INTRODUCTION

In consideration of such reasons as the low pump station pressure, serious pipeline damage, and improper artificial operation, the actual setting load of hydraulic support of China’s a majority of fully mechanized coal mining faces is far lower than 80% of the rated setting load and even some fully mechanized coal mining faces are lower than 15 MPa.1-3 As the hydraulic support cannot exert its normal supporting performance, the too early crushing and sinking of top plate can be hardly inhibited and dynamic pressure impact easily happens, which finally leads to the frequent safety accidents of coal mines.4-8
Song et al⁹ proposed the support setting load could be ensured by using an active support hydraulic system and designed a setting load guarantee valve that can guarantee the liquid supply time. Zhang et al¹⁰ proposed to use DCF-PZ200/40 setting load operating valve system to calibrate and guarantee support setting load. In consideration of the complexity, tedious pressure regulation, high labor strength, high influence on the working environment, and high costs, the guarantee valve and liquid supply system cannot cope with China’s current gloomy coal field or resolve the problem of poor support setting load thoroughly. Mo et al¹¹ suggested improving or guaranteeing the setting load by improving pump station pressure, reducing pressure loss, designing different liquid supply systems, etc, but the pressure in a majority of pump stations cannot reach the liquid supply requirements due to the high restrictions on the pump station’s liquid supply pressure and relatively backward technical level, and therefore, setting load can hardly satisfy the working requirements.

As for the issue above, this paper designs an automatic setting load enhancement device that can be directly connected with stand column system by a method that combines hydraulic and mechanical technique and applies it to the hydraulic support of common and large mining height working surface so as to ensure and improve bottom cavity pressure directly and quickly when stand column is loaded preliminarily and get rid of the restrictions of poor pressure supply of pump station.¹²-¹⁴

2 | PRINCIPLE DESIGN OF AUTOMATIC PRESSURIZING DEVICE LOOP

The pressurizing control loop design can finish two working processes, that is, pressurizing preparatory stage and quick pressurizing stage. Pressurizing control loop is connected with stand column system in a parallel manner.¹⁵

The pressurizing control loop increases pressure according to the preset pressure ratio. If the initial pressurized pressure is a little high, the pressure after pressurization may largely exceed the setting load required by hydraulic support. Therefore, a safety valve is set at the rod port oil circuit of pressure cylinder to limit the setting load entering the bottom cavity of stand column within the value required for working. The pressurizing loop is determined based on the points above, as shown in Figure 1.

The pressurizing control loop is mainly composed of pressure cylinder, pilot-operated directional control valve, check valve, safety valve, and hydraulic pipeline. When the pressure at the rod port opening of hydraulic cylinder is smaller than the opening pressure of pilot-operated directional control valve, the pilot-operated directional control valve is at the right position and the emulsion entering the automatic pressurizing loop will enter the rod port of pressure cylinder. Piston will move toward head port direction to get prepared for pressurizing. The emulsion will enter the bottom cavity of stand column via check valve to supply liquid, and at this time, the pressurizing device will not play a role in pressurizing any longer. When the pressure at the rod port opening of hydraulic cylinder is larger than the opening pressure of pilot-operated directional control valve, the pilot-operated directional control valve is at the left position. Emulsion enters the head port of pressure cylinder via pilot-operated directional control valve to drive piston move. The rod port pressure of pressure cylinder increases, which finally improves the bottom cavity pressure of stand column. Automatic pressurizing loop and stand column system share one liquid supply reverse control valve. The pressurizing loop can work for pressurizing as long as stand column supplies liquid to bottom cavity.¹⁶

3 | AUTOMATIC PRESSURIZING DEVICE STRUCTURAL DESIGN

According to the control loop, automatic pressurizing loop can be functionally divided into two parts: The first part includes pressurizing structure which comprises pressure cylinder and pressurization control structure while the second is an auxiliary structure which includes one-way breakover structure, safety structure, etc.¹⁷ All structural compositions are arranged and connected based on their functions and centrally designed on the tight and reasonable hydraulic valve block to realize the fast pressurization of support setting load.

3.1 | Pressurization structural design

3.1.1 | Pressure cylinder

The piston rod of pressure cylinder does not need to act externally, and its movement is just for the purpose of pressurization preparation and pressurization. The oil hydraulic pressure is increased by leveraging the different piston sections at both sides of
pressure cylinder. What is more, the borehole environment of coal face is severe with many pollutants such as dust. Therefore, piston rod cannot extend outward, as shown in Figure 2.

In order to reduce the volume and weight of the whole automatic pressure increasing valve, the rod port of piston is designed in hollow mode so as to realize displacement overlapping. The head port of piston is connected with pilot-operated directional control valve and oil tank according to the working principle of pressurizing control loop so an opening P₁ is reserved according to design.

3.1.2 Pressurizing control mechanism

According to the working principle of pressurizing control loop, the pressurizing control mechanism is connected with four oil circuits, including head port liquid supply oil circuit, head port oil circuit of pressure cylinder, rod port oil circuit of pressure cylinder and oil tank circuit, and two kinds of oil circuits can be connected/disconnected under its control effect: The head port liquid supply oil circuit can be connected with head port of pressure cylinder. At this time, the oil tank circuit is under cutoff status; when the head port of pressure cylinder is connected with oil tank circuit, the liquid supply oil circuit of head port is under cutoff status. The rod port oil circuit does not contact the rest three oil circuits via pressurizing control structure so it is relatively independent. Figure 3 shows the pressurizing control mechanism, where P₂ is the liquid supply port of head port, P₃ is the opening of head port, P₄ is the opening of oil tank, and P₅ is the opening of rod port.

In the process of pressurization preparation, the liquid supply circuit of head port is under cutoff status and the oil tank circuit is on. The two states are changed in course of quick pressurization, and the process can be transformed simply by a way that combines the large push rod with limit boss, small push rod with liquid circuit channel, sealed check ring, steel ball, and combined spring. It means when the liquid supply circuit opening of head port is blocked by steel ball under the effect of spring compressive force in the process of pressurizing preparation, the large push rod is under the original position, the small push rod does not have dynamic contact with steel ball and the oil tank circuit is connected with head port oil circuit under the effect of the other compressive spring. When the acting force applied to one side of the large push rod by the rod port, emulsion is larger than that of the compressive spring and the large push road will move, contact small push rod quickly and push it to move continuously and contact steel ball to move steel ball to connect the liquid supply oil circuit of head port and head port oil circuit. At this time, the gasket at the end of large push rod will block the liquid circuit of small push rod to cut off oil tank circuit.

In course of system unloading, the large push rod will return to the original position under the effect of large spring and steel ball will be pressed on valve seat again under the effect of small spring; push small push rod to move for a small distance but it cannot push the small push rod back to the initial position. In this way, the normal connection/disconnection of all oil circuits will not be affected. Therefore, the large push rod will still contact the small push rod first in next quick pressurizing process before the steel ball is pushed by small push rod in order to ensure the oil circuit disconnection and connection sequence. As the hydraulic impact incurred when the hydraulic system is just started easily leads to push rod malfunction, there is a certain axial spacing between the large and small push rods to avoid the connection of liquid supply oil circuit of head port and head port under the impaction.

3.2 Auxiliary structure

3.2.1 One-way connection structural design

It can be known from the pressurizing control loop that the automatic pressurizing device should include two one-way
connection mechanisms: One is opened by the liquid supply opening of pressurizing device toward the rod port, as shown in Figure 4A. The other, as shown in Figure 4B, is opened by the rod port of pressure cylinder toward pressurizing device outlet. The structure of both combines spring and steel ball to ensure the liquid inlet of pressurizing device flows unidirectionally.

3.2.2 | Safety structural design

Figure 5 shows the safety structure, which consists of valve seat, check ring, cone valve, spring, pressure regulating screw, and plug. According to the principle of pressurizing control loop, P10 opening connects the rod port of pressure cylinder while P11 opening connects oil tank for the purpose of discharging unload emulsion. The pressure regulating screw can be used for regulating the pressure required to satisfy different setting load requirements of different working faces and improve the adaptability of automatic pressurizing device. A boss is designed at the rear side of cone valve and the bottom of pressure regulating screw respectively to improve spring stability. The boss is set in the middle of spring to prevent the central axis from deviating excessively while the spring works.

4 | OVERALL STRUCTURE

Figure 6 shows the final design structure of automatic pressurizing device.

Working process of automatic pressurizing device: Connect the automatic pressurizing device to stand column system according to the working position of pressurizing control loop in parallel. The initial status of all structures is shown in Figure 6. By operating reverse control valve, the pump station will supply liquid to the whole hydraulic system and emulsion enters the bottom cavity of stand column via pilot-operated check
valve through main oil circuit so that the support raises column quickly. The other circuit enters automatic pressurizing device via P₆ opening. The emulsion entering pressurizing device flows to P₂ opening. As P₂ opening is under cutoff state at this time, emulsion can fill the oil channel only. The other circuit moves the steel ball of one-way connection structure of liquid inlet oil circuit and flows to the rod port of pressure cylinder via P₇ opening. Part of the emulsion entering the rod port of pressure cylinder opens the one-way connection structure of liquid outlet oil circuit via P₉ opening and flows to the bottom cavity of stand column via liquid outlet P₈ of pressurizing device. The other part pushes piston rod to move toward the direction of head port. The emulsion inside head port will drain to the working face environment via P₁ opening, elbow, P₃ opening, pressurizing control structure, and P₄ opening until the piston moves to the limit position. The pressurizing preparation process is thus finished.

When the top beam contacts top plate, liquid cannot be supplied largely via main liquid supply oil circuit and the pressure at the bottom cavity of stand column increases immediately and finally reaches the control pressure of pressurizing control structure of automatic pressurizing device. The large push rod will move quickly to contact small push rod, close oil tank circuit, and then move quickly together with small push rod to move the steel ball at the closed P₂ opening. The emulsion entering valve will enter the head port of pressure cylinder via P₂ opening, pressurizing control structure, P₃ opening, elbow, and P₄ opening to push the piston to move toward the rod port. At this time, the one-way connection structure of liquid inlet oil circuit has been closed and emulsion pressure of pressure cylinder rod port connected with the bottom cavity of stand column will increase according to the designed pressure ratio under the effect of Pascal law. It means the pressure of bottom cavity of stand column increases. At this time, small displacement happens to stand column and the emulsion inside the rod port of pressure cylinder can be used for supplementation to finish the quick pressurization process. If the increased pressure of the bottom cavity of stand column is too large, the safety valve of automatic pressurizing device will open to relieve load automatically so as to make the setting load of stand column stable. Operate reverse control valve and close the oil circuit of bottom cavity of stand column after the completion of liquid supply. After stand column unloading, a majority of structures of automatic pressurizing device will recover to the original status but piston and small push rod cannot. However, it does not affect the pressurizing device from working next time.

5 | SIMULATION ANALYSIS ON THE DYNAMIC CHARACTERISTICS OF AMESIM-BASED AUTOMATIC PRESSURIZING DEVICE

5.1 | Simulation analysis on control loop

The simulation model of control loop of automatic pressurizing device is established by considering the pressurizing principle of automatic pressurizing device of hydraulic support above and by using AMESim computer simulation software, as shown in Figure 7. In the simulation modeling process, one automatic pressurizing device is connected in parallel in the original support lifting hydraulic system to verify whether the setting load of hydraulic support can be improved effectively and resolve the support problem of coal face.

Suppose the rated pressure of emulsion pump station is 31.5 MPa, and the rated flow is 500 L/min; the high face mining length is generally long, and the diameter of main liquid inlet and outlet pipes used from the emulsion pump station to the working face hydraulic support is 50 mm and 65 mm, respectively, and the pipe length is 300 m; the working media is the emulsion made from 1:19 oil-water mixture. Hydraulic cylinder the pressure ratio of which is 1.6 is used. See Table 1 for the parameter setting of other main simulation model.

Simulation analysis is carried out according to the settings of the said simulation parameters. Suppose the simulation time is xs, the interval is 10⁻³ seconds and allowable simulation error is 10⁻¹¹, standard resolver mixed error is used for simulation analysis. See Figure 8 for the curve of its simulation result.

It can be concluded from Figure 8 that column lifting is finished at 2.52 seconds and stand column rises to reach the top. The bottom cavity pressure of stand column in the setting
Load resistance increase stage can reach 24 MPa only. After the automatic pressurizing device is connected in parallel, the pressure curve in the first 2.52 seconds of setting load is almost consistent with the case when no pressurizing device is used. It means that the access of the pressurizing device does not affect the speed of support column rising. At 2.52, the automatic position selector valve is opened through operation and the bottom cavity pressure of stand column rises abruptly. The pressure reaches 31.4 MPa at 3.28 seconds, after which, pressure tends to be stable. It can be concluded from the above that the automatic pressurizing device reacts quickly and can finish pressurization significantly within a short period so as to reach the value required by support setting load and accelerate the supporting and movement speed of support.

### 5.2 Simulation analysis of column lifting hydraulic system of hydraulic support

To verify the pressurizing effect of the hydraulic loop of large mining height hydraulic support standard column consisting of reverse control valve, pilot-operated check valve, safety valve, and automatic pressurizing device in Figure 1, AMSim simulation analysis should be carried out for the whole control loop that it forms.

The simulation model of hydraulic control system elements of support column lifting is established according to the actual conditions of support, through analyzing the lifting process of support stand column and by considering the actual pipeline and hydraulic elements of Type ZY11000/28/63D two-column shielded hydraulic support in the coal face, as shown in Figure 9. According to the said analysis on automatic pressurizing device and automatic pressurizing control loop and the realities of hydraulic support column lifting process in working face, the rated pressure of emulsion pump station is 31.5 MPa, the rated flow is 500 L/min and the working media is emulsion consisting of 95% water and 5% hydraulic oil; the pressure value of stand column overflow valve is 42 MPa. See Table 2 for other main simulation parameters.

Simulation analysis is made by supposing the simulation operation time is 3 seconds, the starting time is 0 seconds, the time interval is $10^{-3}$ seconds and the allowable simulation error is $10^{-11}$ seconds. The emulsion output from constant flow source enters the lower cavity of stand column via position selector valve and check valve to push the rising of stand column. The automatic pressurizing device is started after the support column lifting is finished and stand column reaches the top. At this time, the pressure of stand column

### TABLE 1 Settings of simulation model parameters

| Model | Oil source | Automatic pressurizing device | Hydraulic cylinder |
|-------|------------|--------------------------------|--------------------|
|       | Density/ (kg m$^{-3}$) | Bulk modulus/ MPa | Absolute viscosity/ cp | Diameter of piston left cavity/mm | Diameter of piston right cavity/mm | Piston stroke/mm | Diameter of piston lower cavity/mm | Diameter of piston upper cavity/mm | Piston stroke/mm |
| Value | 998 | 1860 | 1.05 | 70 | 55 | 150 | 200 | 160 | 750 |

**FIGURE 8** Bottom cavity curve of stand columns before and after the application of pressurizing device

**FIGURE 9** Simulation model of support column lifting hydraulic system
lower capacity increases abruptly and reaches the rated value immediately so as to satisfy the rated setting load requirements of support stand column. See Figure 10 for the comparison curve of output pressure curve after the application of automatic pressurizing device of setting load of support stand column and the pressure of column lifting hydraulic loop system.

First, open the hydraulic loop system of support lifting column, and three-position four-way directional control valve will work at the left side; the liquid enters bottom cavity of stand column and returns to upper cavity via pilot-operated check valve until the stand column touches the top plate to finish column lifting. It can be known from Figure 10 that the valve element of automatic pressurizing device can realize instantaneous operation, increase pressure quickly and output a few oils so as to make the pressure of stand column liquid supply pipe increase quickly by increasing from the original 24 MPa (the pressure loss of the system along the route and local oil leakage) to the rated pressure value 31.5 MPa of emulsion pump station) to support working face top plate safely and effectively.

It can be known by comparing and analyzing the said simulation curve result: The emulsion pressure slightly fluctuates within a short period in the preliminary stage of support column lifting loop system. The duration is about 0.01 seconds but the pressure peak is relatively small, 50 bar. Therefore, no significant influence is posed to the whole system. It can be known from Curve 2 that pressure at the bottom cavity of stand column can reach 24 MPa only in the support setting load stage due to the pressure loss of hydraulic system and pipe along the route. At this time, the automatic pressurizing device is started to supply liquid again to the lower cavity of stand column to increase pressure. Therefore, constant resistance stage will come after
FIGURE 13  (A) Comparison diagram of setting load. (B) Comparison diagram of setting time. (C) Comparison of resistance increase
the completion of setting load stage. It can be known from the output pressure curve 1 of automatic pressurizing device that the whole lifting process of support stand column lasts for about 2.08 seconds. After the pressure increase for 0.12 seconds, which means the pressure of the bottom cavity of stand column tends to reach stable rated value 31.5 MPa at 2.2 seconds, the hydraulic system is stable and does not fluctuate obviously. It conforms to the expected pressurization design requirements.

6 | APPLICATION

Figure 11 shows the automatic pressurizing device prototype processed and manufactured according to design principle diagram.

Connection method of prototype in course of test: Connect a T-junction at the inlet of bottom cavity of stand column and the liquid feeding site along the positive starting direction of pilot-operated check valve, respectively. On the basis of the normal connection of the original loop, connect the T-junctions at the prototype inlet and at pilot-operated check valve with high pressure hose, and connect the T-junctions at the prototype outlet and bottom cavity of stand column, as shown in Figure 11.

Automatic pressurizing device test is carried out at Type ZY11000/28/63D support of large mining height working face of one Inner Mongolia Coal Mine 3-1. The automatic pressurizing device is installed on the base in the middle of two support stand columns according to the site conditions of the borehole coalface and connected with the original hydraulic loop system of support lifting column in parallel via hydraulic oil pipe and main pipe, as shown in Figure 12. Collect 170 supports from 0# support by choosing one from every other one as the test support and number them as 1-170, respectively. Collect and analyze three parameters (setting load, setting time, and resistance increase time) and prepare a line chart, as shown in Figure 9. 0# support is close to the near transport mining roadway, 170# support is closed to track mining roadway (near pump station) so the pressure of 1-170# support increases gradually.

Figure 13A is the change diagram of hydraulic support setting load before and after applying pressurizing device. It can be concluded from the support setting load before application is about 23.5 MPa and that after application of pressurizing device is about 32 MPa. About 8.5 MPa pressure is increased to the pressure of bottom cavity of stand column. From the above, we can know that the automatic pressurizing device can effectively improve the setting load of support. Figure 13B is the comparison graph of setting time before and after the application of pressurizing device. It can be known from the figure that the setting time of all test supports after the application of pressurizing device is smaller than the value before the application, mainly because the setting load of support increases, the difference with working resistance becomes smaller and the resistance increase speed becomes faster.14 It can be known from the graph that the slight difference among the airtightness of different supports, pressure loss along the route, and pipe resistance loss leads to the tiny deviation of different supports for the same data parameter but the overall trend is the same.

7 | CONCLUSION

By analyzing test phenomenon through theoretical design, prototype making, and site test, the following conclusion is mainly made:

1. The automatic pressurizing device combining hydraulic and mechanical technique is designed to resolve the problem of poor supporting setting load. No electrical component is used, contributing to high reliability.

2. The automatic pressurizing device is designed theoretically based on pressurizing structure and auxiliary structure by the method of reserving opening on the basis of pressurizing control loop and unit design. The pressurizing control structure is designed in dual-push rod structure through analysis and improvement so as to control oil circuit connection/disconnection quickly and simply. The pressurizing device is simple in design, convenient in installation and use, high in mechanical automation, and small in the modification of the original system loop. The pressurizing device design is not confined to the specific working face condition and model of hydraulic support and has strong generality and favorable promotion and application value.

3. The stand column and support are lifted by using position selector valve of stand column loop in the test. After the support top beam contacts top plate for 2 seconds, reset position selector valve to stop supplying liquid to stand column. The following phenomenon can be observed: There is a little emulsion spraying in the safety valve overflow port of pressurizing device; the pressure meter of bottom cavity of stand column is about 32 MPa according to the observation and statistics. Compared with the pressure before application, 8.5 MPa is increased to the bottom cavity pressure of stand column and the setting load conforms to the design requirements.
4. Test shows that the automatic pressurizing device is able to improve the setting load of hydraulic support effectively to about 32 MPa without increasing the setting time of secondary pressurization. The resistance increase time is reduced to improve the working performance of hydraulic support so as to ensure and improve the bottom cavity pressure when the stand column is set directly and quickly, satisfy design requirements, prevent the coal bed top plate from being separated, broken, or falling too early, and improve the safety of mine coal face.

ORCID
Lianmin Cao https://orcid.org/0000-0002-0375-0371

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