the fast forward condition in the large press, the pressure in the master cylinder chamber reduces rapidly as the master cylinder moving downward, then the oil in the inflatable tank is immediately filled in the master cylinder though the filling valve. In this moment, we can control the directional valve 5 to realize that the compound cylinder's port A is filled with the high-pressure oil and the port B is connected with the oil tank, then the upper piston and the under piston of the compound cylinder simultaneously retract. The upper piston in the compound cylinder is fixed with the main spool 1 and the under piston is fixed with the auxiliary spool 2, so the main spool 1 moves downward to open the main orifice and the auxiliary spool 1 moves upward to open the auxiliary orifice, eventually forming compound filling channels based on the main and auxiliary orifices, as shown in Figure 4. Comparing to the traditional filling valve with a single channel, the novel valve with compound channels can significantly improve the flow capacity. When the filling is completed and the filling valve need to be closed, it just only needs to change the position of directional valve 5 to realize that the high pressure oil connects with the port B and the other oil returns back to the tank through the port A. Then the filling valve is closed because of the upper piston and the under piston stretching out.



1 main spool, 2 auxiliary spool, 3 compound cylinder, 4 valve body, 5 two position four-way directional valve

Figure 4. The Compound Filling State based on the Main Orifice and Auxiliary Orifice

Secondly, we analyze the state of the valve in the pressure relief working condition, which includes multi-stage pressure relief and compound through-flow. When the booster step in the large press is completed, the master cylinder is needed to release the high pressure. The high pressure can be released directly through the designed filling valve without installing any other external unloading valves. At this moment, the directional valve 5 is controlled to make the port A connect with high-pressure oil and the port B connect with oil tank, then the under piston of the compound cylinder has a tendency to move downward and the under piston has a tendency to move upward, which implies that ports of the main and auxiliary valve all trend to open. Because of the high-pressure in the master cylinder, the main spool 1 is firmly pressed against the valve body 4 and the main valve port is closed. Meanwhile, as there is effective area difference between the upper effective area S_1 and the under effective area S_2 of the auxiliary spool 2, the auxiliary spool 2 is also firmly pressed against the inside of the main spool 1 and the auxiliary valve port is also closed. As the effective working area of the main spool 1 is larger than the area of the auxiliary spool 2, the hydraulic force that high pressure oil of the master cylinder acts on the main spool (set as F_1) is much greater than the hydraulic force that effects on the auxiliary spool (set as F_2), namely $F_1 > F_2$.

Set the working force as F_3 that acts on the upper piston by the high-pressure oil entered from port A. Through reasonable setting the inlet pressure of the port A, we can make the F_3 slightly larger than the F_2, then the auxiliary spool 2 can be raised slightly. At this moment, the master cylinder enters into the multi-stage pressure relief condition. When the auxiliary spool 2 lifts, hydraulic resistance of the annular gap between the main spool 1 and the auxiliary spool 2 are all involved in the work, as shown in Figure 3. Firstly, the annular hydraulic resistance R_1, R_2 and R_3 are all involved in the work and three hydraulic resistances are in series connection, so the total resistance is largest and the pressure releases slowly. Secondly, the under piston moves upward with the effect of F_3, then the hydraulic resistance R_1 gradually opens and the other two hydraulic resistances maintain in series connection. The total resistance decreases and the pressure releases faster. Thirdly, the under piston continues to move upward and the hydraulic resistance R_2 opens as well. At the moment, only one single hydraulic resistance is involved in the work, so the pressure relief further accelerates. Finally, as the under position further moving upward, all hydraulic resistances fail and the ports of the auxiliary valve are fully open to release pressure more quickly. Obviously, the former process of the pressure relief is slow and the latter process is fast, so it can balance the stability and rapidity of the pressure relief. When the pressure in the master cylinder reduces to a certain value, namely $F_1 < F_3$, the main valve port will open to further accelerate the pressure relief. To ensure a smooth former process and rapid latter process of pressure relief, we can make the main valve port open after three hydraulic resistances of the auxiliary valve port all fail by setting a reasonable structure dimension in the filling valve.

In conclusion, the filling valve can effectively realize smooth pressure relief and rapid fluid filling based on the structures of multi-stage pressure relief and compound flow channels.

3. The Mathematical Model of Multi-Stage Hydraulic Resistance

The structure of multi-stage hydraulic resistance is the key structure for stable pressure relief of the filling valve, and the structure of the annular gap is the core part to generate the damping effect. If the resistance is extremely strong, the pressure relief is so slow that affect the working efficiency. On the contrary, if the damping is too feeble, the pressure relief is so fast that it is easy to generate impact. So it needs to analyze the influence laws that the key parameters of the structure of the annular gap act on the characteristics of pressure relief in detail.

Combining with equations of annular gap flow, a mathematical model on the condition of multi-stage pressure relief is built [8], which is based on the structure of the annular gap shown in Figure 2:

$$q = \frac{\pi d_1 h_1^3}{12\mu(l_1 - vt)}(p - p_1)\ . \tag{1}$$

$$q = \frac{\pi d_2 h_2^3}{12\mu(l_2 - vt)}(p_1 - p_2)\ . \tag{2}$$

$$q = \frac{\pi d_3 h_3^3}{12\mu(l_3 - vt)}(p_2 - p_3)\ . \tag{3}$$

$$0 - q - vS_2 = \frac{V}{\beta}\frac{dp}{dt}\ . \tag{4}$$

Where q is the flow rate that flows into multi-stage hydraulic resistance; p indicates the pressure in the main cylinder; d_1, d_2, d_3 denote the inner diameter of the three-level annular gap respectively; h_1, h_2, h_3 ,respectively, present the thickness of the three-level annular gap; l_1, l_2, l_3, respectively, describe the effective length of the three-level annular gap; V shows the volume of main cylinder; v expresses the upward velocity of the auxiliary spool; S_2 means the effective area of the auxiliary spool on the lower end-face; β signifies the oil elastic modulus; μ represents the oil power viscosity. The equations (1)~(4) are the mathematical model of pressure relief of multi-stage hydraulic resistance, it demonstrates that parameters h, *l*, *d* in the structure of the annular gap have an impact to the flow rate, and they are the main factors affecting the pressure relief characteristics.

As we can be seen from the formula (1)~(3), the thickness of the annular gap is the most significant parameters to affect the relief characteristics. Based on the above mathematical model, we can analyze the influence of the parameters on the pressure relief characteristics. To simplify the analysis, we can select relief working conditions of single-stage annular gap to analyze and assume the velocity of upward movement of the auxiliary spool is extremely low, so we can set the $v = 0$. Numerical analysis based on the data shown in Table 1 is revealed below, we analyze the relief characteristics when thickness of the annular gap respectively is 0.05mm, 0.1mm, 0.2mm, 0.3mm, 0.4mm and 0.5mm, drawing out the pressure relief curves under the different thickness of the annular gap shown in Figure 5. It is observed that the thickness of the annular gap have a significant impact on relief characteristics, when the thickness of the annular gap is 0.5mm, the high pressure oil can be released completely in less than 0.5s in the condition that the volume is 0.11m^3 and the pressure is 30MPa. Such a kind of relief structure is capable of relieving rapidly.

Table 1. Main Parameters Under Relief Working Condition with the Single-Stage Annular Gap

Parameters	Value	Parameters	Value
Initial pressure of the main cylinder /MPa	30	d_1/mm	100
h_1/mm	0.05~0.5	l_1/mm	40
μ /Pa·s	0.04	v /mm/s	0
V/m^3	0.11	β/MPa	800

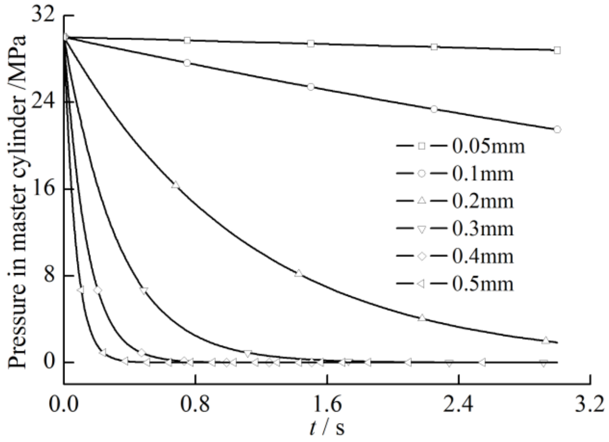


Figure 5. The Pressure Relief Curves of Different Thicknesses of the Annular Gap

4. Pressure Relief Numerical Analysis with Multi-Stage Hydraulic Resistance

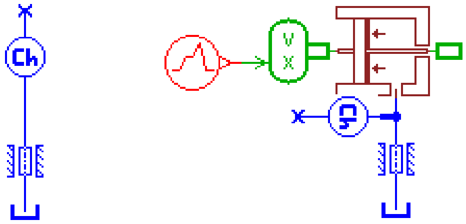
4.1. Numerical Analysis Base on AMESim

According to the above analysis of the mathematical model, the thickness of the annular gap has a more significant impact on the relief characteristics. In addition, the other parameters of the effective length and inner diameter of the annular gap also affect the relief features. The theoretical analysis has not considered the influence factors of the auxiliary spool movement and multi-stage hydraulic resistance acting on relief characteristics. Considering the foundations of various factors, we can comprehensively analyze the laws that the key parameters of the annular gap act on the pressure relief characteristics base on the numerical analysis platform of AMESim [9, 10].

A. Hydraulic resistance of the single-stage annular gap

Firstly, we analyze conditions of the hydraulic resistance with the single-stage annular gap. The comparison simulation model shown in Figure 6 was established and the influence of the auxiliary spool movement on the pressure unloading characteristics in the master cylinder was also analyzed. Figure 6 (a) represents a simulation model without the auxiliary spool movement, while Figure 6 (b) describes a simulation model with the auxiliary spool movement. The curves of the pressure unloading in the master cylinder are shown in Figures 7 and 8, which are based on the data in Table 1 and v = 30mm/s, showing that the auxiliary spool movement has an influence on the characteristics of pressure relief, and the smaller of thickness of the annular gap, the larger of the influence.

Due to faster opening of the auxiliary spool that has an impact on the relief characteristics, so the movement of the auxiliary spool must be considered in the simulation analysis.



(a) (b)

Figure 6. The Comparison Simulation Model that the Auxiliary Spool Movement Affects on the Pressure Unloading Characteristics in the Master Cylinder

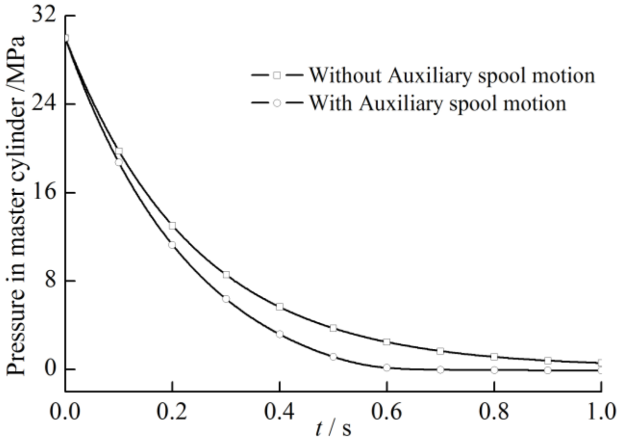


Figure 7. The Curves of Comparison Analysis that the Auxiliary Spool Movement Affects on the Pressure Unloading Characteristics in the Master Cylinder (*h*=0.3mm)

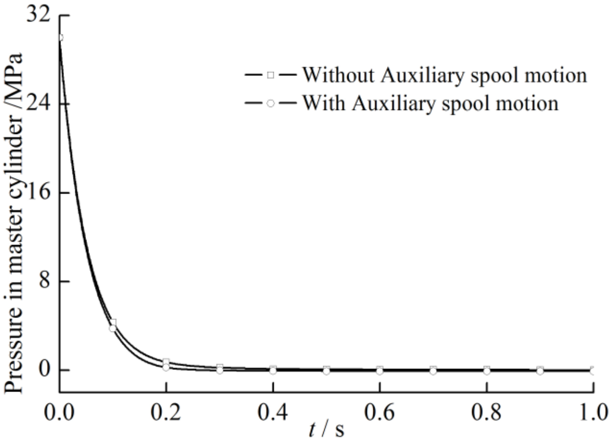


Figure 8. The Curves of Comparison Analysis that the Auxiliary Spool Movement Affects on the Pressure Unloading Characteristics in the Master Cylinder (*h*=0.5mm)

Based on the model shown in Figure 6 (b), we can analyze the influence rules that key parameters of the thickness, effective length and inner diameter of the annular gap effect on the relief characteristics.

Firstly, we analyze the influence rules that different thickness of the annular gap effect on the relief characteristics. Based on the data in Table 1, the thickness of the annular gap was respectively set to 0.05mm, 0.1mm, 0.2mm, 0.3mm, 0.4mm and 0.5mm. According to the simulation analysis, the family curves shown in Figure 9 were obtained, describing that the thickness of the annular gap has a great influence on the relief characteristics. As the thickness of the annular gap is larger, the rate of the pressure relief is faster. When the thickness of the annular gap is 0.3mm, the pressure relief already has a faster speed.

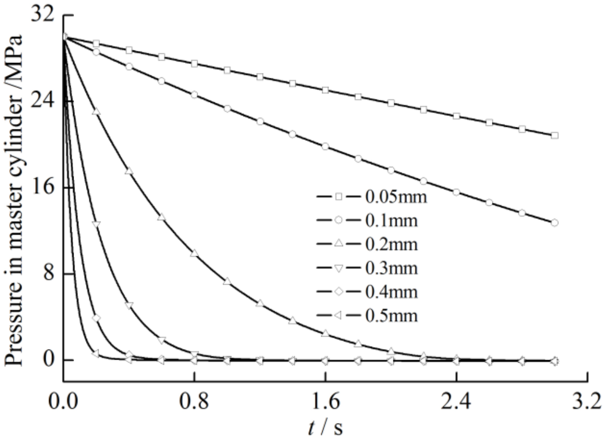


Figure 9. The Influence that Different Thicknesses of the Annular Gap Affect on the Relief Characteristics

Secondly, we analyze the influence rules that the different effective length of the annular gap act on the relief characteristics. Based on the data in Table 1, the effective lengths of the annual gap were respectively set to 20mm, 30mm, 40mm, 50mm, 60mm and 70mm. Then we obtained family curves shown in Figure 10, presenting that the effective length has a certain influence on the relief characteristics, but the impact of the effective length of the annular gap is relatively smaller than the thickness. With the decrease of the effective length of the annular gap, the speed of pressure relief increases.

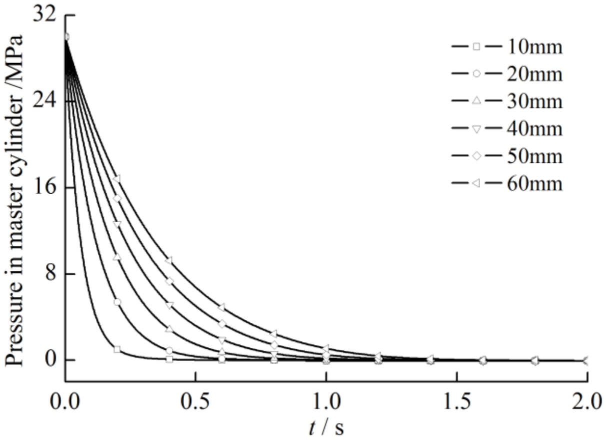


Figure 10. The influence that Different Effective Lengths of the Annular Gap Affect on the Relief Characteristics

Finally, we analyze the influence rules that the different inner diameter of the annular gap act on the relief characteristics. Based on the data in Table 1, the thickness of the annular gap was set to 0.3mm, the effective length of the annular gap was set to 40mm, and the inner diameters of the annular were respectively set to 75mm, 80mm, 85mm, 90mm, 95mm and 100mm. Then we obtained family curves shown in Figure 11, representing that the different inner diameter of the annual gap has a certain influence on the relief features, but influence is relatively slight.

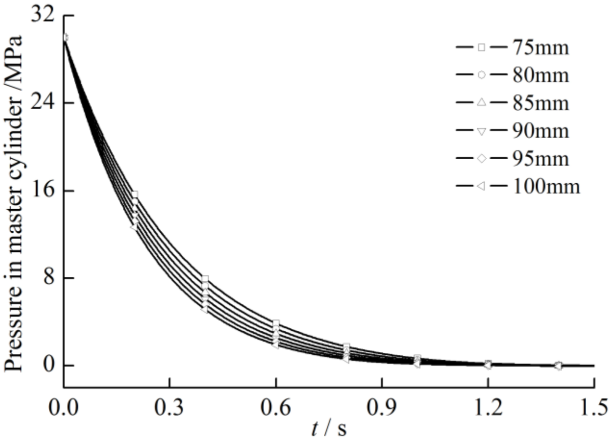


Figure 11. The Influence that Different Inner Diameters of the Annular Gap Affect on the Relief Characteristics

The above analysis shows the key parameters affecting on the relief characteristics in sequence from strong to light are the thickness, the effective length and the diameter of the annular gap. In the structure design of the annular gap, the thickness of the annular gap becomes the main design parameter. Meanwhile, the effective length of the annular gap is also considered to design, and the inner diameter needn't to consider in the design.

B. Hydraulic resistance of the multi-stage annular gap

Firstly, the model of the hydraulic resistance with three-stage annular gap was established in Figure 12 based on AMESim. From top to bottom in Figure 12, hydraulic resistance can be called the pre-stage hydraulic resistance, the mid-stage hydraulic resistance and the rear-stage hydraulic resistance. In the actual structure shown in Figure 2, there is a small cavity between hydraulic resistances, so we can set some small cavities in AMESim (the volume of each cavity can be set 1cm^3) to connect each hydraulic resistance. In addition, in order to simulate the open process of each hydraulic resistance when the auxiliary spool moves upward, the parallel switch valves were controlled to short the corresponding hydraulic resistance. To reduce influence of the parallel switch valves as more as possible, we set the natural frequency of the valve 2000Hz and flow capacity 10000L/min per 1MPa.

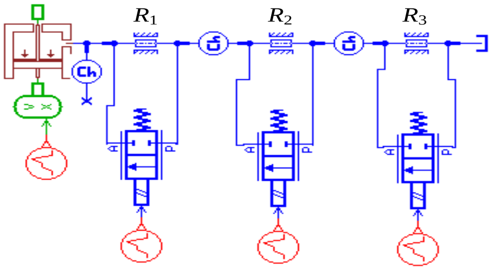


Figure 12. The Pressure Relief Simulation Model of Three-Stage Annular Gap based on AMESim

As the thickness of the annular gap hydraulic resistance is the most critical parameters affecting the relief characteristic, the function of multi-stage pressure relief in the master cylinder can be realized through matching several hydraulic resistances with different thickness annual gaps. Through the repeated testing based on the data in Table 1, the pressure relief process has features of multi-stage pressure release and the process can balance the stability and rapidity of the pressure relief, when the thicknesses of the pre-stage, mid-stage and rear-stage annular gap hydraulic resistance are set respectively to 0.1mm, 0.2mm and 0.5mm.

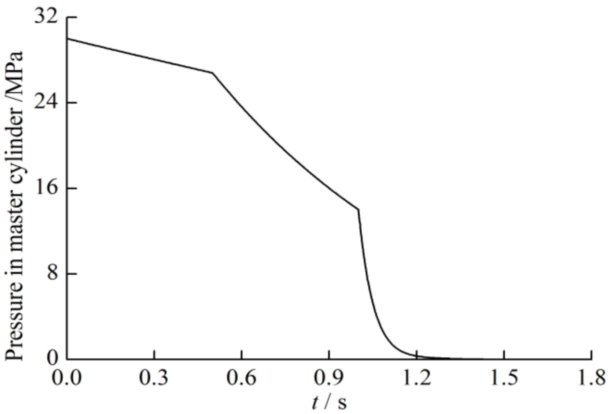


Figure 13. The Multi-Stage Relief Curve of Hydraulic Resistance with the Three-Stage Annular Gap (thicknesses of 0.1mm, 0.2mm and 0.5mm in sequence)

4.2. The numerical analysis base on Fluent

A. The meshing and boundary conditions

In the multi-stage pressure relief simulation with three-stage annular gap based on AMESim, we have realized the function of multi-level pressure relief. However, the above simulation ignores the influence of the actual structure of three-stage annular gap. A more accurate analysis of the multi-stage hydraulic resistance relief characteristic was analyzed on the foundation of computational fluid dynamics method. To simplify the analysis, we assume that the pressure and speed of fluid have nothing to do with the temperature of oil at a stable time, and the fluid cannot be compressed. So the test conditions meet the two basic equations of 3-D steady turbulent motion, namely the continuity equations and the equations of motion as follows [11, 12].

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0\,. \tag{5}$$

$$\begin{cases} f_x-\dfrac{1}{\rho}\dfrac{\partial p}{\partial x}+v\left(\dfrac{\partial^2 v_x}{\partial x^2}+\dfrac{\partial^2 v_x}{\partial y^2}+\dfrac{\partial^2 v_x}{\partial z^2}\right)=0 \\ f_y-\dfrac{1}{\rho}\dfrac{\partial p}{\partial y}+v\left(\dfrac{\partial^2 v_y}{\partial x^2}+\dfrac{\partial^2 v_y}{\partial y^2}+\dfrac{\partial^2 v_y}{\partial z^2}\right)=0 \\ f_z-\dfrac{1}{\rho}\dfrac{\partial p}{\partial z}+v\left(\dfrac{\partial^2 v_z}{\partial x^2}+\dfrac{\partial^2 v_z}{\partial y^2}+\dfrac{\partial^2 v_z}{\partial z^2}\right)=0 \end{cases}. \tag{6}$$

Where *x*, *y*, *z* are the coordinate directions; v_x, v_y, v_z is the velocity vector of each component; f_x, f_y, f_z are the force per unit mass of each component; *p* is the pressure in the main cylinder; ρ is the liquid density; v is the kinematic viscosity of the fluid.

When oil flows through the filling valve spool, the flow significantly changes, so we use a standard k-ε turbulence model for fluid flow analysis. Equations of the turbulent kinetic energy *k* and the dissipation rate ε are:

$$\begin{cases} \dfrac{\partial}{\partial x}\left[\left(\mu+\dfrac{\mu_t}{\sigma_k}\right)\dfrac{\partial k}{\partial x}\right]+G_k-\rho\varepsilon=0 \\ \dfrac{\partial}{\partial x}\left[\left(\mu+\dfrac{\mu_t}{\sigma_\varepsilon}\right)\dfrac{\partial \varepsilon}{\partial x}\right]+C_{1\varepsilon}\dfrac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\dfrac{\varepsilon^2}{k}=0 \\ \rho C_\mu\dfrac{k^2}{\varepsilon}=\mu_t \end{cases}. \tag{7}$$

Where *k* is the turbulent kinetic energy; ε is the turbulent dissipation rate; σ_k is the *k* of Prandtl number, namely σ_k=1.0; σ_ε is the ε of the Prandtl number, namely σ_ε=1.3; G_k is the average velocity gradient that cause turbulent kinetic energy; μ is the dynamic viscosity of the liquid; μ_t is turbulent viscosity coefficient; $C_{1\varepsilon}$, $C_{2\varepsilon}$ and C_μ are empirical constants, namely $C_{1\varepsilon}$=1.44, $C_{2\varepsilon}$=1.92 and C_μ=0.09.

Based on the above theory, we can apply Fluent which is professional computational fluid dynamics numerical analysis software to analyze and study the multi-stage pressure relief characteristics of the filling valve. Firstly, the multi-stage pressure relief simulation model of filling valve based on Fluent was constructed and shown in Figure 14. As three-dimensional model of the filling valve is symmetrical, the model can be simplified as a two-dimensional model of rotationally symmetrical to reduce calculation, which uses the center line of the master cylinder as the axis of symmetry. The model mainly includes two parts, the master cylinder cavities and the annular gap hydraulic resistance. In order to take account of the numerical calculation accuracy and speed, the model is divided into a grid with a gradient way from coarse to fine, which becomes dense from the outside of the master cylinder to the gap hydraulic resistance gradually. The parameters of corresponding model are shown in Table 2.

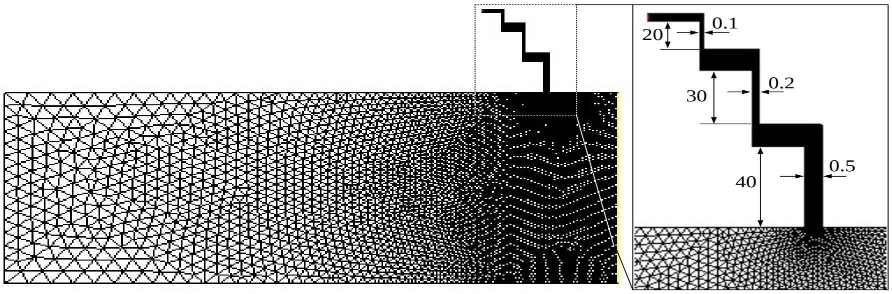


Figure 14. The Mesh Model of Filling Valve with Multi-Stage Annular Gap base on Fluent

Table 2. Main Parameters of the Simulation Model of the Filling Valve based on Fluent

Parameters	Value	Parameters	Value	Parameters	Value
The diameter of main cylinder *D*/mm	900	h_3/mm	0.1	d_1/mm	100
The height of main cylinder *H*/mm	180	l_1/mm	40	d_2/mm	110
h_1/mm	0.5	l_2/mm	30	d_3/mm	120
h_2/mm	0.2	l_3/mm	20		

Secondly, we set the appropriate boundary conditions to make simulation model based on Fluent reflect the pressure relief conditions of the actual filling valve. The master cylinder begins to release pressure after pressure boost motions of the master cylinder. At the moment, the inlet port to the main cylinder is closed. And if the filling valve is open, the cavity in the master cylinder will connect with the tank. Therefore, each corresponding side of the master cylinder can be set as the wall, and the terminals of annular gap that is back to the tank can be set as the outlet. Since the auxiliary spool is in motion in the open process, we can set the corresponding boundaries of the auxiliary spool as the moving boundaries, reflecting the state of the auxiliary spool opening movement. Based on the above boundaries conditions, we analyze distribution and changes of the pressure in the hydraulic resistance gaps and the main cylinder, thereby obtaining relief features of multi-stage annual gap hydraulic resistance. The corresponding key parameters are set and shown in Table 3.

Table 3. Main Parameters of the Simulation Model of the Filling Valve based on Fluent

Parameters	Value	Parameters	Value
The pressure of main cylinder *p*/MPa	30	Liquid viscosity μ/Pa·s	0.04
The pressure of outlet p_{out} /MPa	0	Acceleration of gravity *g* /m/s^2	9.8
Density of liquid ρ /kg/m^3	887	Open velocity of the spool *v* /mm/s	30

B. The analysis of simulation results

Based on numerical analysis of Fluent, we can know that the structure of multi-stage annular gap hydraulic resistance can realize the effective pressure relief from the corresponding pressure and velocity contours shown in Figure 15 and Figure 16. After the auxiliary spool is open, the pressure of main cylinder begins to decline with multi-stage hydraulic resistance opening in sequence. Velocity field gradient and pressure field gradient in the process of pressure relief mainly concentrate in area of the multi-stage annular gap, namely the throttling effect is primarily produced in this area, the pressure unloading process in most area of the master cylinder is uniform and velocity is close to zero. Meanwhile, throttling effect generates when fluid flows through each annual gap, thus achieving multi-stage pressure relief. As we can see from the pressure and velocity contours, there are vortexes in the cavity of the annular gap that would affect the relief process, but the influence is slight.

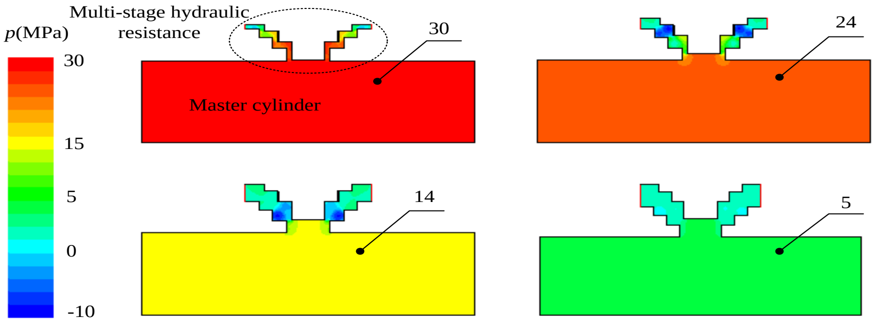


Figure 15. The Pressure Contours of Relief Process with Multi-Stage Hydraulic Resistance

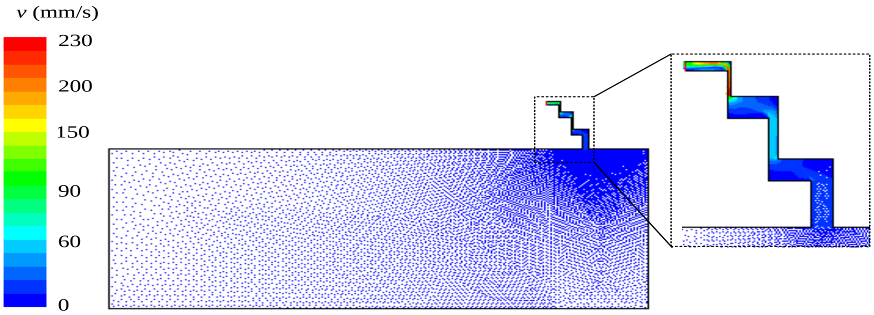


Figure 16. The Velocity Contours of Relief Process with Multi-Stage Hydraulic Resistance

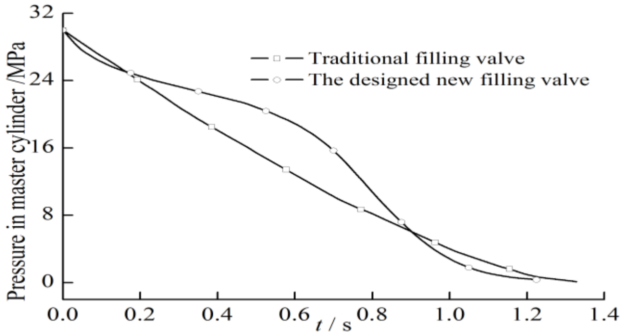


Figure 17. Unloading Curves of the Pressure in the Master Cylinder based on Multi-Level Relief Filling Valve

Furthermore, we can get the multi-stage pressure relief curve of the new filling valve, which is compared with the relief curve of the traditional single-stage pressure relief filling valve in the same size shown in Figure 17. The curves show that the new multi-stage filling valve possesses significant characteristics of the multi-stage pressure relief. The initial stage of pressure relief process is gentle, and the pressure releases rapidly when the pressure reduces to a certain value. The novel filling valve has advantages that not only the process of pressure relief is faster than the conventional pressure relief process of the single-stage filling valve, but also the initial stage process of pressure relief is more stable.

5. The Numerical Analysis of Compound Flow Channels

The novel designed multi-stage pressure relief filling valve also has a characteristic of the compound flow channels that can further enhance the filling speed of the valve. The numerical computing analysis based on Fluent can effectively reflect the flow characteristics of the compound flow channels. Thus, on the basis of aforementioned structure of the multi-stage annular gap, the section of compound channels was added and the corresponding numerical model based on Fluent was also established. In order to investigate the promotion effect on the filling rate with the compound flow channels, the simulation analysis under two kinds of working conditions of partially full opening and full opening were achieved comparing with traditional single-channel filling valve. The simulation results are shown in Figure 18 and Figure 19.

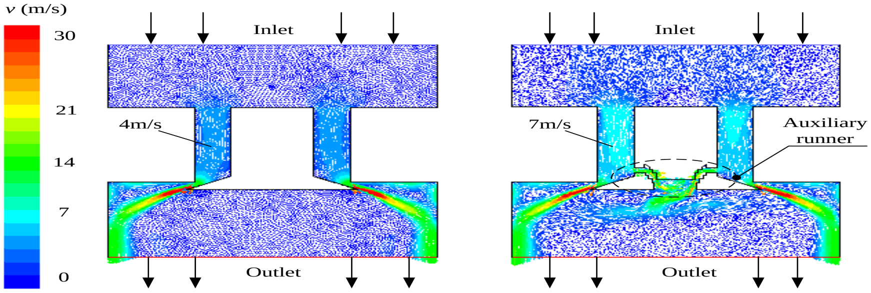


Figure 18. The Flow Velocity Contrast Contours between the Novel Filling Valve with Compound Flow Channels and the Traditional Filling Valve (Under the Condition of Partially Opening)

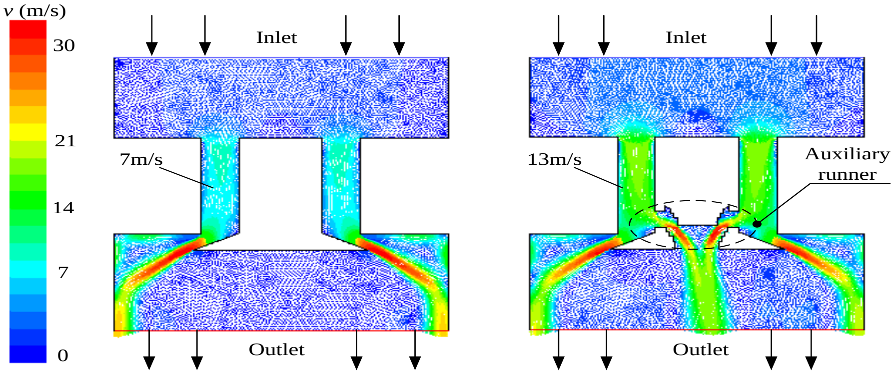


Figure 19. The Flow Velocity Contrast Contours between the Novel Filling Valve with Compound Flow Channels and the Traditional Filling Valve (Under the Condition of Fully Opening)

In the working condition that the valve has not fully opened, the flow rate of traditional single-channel filling valve is 4m/s, while flow rate of the new filling valve with compound channels can be upgraded to 7m/s, namely the flow rate has improved by 75%. In the working condition that the valve has fully opened, the flow rate of the new filling valve can be increased from 7m/s to 13m/s, and the flow rate has improved 85.7%. Obviously, the compound flow channels can significantly improve filling speed of the filling valve without increasing the basic structure dimension, which has good application value in engineering.

6. Conclusions

Firstly, the novel high-flow filling valve based on multi-stage hydraulic resistance and compound flow channels was designed. It can effectively guarantee the stability of the flow filling and the rapidity of the pressure unloading. So the master cylinder under the high pressure condition in large press can directly unload steadily.

Secondly, the simulation model of multi-stage hydraulic resistance with the annular gap based on AMESim was established, and the simulation results show that the structure of multi-stage annual gaps can realize stably multi-stage pressure relief. Meanwhile, the thickness, effective length and inner diameter of the annular gap are the critical parameters affecting relief features. Compared to other parameters, the thickness has the most significant influence on the pressure relief characteristics.

Then, the numerical analysis model of the actual structure with multi-stage annular gap based on Fluent was built. The simulation results present that the pressure relief process of initial phase is gentle, and the pressure releases rapidly when the pressure is above a certain value. Compared with traditional single-stage filling valve, the designed new filling valve has an advantage of pressure unloading fast and smoothly.

Finally, the simulation model of multi-stage relief filling valve with compound flow channels based on Fluent was established. The simulation results show that the filling speed can improve 85% with the novel filling valve comparing to the traditional single-channel filling valve when the valve has fully open. So the designed novel filling valve represent good application value in engineering.

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