Research on Parallel Operation Characteristics of High-pressure Pumps Applied in Coal Mine Hydraulics

permeability improvement

Kai Shen123, Wei Xiong23, Quanbin Ba23, Yin Liao23 and Lipeng He12*

1School of Resources and Safety Engineering, Chongqing University, Chongqing, 400044, China
2State Key Laboratory of the Gas Disaster Detecting, Preventing and Emergency Controlling, Chongqing, 400037, China
3CCTEG Chongqing Research Institute, Chongqing, 400037, China
*Corresponding author’s e-mail: helipeng@cqu.edu.cn

Abstract. Nowadays, plunger high-pressure water pumps applied in large-scale mine are mostly used in coal mine hydraulics to increase permeability, and it is difficult to transport objections underground. Besides, the permeability improvement is affected during overhaul too. Therefore, multiple small high-pressure water pumps operating in parallel can be used to solve the problems mentioned above instead of large high-pressure water pumps. Moreover, the operating principle of the plunger high-pressure pump determines the specific flow fluctuation characteristics during its operation, and similar flow fluctuations also exist during the operating of parallel pump sets. The transmission model and AMESim hydraulic simulation model of single, parallel plunger pumps are established, taking the BQW-22/50 high-pressure water pump as an example. The operating characteristics of a single plunger pump and a parallel pump group are analyzed in this paper. The results are obtained as follows: the instantaneous discharge flow curve of a single plunger pump conforms to a sine function; the flow of the parallel pump set is the superposition of the flow of multiple plunger pumps; the instantaneous discharge flow curve changes under the influence of the phase deviation angle between the pumps; when parallel pump sets are running, there is an optimal phase deflection angle between the pumps, which minimizes the flow fluctuation of the pump sets; when four high-pressure water pumps are operated in parallel, the optimal phase deflection angle between the pumps is $\pi/12$ or $\pi/4$.

1. Introduction

According to statistics, the coal yield of coal mines with high gas as well as coal and gas outburst accounts for about 30% of total coal output in China. It has always been the top priority of coal mine safety to prevent and control gas disasters. Moreover, the occurrence of coal seam gas in China has the characteristics of “three lows and one high”, namely low saturation, low permeability, low reservoir pressure, and high degree of metamorphism. The permeability improvement of coal seams in most mining areas is $10^{-7}$-$10^{-6} \mu m^2$, which is three to four orders of magnitude lower than the United States, Australia and other countries[1]. In addition, the low permeability improvement of the coal seam greatly limits the effect of gas drainage. In other words, the mine gas drainage rate is low, and it takes a long time for the drainage to reach the standard. Therefore, it is necessary to take measures to increase permeability and production of reservoirs, improving the effect of gas drainage and avoiding problems...
such as tight drainage connection caused by low drainage efficiency. Currently, hydraulic permeability improvement is the most widely used and effective down-hole permeability improvement technology for coal seams, among which the most representative ones include ultra-high pressure hydraulic slitting technology and hydraulic fracturing technology[2]. The high-pressure water pump is the key equipment of hydraulic permeability improvement technology, which mainly uses a single large-scale high-pressure water pump to supply liquid, but the equipment is heavy and bulky. For example, the BQW-125/100 mining high-pressure water pump unit used in hydraulic slitting technology weighs 4.15 tons[3], while the BYW78/400 mining high-pressure water pump unit used in hydraulic fracturing technology weighs 13.5 tons[4]. It is difficult for underground transportation. In addition, if the pump unit is running abnormally for maintenance, the hydraulic anti-reflection measures cannot be operated, which seriously affects the construction efficiency.

As for this problem, multiple small high-pressure pumps can be operated in parallel instead of a single large-scale mining pump set. The small high-pressure pumps are small in size and low in weight, which can be used to solve the difficult problems of large-scale high-pressure pump handling and maintenance. When the flow of a single pump cannot meet the needs of the site, it is also necessary to use multiple high-pressure pumps operating in parallel to increase the flow of the pump set[5]. Moreover, the mining high-pressure pump for hydraulic permeability improvement technology in underground coal mines, which is commonly used, is a plunger pump, and there are specific fluctuations in the high-pressure pump during operation due to the working principle of the plunger pump. If multiple pump sets are operated in parallel, the fluctuation characteristics will be amplified, which will affect the reliability and stability of the entire system[6-7]. Therefore, analyzing the working principle of the mining plunger high-pressure pump, the methods of model analysis and numerical simulation are respectively adopted in this paper to study the flow fluctuation characteristics of a single pump and multiple pumps operating in parallel. Thus, theoretical support can be provided for the design of a small high-pressure pump set in parallel to replace a single large high-pressure pump set.

2. Operation Characteristics of Mining Plunger with High-pressure Pump

2.1 Operation Principle

The mining high pressure pump used in hydraulic permeability improvement technology is a radial plunger pump with valve distribution, and the motion part of the pump mainly includes motor, crankshaft, connecting rod, plunger and cross-head. Taking the three-plunger high-pressure pump as an example, its operation process is as follows: the external power source drives the crankshaft to rotate[8], and then the crankshaft forces three groups of connecting rods, cross-heads and plungers to reciprocate. When the plunger moves inversely to the hydraulic end, the negative pressure will be formed in the pump cylinder, and the liquid will enter the pump cylinder through the suction valve. When the plunger moves to the hydraulic end, the liquid in the cylinder will be squeezed, increasing the pressure. Then the suction valve closes, the discharge valve opens, and the liquid will be discharged. Moreover, the three operation chambers that can be called cylinders as well in the hydraulic end of the high-pressure pump are replaced to form a partial vacuum or high pressure, so that the three groups of inlet and outlet valves can be alternately opened or closed to complete the suction and discharge processes.

2.2 Operation Model of the Three-plunger Pump

According to the operation principle of the three-plunger pump, the structure and process of the suction and discharge are simplified. One cylinder transmission model of the three-plunger pump is extracted as shown in Figure 1.
The instantaneous velocity \( u \) of the plunger is expressed by Formula (1). The positive value indicates that the plunger is in the discharge process, and the negative value shows that the plunger is in the suction process.

\[
    u = \frac{dx}{dt} = -r\omega \left( \sin \phi + \frac{\lambda}{2} \frac{\sin 2\phi}{\sqrt{1 - \lambda^2 \sin^2 \phi}} \right) \tag{1}
\]

Usually \( \lambda \) is very small and Formula (1) can be simplified to

\[
    u = -r\omega \sin \phi \tag{2}
\]

In the formula, \( x \) refers to the plunger movement displacement, whose unit is \( mm \), and \( \phi \) is crank angle, which is positive when rotating counterclockwise. Besides, \( r \) indicates crank radius (Unit: \( mm \)), and \( \omega \) represents crank angular velocity (Unit: \( r/min \)). In addition, \( \lambda \) denotes the ratio of the crank radius \( r \) to the connecting rod \( L \).

The instantaneous discharge flow \( q \) of the cylinder can be expressed as follows:

\[
    q = Au = -Ar\omega \sin \phi \tag{3}
\]

In the formula, \( A \) refers to the cross-sectional area of the plunger (Unit: \( mm^2 \)).

For the three-plunger pump, the phase deflection angle difference among three-cylinder cranks is \( 2\pi/3 \), and the flow will be discharged when the phase deflection angle is discharged at the crank corner. Therefore, the three-cylinder instantaneous discharge flow can be expressed as follows:

Instantaneous discharge flow of the first cylinder \( q_{11} \):

\[
    q_{11} = \begin{cases} 
    0 & (\phi=0 : \pi) \\
    -Ar\omega \sin \phi & (\phi=\pi : 2\pi) 
    \end{cases} \tag{4}
\]

Instantaneous discharge flow of the second cylinder \( q_{12} \):

\[
    q_{12} = \begin{cases} 
    0 & (\phi=\pi/3 : \frac{5\pi}{3}) \\
    -Ar\omega \sin(\phi-\frac{2\pi}{3}) & (\phi=0 : \frac{2\pi}{3}, \frac{5\pi}{3} : 2\pi) 
    \end{cases} \tag{5}
\]

Instantaneous discharge flow of the third cylinder \( q_{13} \):

\[
    q_{13} = \begin{cases} 
    0 & (\phi=0 : \frac{\pi}{3}, \frac{4\pi}{3} : \frac{2\pi}{3}) \\
    -Ar\omega \sin(\phi+\frac{2\pi}{3}) & (\phi=\frac{\pi}{3} : \frac{4\pi}{3}) 
    \end{cases} \tag{6}
\]

The three plungers of three-plunger pump work at the same time, so the instantaneous total discharge
flow $q$ of the pump can be obtained according to Formulae (4)-(6)

$$q_t = q_1 + q_2 + q_3$$  \hspace{1cm} (7)

In the formula, $q_t$ whose unit is $L/min$ is instantaneous discharge for single three plunger pump.

### 2.3 Flow Fluctuation Characteristics of the Three-plunger Pump

In this paper, the BQW-22 / 50 high pressure water pump is taken as the research object to analyze the flow fluctuation characteristics of the three-plunger pump. The parameters such as pump speed and crank radius are shown in Table 1.

**Table 1. Technical parameters of bqw-22 / 50 high-pressure water pump**

| Technical Index          | Unit | Value |
|-------------------------|------|-------|
| Rated Operation Pressure | MPa  | 50    |
| Rated Operation Flow    | L/min| 22    |
| Power                   | Kw   | 22    |
| Crank Speed             | r/min| 1450  |
| Plunger Diameter        | mm   | 12    |
| Crank Diameter          | mm   | 40    |

The parameters of the BQW-22/50 high-pressure water pump are introduced into Formulae (4) to (7), to obtain the instantaneous discharge flow rate of the pump during the 360° cycle of crank rotation over time.

![Instantaneous discharge flow curve of three-plunger pump](image)

**Figure 2. Instantaneous discharge flow curve of three-plunger pump**

It can be seen from Figure 2 that the flow rate of each cylinder in the three-plunger pump shows regular periodic changes, and the instantaneous discharge flow of the pump is sinusoidal periodic function distribution, so the three plunger-pump has regular flow fluctuation characteristics during operation. The fluctuation coefficients $\delta_{q_1}$ and $\delta_{q_2}$ are used to represent the fluctuation amplitude of system flow, which can be expressed as follows:

$$\delta_{q_1} = \frac{(q_{\text{max}} - q_m)}{q_m}$$ \hspace{1cm} (8)

$$\delta_{q_2} = \frac{(q_m - q_{\text{min}})}{q_m}$$ \hspace{1cm} (9)
In the formula, \( q_{\text{max}} \) refers to the maximum instantaneous discharge flow in the system, and \( q_{\text{min}} \) denotes the minimum instantaneous discharge flow of the system. \( q_m \) indicates the average discharge in the system.

When single BQW-22 / 50 high-pressure pump is running, the maximum instantaneous discharge flow is 23.48 L/min, the minimum instantaneous discharge flow is 23.48 L/min, and the average discharge flow is 22.4 L/min. The flow fluctuation of coefficient \( \delta_{q1} \) and \( \delta_{q2} \) are 4.77 % and 9.27 %.

3. Analysis of Operation Characteristics in Parallel Pump Group

When the high-pressure water system adopts the parallel operation mode of multi-plunger pump, the instantaneous discharge flow of the pump group is superimposed by the instantaneous discharge flow in each cylinder of each plunger pump. However, due to the inherent flow fluctuation characteristics of the three-plunger pump, there is also a certain regular flow fluctuation after the pump group is paralleled.

3.1 Parallel Operation Model of Plunger Pump

Figure 3 shows the transmission model when multiple sets of three-piston pumps are used in parallel[9].

![Diagram](image)

(a) Transmission model of the first pump after parallel connection  
(b) Transmission model of the \( n \)-th pump after parallel connection

Figure 3. Parallel transmission model of multi-plunger pump

Three-cylinder instantaneous discharge flow \( q_{11}, q_2 \) and \( q_{13} \) of the first plunger pump conform to Formulae (4)-(6). What is more, the crank angle of the other parallel plunger pumps has a phase deflection angle relative to the plunger pump. In addition, it is assumed that the crank angle of the \( n \)-th parallel plunger pump has a phase deflection angle \( \phi_n \) (counterclockwise) relative to the plunger pump, and the three-cylinder instantaneous discharge flow can be expressed as follows:

Instantaneous discharge flow of the first cylinder \( q_{n1} \) is as follows.

\[
q_{n1} = \begin{cases} 
0 & \text{(}\phi=0: \phi_n) \\
-Ar\omega \sin(\phi+\phi_n) & \text{(}\phi=\pi-\phi_n: 2\pi-\phi_n) 
\end{cases}
\]  

Instantaneous discharge flow of the second cylinder \( q_{n2} \) is as follows:

\[
q_{n2} = \begin{cases} 
0 & \text{(}\phi=\frac{2\pi}{3}-\phi_n: \frac{5\pi}{3}-\phi_n) \\
-Ar\omega \sin(\phi+\phi_n-\frac{2\pi}{3}) & \text{(}\phi=\frac{5\pi}{3}-\phi_n: 2\pi, 0: \frac{2\pi}{3}-\phi_n) 
\end{cases}
\]  

Instantaneous discharge flow of the third cylinder \( q_{n3} \) is as follows.

\[
q_{n3} = \begin{cases} 
0 & \text{(}\phi=0: \frac{\pi}{3}-\phi_n, \frac{4\pi}{3}-\phi_n: 2\pi) \\
-Ar\omega \sin(\phi+\phi_n+\frac{2\pi}{3}) & \text{(}\phi=\frac{\pi}{3}-\phi_n: \frac{4\pi}{3}-\phi_n) 
\end{cases}
\]  

After connecting the multi-plunger pump in parallel, the instantaneous discharge flow of the parallel pump group is formed by the superposition of the instantaneous discharge flow in each plunger pump cylinder.
\[ Q_t = \sum_{i=1}^{n} (q_{i1} + q_{i2} + q_{i3}) \]  

(13)

In the formula, \( Q_t \) is instantaneous discharge flow of \( n \) sets parallel pump, (Unit: \( \text{L/min} \)). \( q_{i1} \), \( q_{i2} \) and \( q_{i3} \) are the \( i \)-th (\( i=1,2,3 \)) instantaneous discharge flow in each cylinder of plunger pump, (Unit: \( \text{L/min} \)).

### 3.2 Operating Characteristics of Parallel Plunger Pump Group

In this paper, four parallel pumps composed of BQW-22/50 high-pressure pumps are taken as the research object, and the parameters of BQW-22/50 high-pressure pumps are introduced into Formulae (10) - (13). Then, the instantaneous discharge flow of the pump group is calculated when the initial phase deflection angle between the adjacent two pumps is \( 0 \sim \pi/4 \), as is shown in Figure 4.

![Instantaneous Discharge Flow Rate of Parallel Pump Set Under Phase Deflection Angle](image)

(a) 0-\( \pi/12 \) phase deflection angle  
(b) \( \pi/9-\pi/4 \) phase deflection angle

Figure 4. 0-\( \pi/4 \) Instantaneous Flow Rate of Parallel Pump Set Under Phase Deflection Angle

From the instantaneous discharge flow curve of the parallel pump group, it can be seen that the flow rate of the pump group after multi-plunger pump is connected in parallel, which is approximately equal to the sum of the flow rates in the plunger pumps. However, due to the periodic flow of single-plunger pump, the flow rate of the parallel pump group also has specific characteristics. Meanwhile, the instantaneous flow rate of the pump group is affected by the phase deflection angle with different regularity. In addition, the flow fluctuation coefficients of the pump group under different phase offset angles are shown in Table 2.

| Phase Deflection Angle | 0     | \( \pi/18 \) | \( \pi/12 \) | \( \pi/9 \) | \( \pi/6 \) | \( \pi/4 \) |
|------------------------|-------|-------------|-------------|-------------|-------------|-------------|
| Maximum/L·min\(^{-1}\) | 93.92 | 92.14       | 89.94       | 91.08       | 90.72       | 89.94       |
| Minimum/L·min\(^{-1}\) | 81.33 | 87.61       | 89.17       | 86.91       | 87.62       | 89.17       |
| Average/L·min\(^{-1}\) | 89.64 | 89.68       | 89.68       | 89.67       | 89.67       | 89.68       |
| Coefficient \( \delta_{q1} \) | 4.77% | 2.74%       | 0.29%       | 1.57%       | 1.17%       | 0.29%       |
| Coefficient \( \delta_{q2} \) | 9.27% | 2.31%       | 0.57%       | 3.08%       | 2.29%       | 0.57%       |

Under different phase angles between plunger pumps, the amplitude and frequency of instantaneous discharge flow in parallel pump groups are different. When the phase deflection angle is 0, the instantaneous discharge flow curve of each plunger pump is consistent, and the flow peak is superimposed synchronously, with the maximum flow fluctuation range of the pump set. Meanwhile, the coefficient \( \delta_{q1} \) and \( \delta_{q2} \) are 4.77 % and 9.27 %. Moreover, when the phase deflection angle is non-zero, the flow curve of the plunger pump is overlapped, and the flow peak is reduced to different degrees. Besides, the flow amplitude is slashed too. What is more, when the phase deviation angle is \( \pi/12 \) or \( \pi/4 \), the peak flow value of the plunger pump is superimposed with the flow trough value of the other plunger.
pump, so the instantaneous discharge flow amplitude of the parallel pump group is the smallest, and the coefficients \( \delta_{q1} \) and \( \delta_{q2} \) are 0.29 \% and 9.27 \%, which are the optimal phase deviation angle between the pumps of the four parallel-plunger pumps.

4. Operation Simulation of Parallel Pump Set Based on AMESim
AMESim software is a software based on the modeling, simulation and dynamic analysis of the hydraulic/mechanical system in bond graphs, which provides users with a rich component library that can be used directly. Meanwhile, the connection between the various components in the system is described in a graphical manner. An interface can transfer multiple variables, which greatly simplifies the modeling process and model scale. In addition, the software has a variety of simulation methods to ensure the accuracy of simulation results, such as steady-state simulation, dynamic simulation, batch simulation, etc.

In this paper, AMESim software is used to respectively establish single operation and four parallel operation models of the BQW-22/50 high-pressure water pump, to simulate and analyze the flow and pressure characteristics of the two models.

4.1 Establishment of Simulation Model
According to the structure of the BQW-22/50 high-pressure water pump, a valve-distributed radial three-piston pump hydraulic system model is established in the AMESim software[10-11], including plunger, crankshaft, connecting rod, inlet valve, outlet valve and other necessary components, as is shown in Figure 5.

![Figure 5. Model of bqw-22/50 high-pressure water pump hydraulic system](image)

After the hydraulic system model is constructed, the physical parameters of each element will be set in the model. Some parameters have been listed in Table 1, and the rest are shown in Table 3.

| Component parameters                  | Unit | Value |
|---------------------------------------|------|-------|
| Plunger stroke                        | mm   | 21    |
| Diameter of inlet valve disc          | mm   | 11    |
| Inlet valve spring stroke             | mm   | 2.8   |
| Diameter of outlet valve disc         | mm   | 9.5   |
| Outlet valve spring stroke            | mm   | 2.5   |
Under the same component parameters, a hydraulic system model with four BQW-22/50 high-pressure water pumps operating in parallel is established, as is shown in Figure 6.

4.2 Simulation of Operating Characteristics in Plunger Pump

4.2.1. Simulation of the operating characteristics of single plunger pump

The runtime of the hydraulic system model in single plunger pump is set to 1 s, and the sampling period is 0.001 s. After the operation is over, the instantaneous discharge flow and pressure curve at the outlet of the plunger pump are drawn, as is shown in Figure 7.

It can be seen from the figure that the instantaneous discharge flow and pressure of the pump increase rapidly after being turned on, which then fluctuate regularly around a certain value. After being stabilized, the flow and pressure curves are sinusoidal, which is consistent with the theoretical analysis results of the aforementioned single plunger pump. After operating stably, the average instantaneous
discharge flow rate is 21.71 L/min, the maximum is 22.08 L/min, and the minimum is 21.30 L/min. The average value of the instantaneous discharge pressure is 49.93 MPa, the maximum value is 51.60 MPa, and the minimum value is 48.03 MPa.

4.2.2. Characteristic simulation of parallel operation in four piston pumps

The phase angles between the pumps in the hydraulic system model of the four parallel pump groups are respectively set to 0, π/18, π/12, π/9, π/6 and π/4, the runtime is set to 1 s, and the sampling period is 0.001 s. After the pump group model turns on and runs, the instantaneous discharge flow and pressure of the pump group increase with time, and then fluctuate regularly around a certain value, which is the same as the operation of single high-pressure pump. Moreover, to compare the operating characteristics of the pump set at different phase deflection angles more intuitively, the simulation data within the operating time of 0.8-1.0 s is intercepted to draw the instantaneous discharge flow and pressure curves at the outlet of the pump set with phase deflection angles of 0, π/12 and π/6, as is shown in Figure 8.

![Simulation results of operating characteristics of 4 bqw-22/50 high-pressure pumps in parallel system](image)

Figure 8. Simulation results of operating characteristics of 4 bqw-22/50 high-pressure pumps in parallel system

It can be seen from the figure that after the operation of the four parallel pump sets is stable, the instantaneous discharge flow and pressure keep changing synchronously, showing a sinusoidal cycle, and the amplitude and frequency change with the phase deviation angle between the pumps. Moreover, the instantaneous discharge flow rate of the four parallel pump sets is about the sum of the flow rates in the four-plunger pumps, which is 85.37-88.25 L/min. Besides, the instantaneous discharge pressure is approximately equal to the rated working pressure of single plunger pump, which is 48.95-52.25 MPa.

To count the maximum, minimum, average, and coefficients of the pump group flow under each phase deflection angle, as shown in Table 4.

| Phase Deflection Angle | 0  | π/18 | π/12 | π/9 | π/6 | π/4 |
|------------------------|----|------|------|-----|-----|-----|
| Maximum                | 88.25 | 88.03 | 87.19 | 87.78 | 87.47 | 87.19 |
| Minimum                | 85.37 | 85.55 | 86.41 | 85.81 | 86.18 | 86.41 |
| Average value          | 86.81 | 86.8 | 86.79 | 86.8 | 86.81 | 86.79 |
| Coefficient δq1        | 1.66% | 1.42% | 0.46% | 1.13% | 0.76% | 0.46% |
| Coefficient δq2        | 1.66% | 1.44% | 0.44% | 1.14% | 0.73% | 0.44% |

The flow coefficients of the four parallel pump groups are affected by the phase deflection angle.
between the pumps. The flow coefficient is the maximum when the phase deflection angle between the pumps is 0, and the flow coefficient is the minimum when the phase deflection angle is $\pi/12$ and $\pi/4$, which is consistent with the foregoing theoretical analysis results. It is proved that there is an optimal phase deflection angle when the parallel pump set is running, so that the flow rate of the pump set can be reduced to a minimum. In addition, when the number of single-pump plungers and the number of parallel high-pressure pumps change, the optimal phase deflection angle between the pumps also changes[12].

5. Conclusions
(1) According to the working principle of the plunger pump that the multiple cylinders alternatively supply liquid, there are specific characteristics in the flow rate of the plunger pump when it is running. Moreover, when designing multiple pumps in parallel to replace high-pressure pumps applied in large-scale mine, it is necessary to consider the influence of flow rate on the operation stability of the pump set.

(2) The instantaneous discharge flow and pressure of the three-piston pump are distributed in a sinusoidal periodic function when the three-piston pump is running, and the flow curve of four piston pumps with the same model in parallel operation is the superposition of multiple wave forms. What is more, the flow curve changes with the phase deviation angle between the pumps, and the analysis results of the plunger pump transmission model are consistent with the simulation results of AMESim software.

(3) When multiple pumps are operated in parallel, there is an optimal phase deflection angle between the pumps, which minimizes the flow of the parallel pump group. Furthermore, according to the comparison between the theoretical model and the numerical simulation analysis, when the four BQW-22/50 high-pressure water pumps operate in parallel, the optimal phase deflection angle between pumps is $\pi/12$ or $\pi/4$.

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