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Original scientific paper

ANALYSIS OF THE INFLUENCE OF ACCUMULATOR CONFIGURATION ON STABLE LIQUID SUPPLY

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Abstract
To improve the stability of liquid supply and solve the problems of pressure, flow pulsation, and hydraulic impact, this study established the mathematical model in the working process of an accumulator from the perspective of the accumulator station, with the liquid supply system of a fully mechanized working face as the research object, and established the simulation model of the entire liquid supply system using AMESim. The influence of the relevant parameters of the accumulator on the working process of a single pump in the working face was analysed, and the combination scheme of the accumulator station was optimized. Results demonstrate that the pump equipped with an accumulator can effectively improve the liquid supply performance of the system. For the liquid supply system of the working face, the accumulation station combination scheme of 8 × 63 L and the initial accumulator charging pressure of 75 % of the working pressure could increase the stability of the system pressure and flow. The proposed research method provides evidence for achieving a stable liquid supply at the working face.
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Key Words: Emulsion Pump Station, Accumulator, Stable Liquid Supply, Optimization Analysis

1. INTRODUCTION

As the power source of fully mechanized working face equipment in coal mines, the emulsion pump station mainly provides power for mining, the driving working face, and other devices [1]. With the development of mining technology in the long wall working face, the increasing length of the working face and the number of supports, and the continuous development of hydraulic supports with a large mining height and a high working resistance, the high pressure and mass flow demand for the liquid supply system is proposed, which inevitably aggravates the pressure, flow pulsation, and impact problems of the liquid supply system.

In view of the above problems, the liquid supply system on the working face is often equipped with a large-capacity energy storage device, namely, the accumulator station, to absorb pressure, flow pulsation, and hydraulic shock [2]. Scholars have conducted numerous research on improving the stability of the working face liquid supply, but most of the research focused on the improvement of the emulsion pump. Meanwhile, the research on the impact of the structure and configuration of the accumulator on the stability of the liquid supply system is limited. Therefore, according to the working performance of the working face, determining the reasonable accumulator volume, number, initial charging pressure, and other parameters is of great significance to giving full play to the role of the accumulator and improving the stability of the hydraulic system. Combined with the actual liquid supply mode of a fully mechanized caving face in the Xinjulong Coal Mine, this study analyses the effect of the structural parameters of the accumulator on the stability of the system's liquid supply, optimizes the combination scheme of the accumulator station, and provides a reference for the reasonable configuration of the accumulator station for other working faces.

2. STATE OF THE ART

To solve the problem of liquid supply instability in the current working face, scholars at home and abroad have carried out many simulation and experimental studies from the perspective of the control methods of emulsion pump stations. Wang and Li optimized the control system of an emulsion pump station and proposed the combination of the frequency converter method and the combination switch to realize a constant pressure liquid supply [3]. Qi forecasted the power demand of the support by predicting the traction speed of the shearer and adopted a mixed particle swarm optimization algorithm to intelligently adjust the outlet pressure and flow of a pump station to match the power of the pump station with the demand [4]. Li proposed to output control signals in advance by predicting the liquid demand for the support to realize the liquid supply on demand [5]. Zhang et al. proposed a multi-pump parallel flow control strategy, which provides a new idea for stable pressure liquid supply technology [6]. Fu et al. proposed the overlapping cooperative control logic of the support, which realizes the adaptive adjustment of and intelligent decision-making on the liquid supply flow has a good effect on voltage stabilization [7]. Yu and Li carried out automatic and intelligent design for an emulsion pump station, which improved the station's reliability and safety, reduced its energy consumption to save energy, and extended the service life of related equipment [8]. Li and Wei analysed the working performance of hydraulic supports and obtained the number of hydraulic supports in operation according to the pressure characteristics and the time history to control the emulsion pump and provide a theoretical basis for multi-pump linkage control [9]. Tan et al. proposed a pressure control method for an emulsion pump station on the basis of the Elman neural network, established a prediction and control model for the system pressure, and verified the rationality and effectiveness of the method through simulation [10]. Zhao et al. proposed an intelligent speed governing system with variable frequency for emulsion pump stations, combining an artificial neural network and a fuzzy expert system for fault diagnosis to ensure the production safety of coal mines [11]. Tian et al. established the pipeline system model of an emulsion pump station in AMESim, introduced power matching control technology, adopted the particle swarm optimization algorithm to adjust the output of the pump station, and built the experimental platform of the intelligent control system of power matching in the pump station for verification [12].

Cao et al. proposed an adaptive accumulator loop model, adjusting the flow area of the front pipeline of the accumulator with sensors collecting flow and pressure information, to achieve the absorption of pressure pulsation [13]. Guo et al. performed simulation analysis on the amplitude-frequency characteristics of the pressure and flow pulsation of a fluid system equipped with an accumulator in the fluid system of a solenoid valve experimental rig and pointed out that the parameters of an accumulator group should be reasonably selected to achieve the best effect [14]. Li et al. established a theoretical model of accumulators, studied the parameters that affect the performance of accumulators, and conducted experimental validation [15]. Ma et al. established a mathematical model of accumulators for the pressure impact of the hydraulic system on construction machinery, theoretically studied the parameters that affect the performance of accumulators, and carried out simulation and experimental validation [16]. Kumykova and Kumykov theoretically and experimentally studied the dynamics of mine accumulators and provided a basis for the design of accumulators [17]. Mamčic and Bogdevičius established dynamic models for accumulators with the eigenfunction method and analysed the effects of the accumulator parameters and spacing on their absorption pressure pulsations [18]. To improve the performance of the hydrostatic pressure guide system, Bi et al. conducted a theoretical analysis of the accumulator in a system, established a simulation model, and studied the impact absorption effect of the accumulator under different charging pressures and the absorption law of the accumulator on pressure and flow fluctuations through experiments [19]. Kumar et al. studied the influence of the hydraulic accumulator on the response of the mining vehicle hydraulic drive system, providing a reference for selecting the appropriate accumulator capacity for the mining vehicle hydraulic drive system [20]. Taking the drainage system of underwater vehicles as the background, Dang designed and optimized an accumulator group and studied the pressure pulsation absorption performance of different accumulators under variable pressure conditions [21]. Guo et al. established the functional relationship between parameters by analysing the dynamic characteristics of the hydraulic pump, analysed the effect of the accumulator's absorption of pressure pulsation, and further proposed a way to improve the effective volume of accumulators [22]. Kumar et al. studied the reducing effect of the accumulator capacity, the charging pressure, and other parameters on pressure fluctuation with the Matlab/Simulink software and proposed that the charging pressure of accumulators should be approximately 90 % of the system working pressure [23]. Ranjan et al. established a simulation model using Matlab/Simulink, studied the impact of the accumulator volume and the charging pressure on the system, and then optimized the structure size of the accumulator [24]. Wang et al. investigated the influence mechanism of different variable speed modes on the performance of a pump [25].

Most of the current liquid supply systems on the working face at home and abroad adopt multi-pump linkage, frequency conversion control, and other methods to adjust the emulsion pump to achieve a stable liquid supply. However, the low precision of multi-pump linkage control and the slow response of frequency conversion technology cannot meet the real-time hydraulic support demand. Especially in a remote centralized liquid supply system, the pipeline pressure loss and response lag problems are serious. This study took the liquid supply system of a specific working face as the research object, established the AMESim simulation model using the numerical simulation method, studied the effect of related parameters of accumulators and their configuration schemes on the liquid supply system, and carried out optimized analysis of the accumulator configuration in the liquid supply system of the working face to provide reference for engineering practice.

The remainder of this article is organized as follows. The third section describes the equipment configuration and modelling of a fully mechanized caving face in the Xinjulong Coal Mine. The fourth section analyses the influence of the accumulator parameters on the working process of a single pump system from multiple aspects. The fifth section studies the influence of different accumulator combination schemes on the stability of the liquid supply system. The sixth section summarizes the paper and presents relevant conclusions.

3. SYSTEM MODELLING

3.1 Analysis of accumulator station configuration

In this study, a fully mechanized working face in the Xinjulong Coal Mine was taken as the research object. The emulsion pump station in the liquid supply system of the working face is mainly composed of four emulsion pumps (three are used and one is on standby), equipped with a 5×100 L accumulator station. The main equipment configuration of the liquid supply system on the working face is as follows. Fig. 1 shows the schematic of the 500 L accumulator station on the working face.

The emulsion pumping station system of the fully mechanized working face in Xinjulong adopts four emulsion pumps; two are TMBRW(630/37.5) R-type emulsion pumps with an industrial frequency, and the other two are TMBRW(630/37.5) RA-type emulsion pumps with variable frequency (four pumps and two boxes). The hydraulic support model used on this fully mechanized working face is ZF15000/23/43D. The main executive components are the column oil cylinder and the push jack. Fig. 2 is the schematic of the emulsion pump station. The main technical parameters of related equipment are shown in Table I.

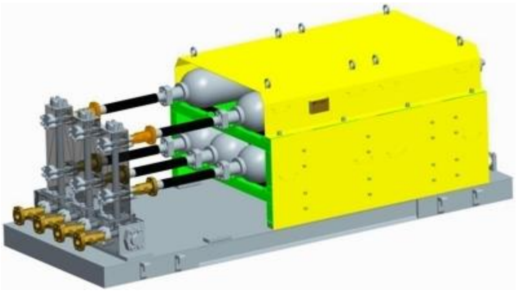


Figure 1: Accumulator Station of 500 L.

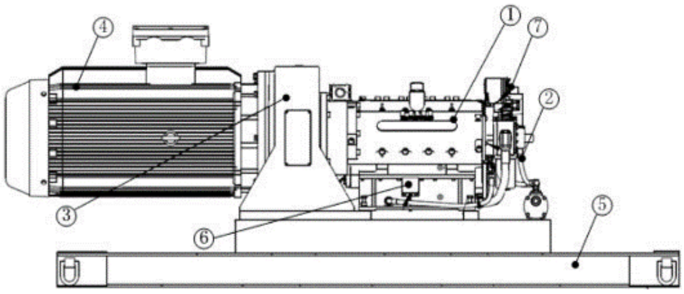


Figure 2: Emulsion pump station.

Table I: Main technical parameters of the related equipment.

Name	Index	Parameter	Name	Index	Parameter
Pump	Rated flow	630 L/min	Push jack	Stroke	960 mm
Pump	Rated pressure	37.5 MPa	Column	Diameter of cylinder	360 mm
Push jack	Diameter of cylinder	180 mm	Column	Diameter of column	340 mm
Push jack	Diameter of rod	120 mm	Column	Stroke	1425 mm

3.2 Mathematical model of the accumulator working process

The bladder accumulator is filled with a sealed gas at a certain pressure and stores energy by compressing the sealed gas. When the system pressure is higher than the initial charging pressure of the accumulator, the gas is compressed to store energy and oil. When the system pressure is lower than the initial charging pressure of the accumulator, the gas expands and releases energy and oil [26]. The difference between the gas volumes under the lowest and highest working pressures of the accumulator is the effective volume (ΔV) [27].

$$\Delta V = V_1 - V_2 \tag{1}$$

where ΔV is the effective volume of the accumulator, V_1 is the gas volume under the lowest working pressure, and V_2 is the gas volume at the maximum working pressure.

The gas in the air sac of the accumulator is approximated as an ideal gas, and its state equation is as follows:

$$p_0 V_0^{\gamma} = p_1 V_1^{\gamma} = p_2 V_2^{\gamma} = C \tag{2}$$

where p_0 is the initial charging pressure, p_1 is the minimum working pressure, p_2 is the maximum working pressure, V_0 is the volume of the accumulator, C is a constant, and γ is the exponent (i.e., $\gamma = 1$ in the isothermal process, and $\gamma = 1.4$ in the adiabatic process).

In the liquid supply system of the working face, the accumulator mainly reduces the pressure and flow pulsation and the absorbing hydraulic impact. The mathematical model of the working process is as follows:

Absorption pump pulsation:

$$V_0 = \frac{AkL(p_1 / p_0)^n \times 10^3}{1-(p_1 / p_2)^{\frac{1}{n}}} \tag{3}$$

where A is the effective acting area of the cylinder, L is the plunger stroke, and k is the coefficient.

Absorption hydraulic impact:

$$V_0 = \frac{m}{2} v^2 \cdot \frac{0.4}{p_0} \left[\frac{10^3}{(p_2 / p_0)^{0.258} - 1} \right] \tag{4}$$

where m is the quality of oil in the pipeline, and v is the flow velocity in the pipe.

3.3 Establishment of simulation model

As shown in Fig. 3, the liquid supply system is composed of four TMBRW630 emulsion pumps (one standby pump is not shown). Each emulsion pump is equipped with safety and electromagnetic unloading valves, taking the main pipe pressure as the input signal to control the loading and unloading of the pump. The accumulator station consists of five 100 L accumulators. The liquid supply pipeline adopts the "two into one back" mode of liquid supply. The load model is established according to the actual structural parameters of the ZF15000 four-column hydraulic support. Fig. 3 shows 4 column cylinders, 6 pushing cylinders, and 1 drawing cylinder from top to bottom, which can simulate a complete basic action process of the hydraulic support lifting column, and 6 supports simultaneously push, lower the column, and draw support.

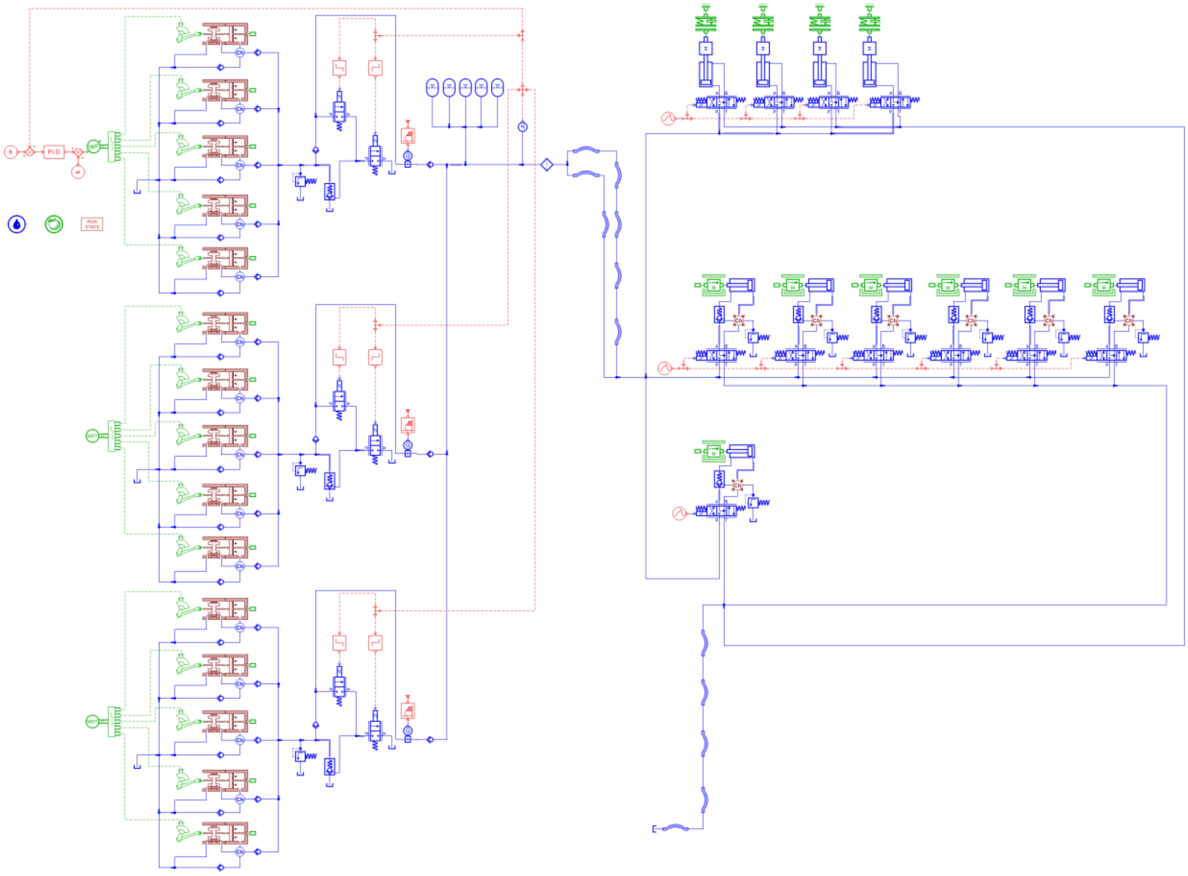


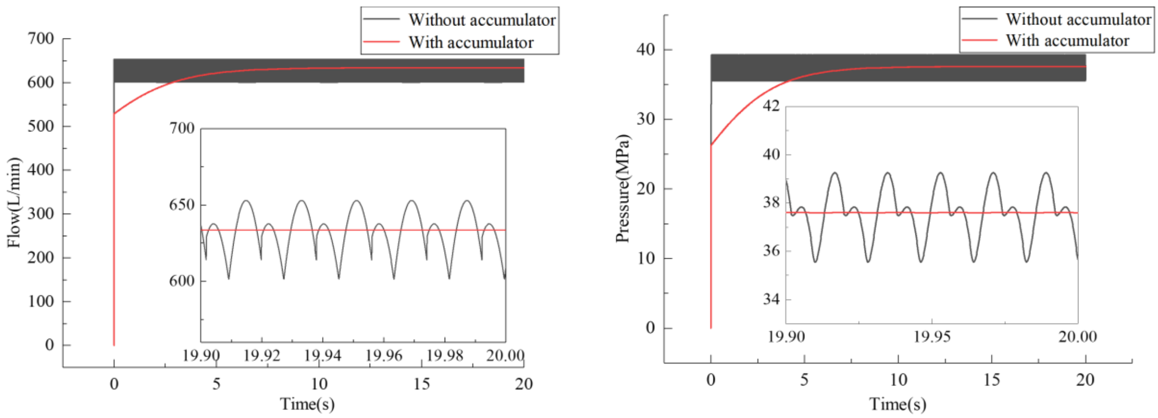
Figure 3: Model of liquid supply system on the working face.

4. ANALYSIS OF INFLUENCING FACTORS OF ACCUMULATOR

In the liquid supply system, the accumulator usually works in three ways: absorbs pressure and flow pulsation, mitigates the hydraulic impact, and acts as an auxiliary power source. In this study, the influence law of the accumulator parameters in a single pump system on the working process was analysed from the three perspectives above, and throttle valve was used as the load to adjust the opening until the emulsion pump worked at the rated operating condition.

4.1 Comparison of the effect with or without the accumulator

The accumulator with a volume of 20 L was selected, with a charging pressure of 70 % of the working pressure (37.5 MPa), that is, 26.25 MPa, and the other parameters were the same. The output pressure and flow of pumps with and without accumulator were simulated and compared.



a) Comparison of output flow
b) Comparison of output pressure

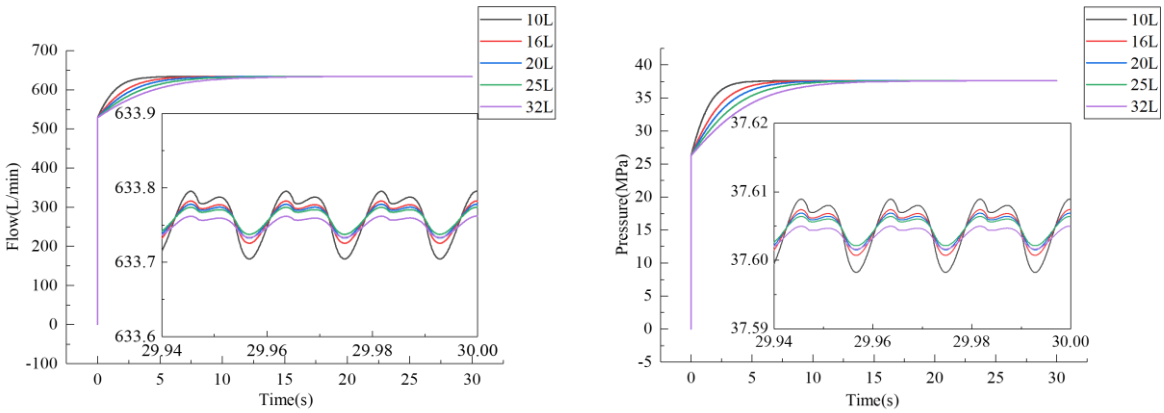
Figure 4: Comparison of output flow and pressure with and without accumulator.

Fig. 4 shows the comparison of the output pressure and flow of the pumps with and without an accumulator. In the absence of an accumulator, the output flow and pressure of the pump fluctuated greatly, as indicated by the structural characteristics of the emulsion pump. After adding an accumulator, the output flow and pressure fluctuation of the pump greatly decreased, indicating that introducing an accumulator plays an important role in stabilizing the output pressure and flow of the pump.

4.2 Analysis of pulsation reduction function

To study the influence of accumulator volume and initial charging pressure on the pump output flow and pressure, the accumulator volume was set to 10, 16, 20, 25, and 32 L according to standard nominal volume range of the accumulator, and the initial charging pressure was set to 26.25 MPa. The initial charging pressure of the accumulator was set to 22.50, 26.25, 30.00, and 33.75 MPa according to 60 % – 90 % of the rated system working pressure, with a constant volume of 20 L. The variation law of the pulsating absorption of the accumulator was studied.

Fig. 5 shows the comparison of the output flow and pressure of the pump under different accumulator volumes. Fig. 6 presents the comparison of the output flow and pressure of the pump under different initial charging pressures of the accumulator.

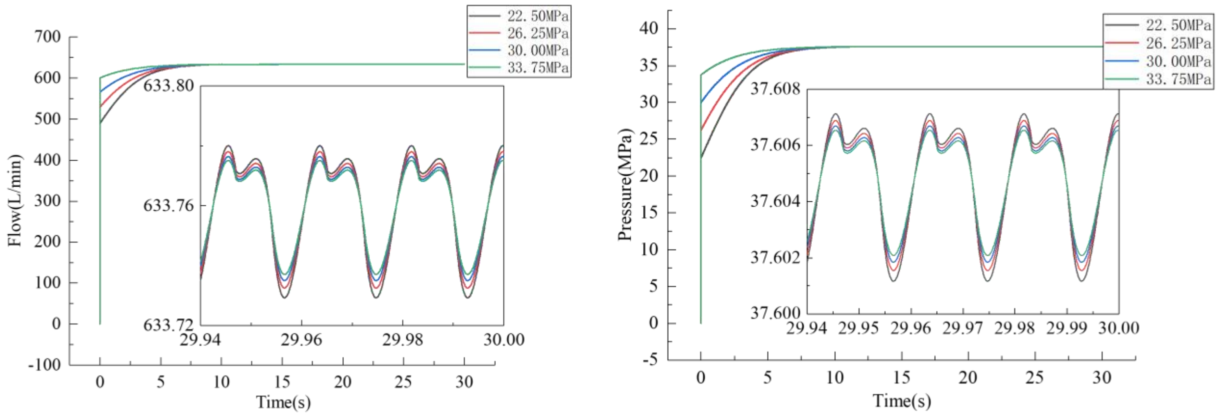


a) Pulsations of the system flow
b) Pulsations of the system pressure

Figure 5: Comparison of system flow and pressure with different accumulator volumes.

As is shown in Figs. 5 and 6, the larger the volume of the accumulator is, the higher the initial charging pressure, the better pulsation absorption effect, and the more stable the pump flow and pressure output are. This phenomenon occurs because the larger the volume of the accumulator is, the larger its effective volume, the higher the initial charging pressure, the less the oil accumulator absorption before it comes into play, and the better pulsation absorption effect are. Therefore, to improve the stability of the output pressure and flow of the pump, the volume of the accumulator and the initial charging pressure can be appropriately increased.

The above analysis indicates that the small accumulator of 20 L could effectively absorb the pressure and flow pulsation of a single pump. Within a reasonable range, regardless of the accumulator station configuration, the pulsation of the pump station could be effectively absorbed. Therefore, a separate analysis of the pulsation absorption of the accumulator is unnecessary in the subsequent analysis.



a) Pulsations of the system flow

b) Pulsations of the system pressure

Figure 6: Comparison of system flow and pressure with different inflation pressures.

4.3 Analysis of impact absorption capacity

In practical application, the working pressure of the emulsion pump is usually slightly lower than the rated pressure. The unloading pressure of the unloading valve was set as 38 MPa to simulate hydraulic impact. The effects of absorbing the pressure impact of accumulators with different volumes and different initial charging pressures were compared and studied.

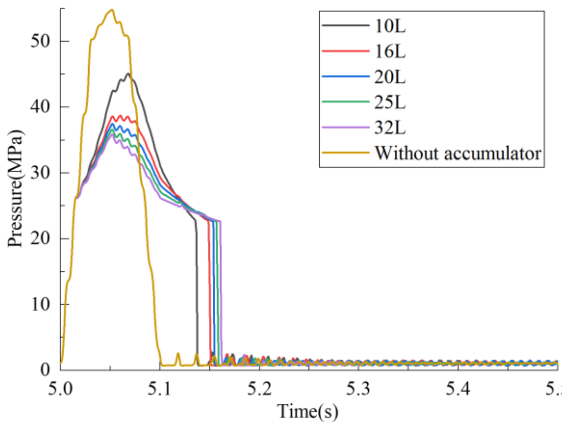


Figure 7: Different accumulator volumes.

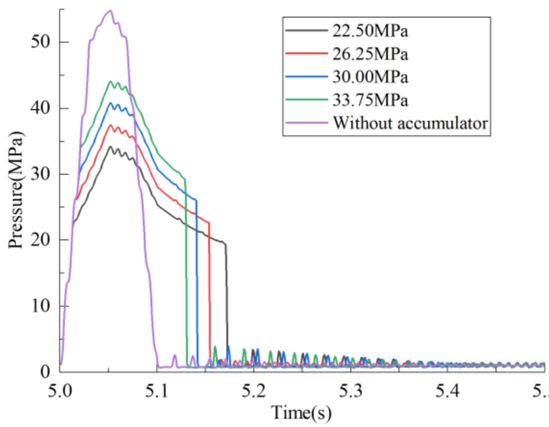


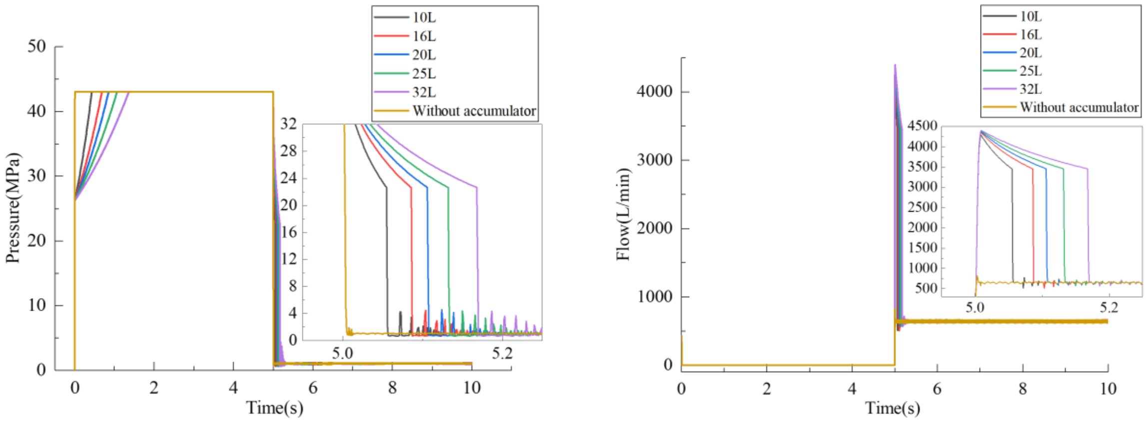
Figure 8: Different charging pressures.

Fig. 7 shows the comparison of the system pressure impacts under different accumulator volumes. The larger the volume of the accumulator is, the smaller the peak value of the system pressure impact is, that is, the better the impact absorption effect is. However, the larger the volume of the accumulator is, the longer the time for the system to reach a stable state is, that is, the slower the response speed is. This phenomenon occurs because the larger the effective volume of the accumulator is, the greater the oil absorption and the more significant the effect are. For this type of emulsion pump, 16, 20, and 25 L accumulators can be selected.

Fig. 8 shows the comparison of the pressure impact in the system with different initial charging pressures of the accumulator. The lower the initial charging pressure of the accumulator is, the smaller the peak value of the system pressure impact is, that is, the better the impact absorption effect is because the higher the initial charging pressure is, the smaller the effective volume of the accumulator is and the more difficult playing an effective role is for the accumulator. However, if the initial charging pressure is extremely low and the compression range of the air sac is extremely large, then the service life of the air sac will be greatly affected. Therefore, setting the initial charging pressure to 70 % – 80 % of the system pressure is reasonable.

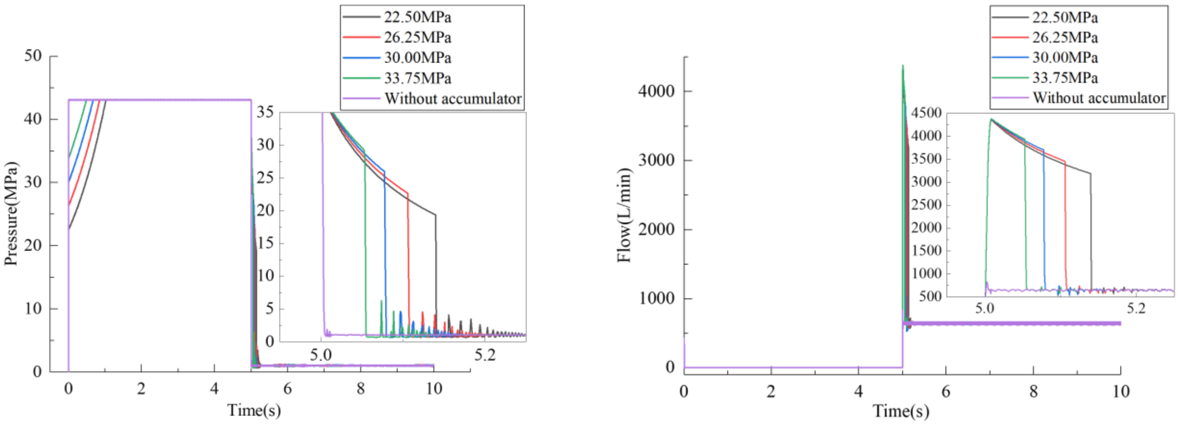
4.4 Analysis of pulsation reduction function

In the working face, if the pump station fails to supply liquid in time when the working condition of the actuator changes, then the accumulator will supply liquid to the system as an auxiliary power source to a certain extent. The working state of the column is set to start acting from static, and the auxiliary liquid supply law of accumulators with different volumes and initial charging pressures at the moment when the action state of the executing components changes was studied.



a) Comparison of system pressures b) Comparison of system flows

Figure 9: Comparison of pressure and flow with accumulators of different volumes.



a) Comparison of system pressures b) Comparison of system flows

Figure 10: Comparison of pressure and flow with different charging pressures.

Figs. 9 and 10 show the influence of accumulator volume and initial inflation pressure on system pressure and flow. Figs. 9 and 10 also indicate that the larger the volume of accumulator and the lower initial charging pressure are, the better the effect of the accumulator is as an auxiliary power source because the larger the volume of the accumulator is, the lower the charging pressure, the greater the oil stored, and the greater the oil released by the accumulator are when the oil cylinder begins to act, so the better the maintenance of the system pressure is. However, in practical application, the larger the volume of the accumulator is, the larger the space occupied, the higher the price, and the slower the reaction speed are. Thus, an accumulator with an extremely large volume is unsuitable. Meanwhile, to avoid excessive compression ratio, which leads to the serious life reduction of the air sac, the general provisions of the compression range should not exceed 1/3 of the maximum volume, preferably not more than 20 %. Therefore, the charging pressure of accumulator should not be too low, generally 70 % – 80 % of the system working pressure.

The above analysis indicates that in the single pump system on this working face, considering the effects of the impact absorption and the auxiliary power source, the volume of the accumulator should be 25 L, and the initial charging pressure should be approximately 75 % of the system working pressure.

5. OPTIMIZATION ANALYSIS OF ACCUMULATOR COMBINATION SCHEME

With the development of long-distance centralized liquid supply technology, the capacity requirements of the emulsion pump accumulator station for medium-thickness coal seams are generally ≥ 450 L, often adopting a 5 × 100 L configuration. The large mining height of an emulsion pump liquid supply station generally requires the capacity of the accumulator station to be ≥ 700 L. Thus, the 8 × 100 L configuration is adopted, and some adopt 1200 L or a larger capacity configuration.

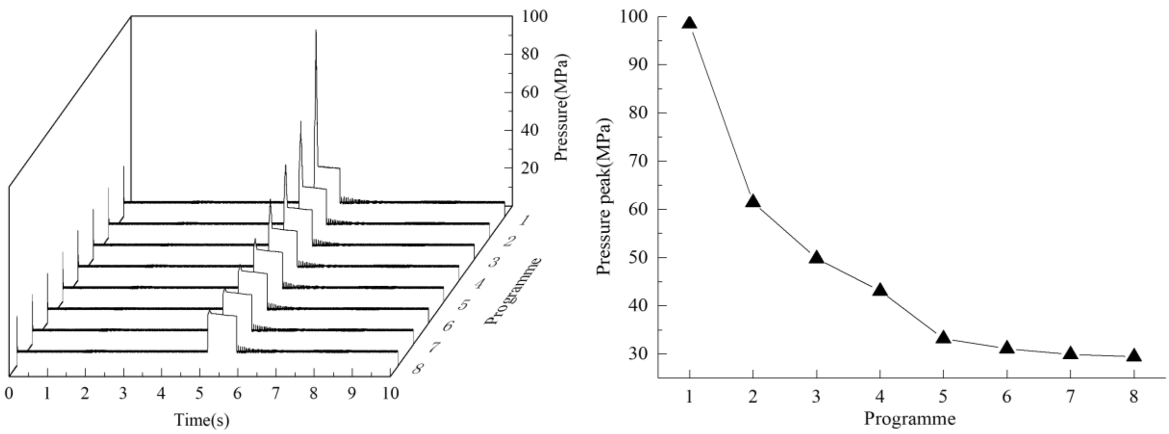
5.1 Influence of accumulator combination scheme on its shock absorption capacity

The working face is currently equipped with 500 L accumulator stations, that is, five 100 L accumulators, but other options exist. The combination schemes of the accumulator stations studied in this section are shown in Table II. The total volume of the accumulator station is approximately 500 L, and impact was applied to compare and study the effects of different combination schemes.

Table II: Main technical parameters of the related equipment.

No.	**Volume** /L	**Number**	**Total volume** /L	**No.**	**Volume** /L	**Number**	**Total volume** /L
1	250	2	500	5	63	8	504
2	160	3	480	6	50	10	500
3	125	4	500	7	40	12	480
4	100	5	500	8	40	13	520

Fig. 11 shows the comparison of the pressure impacts under the different combination schemes of the accumulator station. When the differences of the total volume between accumulator stations are not great, the higher the number of accumulators is, the lower the peak value of the pressure impact and the better the effect of the absorbing pressure impact are, that is, the parallel connection of multiple small accumulators is highly conducive to absorbing pressure impact. However, in actual production application, the higher the number of accumulators is, the higher the number of components in the system is, so the higher the failure rate is. Therefore, in view of the above factors, the fifth combination scheme is the most reasonable, that is, the combination scheme of the accumulator station should be changed from 5 × 100 L to 8 × 63 L.

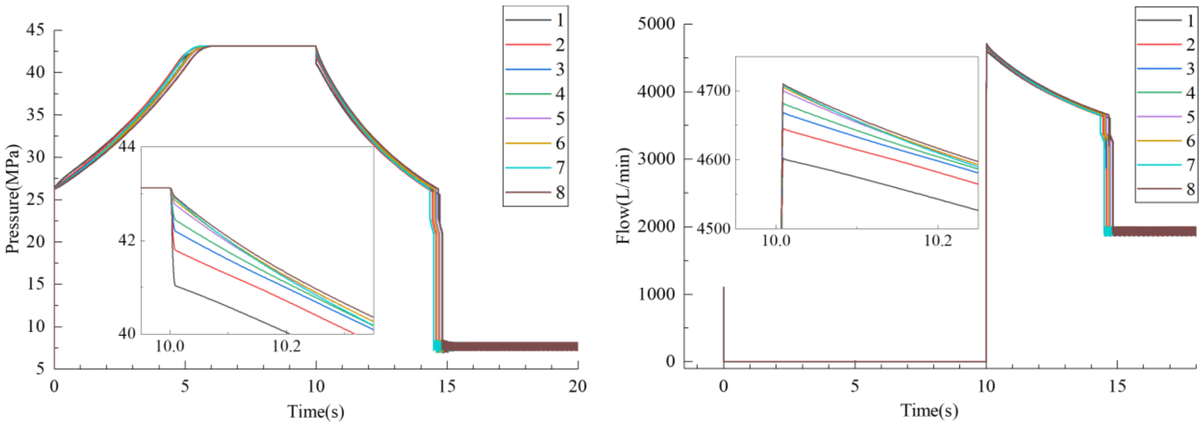


a) Pressure impacts b) Peak pressures

Figure 11: Pressure comparison with different combination schemes of accumulator station.

5.2 Influence of accumulator combination scheme on its auxiliary liquid supply

The column oil cylinder was set to start acting from rest. The accumulator combination schemes are the same as that in Section 5.1. The auxiliary liquid supply effects of different accumulator combinations were compared and studied at the moment when the action state of the executive components changes.



a) System pressures b) System flows

Figure 12: Comparison of results with different combination schemes of accumulator station.

As shown in Fig. 12, the higher the number of accumulators is, the larger the flow and the higher the maintained pressure value are when accumulators come into play. The action duration is affected by the total volume of the accumulator station and the combination schemes. The larger the total volume of the accumulator is and the lower the number of combination schemes and the longer the action time are. These two factors are interrelated. In the case of a small difference in total volume, the greater the accumulators' instantaneous release of oil is, the higher the pressure value is when the accumulator starts to play its role, and the shorter the corresponding action time is.

6. CONCLUSION

The accumulator configuration schemes have important influences on the liquid supply system. The reasonable configuration of the accumulator has great significance in improving the stability of the liquid supply at the working face. According to the study of the accumulator action law, the influence of the accumulator combination scheme on the liquid supply system was studied, and a specific working face was taken as an example to provide an optimization scheme to meet the stable liquid supply demand. The following conclusions could be drawn:

(1) In the fluid supply system, an accumulator is equipped for a single pump, effectively improving the pressure and flow pulsation of the system and mitigating the hydraulic impact.

(2) Considering the impact absorption and the auxiliary power source, a single TMBRW630 emulsion pump should be equipped with a 25 L accumulator.

(3) The analysis and optimization method adopted in this study is applicable to the analysis of the liquid supply system of each working face. For the liquid supply system of the working face of the Xinjulong Coal Mine, the accumulator station was changed from 5 × 100 L accumulators to 8 × 63 L accumulators, and the accumulator charging pressure was changed from 70 % to 75 % of the system working pressure, which is highly conducive to giving full play to the effect of the accumulator and prolonging its service life.

Combined with the specific working face, this study analysed whether a single pump is equipped with an accumulator and the influence of the relevant parameters of the accumulator on the stable liquid supply of a single pump and proposes the optimal combination scheme of the accumulator. However, this study can further optimize the overall configuration scheme of the accumulator station on the basis of the specific actual working conditions and the allocation of the accumulator master station and use the auxiliary accumulator with a reasonable volume at different positions of the working face to maximize the stable liquid supply of the entire working face.

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