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Accurate Modeling, Operation Laws and Commutation Timing Matching for Concrete Pumping Systems

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Abstract: The pump system is the heart of the concrete pump truck, and its main function is to deliver high-pressure concrete into the pipeline through the reciprocating motion and cooperation of the main cylinder and the distribution valve driven by the swing cylinder. However, there are currently problems, such as unclear pumping operation rules and mismatched commutation timing, that result in poor pumping efficiency and short life of wear parts such as spectacle plates and cutting rings. To address above problems, based on AMEsim software and system test data, this thesis establishes an accurate simulation model of the pump system with more than 90% precision. Based on this model, the simulation reveals the operating rules of the main cylinder and the swing cylinder during the pumping process; draws the commutation timing diagram of the pumping system; clarifies that the commutation timing has four characteristics: sequential, hysteresis, coupling and cyclic; and proposes an optimization scheme for the commutation timing, i.e., reducing the relief pressure of the main cylinder and shortening the swing time of the distribution valve. The proposed optimization has been proven in the market and significantly improved the life of wearing parts by more than 90%. This study provides technical reference for the structure and parameter optimization of concrete pumping systems.

Keywords: concrete pumping system; operation law; commutation timing; erosion wear; pump efficiency

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1. Introduction

The concrete pumping truck is a special kind of construction machinery to realize the rapid transportation and pouring of concrete, widely used in transportation, energy, construction, national defense and other fields [1–3]. The concrete pumping system (CPS) is the core unit of concrete pumping trucks, and its performance directly affects the pumping distance and efficiency of concrete flow [4]. The CPS mainly includes the pumping mechanism and the swing mechanism, which realize the continuous delivery of concrete through the reciprocating action of the pumping cylinder and the swing cylinder. Timing matching refers to the coordination of the action of the pumping cylinder and the swing cylinder, which affects the pumping efficiency, impact vibration and service life of vulnerable parts. The existing CPS still has problems such as the large impact of pumping reversal, poor reliability of pumping operation and low pumping efficiency [5,6].

As concrete is enclosed in pipes and difficult to observe, the combination of simulation and experimentation is an important tool to study the flow and pumping characteristics of concrete [7]. Jiang et al. [8] established a 3D model of a concrete pump truck conveying pipe, simulated the concrete pumping process by a CFD-DEM model and investigated the relationship between structural parameters and pressure loss. Secrieru et al. [9] investigated the changes in concrete properties during pumping and the formation of lubricating material under pressure. Choi et al. [10] studied the effect of the coarse aggregate size on pipe flow of pumped concrete. Wu et al. [11] established a virtual prototyping simulation platform for concrete pump trucks based on ADAMS, AMEsim and MATLAB, analyzed the boom system of the pump truck and obtained system coupling levels. The swing unit is one of the core units of the pumping system. Its main role is to quickly and smoothly drive the oscillation of the distribution valve to match the pumping cylinder to change direction, and its dynamic characteristics directly affect the efficiency, reliability and smoothness of the pumping machinery. Gu et al. [12] and Li et al. [13] established a pumping system simulation model based on AMESim software that can more accurately reflect the changes in accumulator pressure, commutation speed and law and save a lot of test costs. To address system pressure shocks during rapid oscillation, Li et al. [14] analyzed the buffering characteristics of parabolic buffers, and Chen et al. [15,16] optimized the buffering structure of the oscillating cylinder. Shi et al. [17] studied the dynamic characteristics and operating rules of pumping systems. Ye et al. [18] used a double reversing valve with an accumulator to suppress hydraulic shocks of the pumping system. Ding et al. [19] proposed a new structure of a variable-speed direct-drive pumping system, established it mathematical model and simulation model and obtained precise control for the concrete cylinder by active disturbance rejection control. These literatures provide useful references for the study of pumping hydraulic systems.

Concrete pumping is an interesting topic, but traditional studies focus mainly on concrete materials. This study does not deal with concrete materials but focuses on the operating laws and optimization of pumping hydraulic systems. The current research has the following shortcomings: the model of the pumping system is not accurate enough, resulting in a simulation model that does not truly reflect the dynamic characteristics of the actual system; there is a lack of joint analysis of the pumping and swing units; and the commutation timing of the two does not match, which results in serious erosion and wear of wearing parts. This paper establishes an accurate simulation platform based on experiments, and studies the operation law and commutation timing matching to reduce erosion and wear. This paper will provide a reference for the design and optimization of the CPS.

2. Materials and Methods

2.1. Structure and working principle of the CPS

The CPS mainly includes a pumping mechanism and a swing mechanism, as shown in Figures 1 and 2. The pumping mechanism consists of a main pump, a main valve, signal valves, two pumping cylinders and two concrete cylinders.

The swing mechanism consists of a swing pump, two swing valves, two swing cylinders and a distribution valve. The main pump is an electrically proportional controlled variable piston pump with constant power control, and the swing pump is a variable pump with constant pressure control [20,21]. The pump and concrete cylinders are fixed to each other. The two pumping cylinders alternately extend and retract to drive the concrete cylinders to suck and deliver concrete. The swing cylinder drives the distribution valve to swing and connects it to the concrete cylinder that pumps concrete [22]. The signal valves are used to sense the displacement of the pumping cylinders and provide a control signal to reverse the swing cylinder, so the signal valve is the unit that connects the pumping mechanism to the swing mechanism. Through the coordinated action of the pumping mechanism and the swing mechanism, the continuous delivery of high-pressure concrete is realized.

The detailed working principle is as follows. The hydraulic oil from the main pump acts on the nonrod cavity of the pumping cylinder through the main valve, causing the main cylinder to extend. When the piston of the main cylinder passes the upper pressure-detection point, a differential pressure signal is generated in the two chambers of the signal valves, and the signal valve is switched to the working position. The pressure oil from the swing pump then acts on the swing valve to change direction through the signal valve, and then the swing valve simultaneously drives the main valve and the swing cylinder to reverse. When the main valve is switched to the working position, the pumping cylinder is reversed and the concrete cylinder changes from pushing to sucking, completing a pumping work cycle.

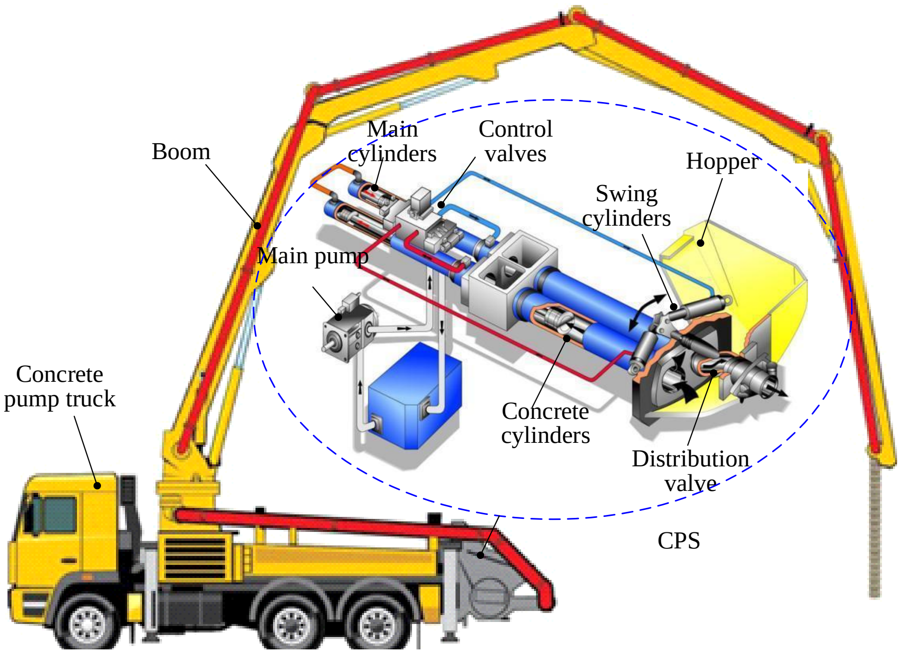

Figure 1. The structure of the CPS.

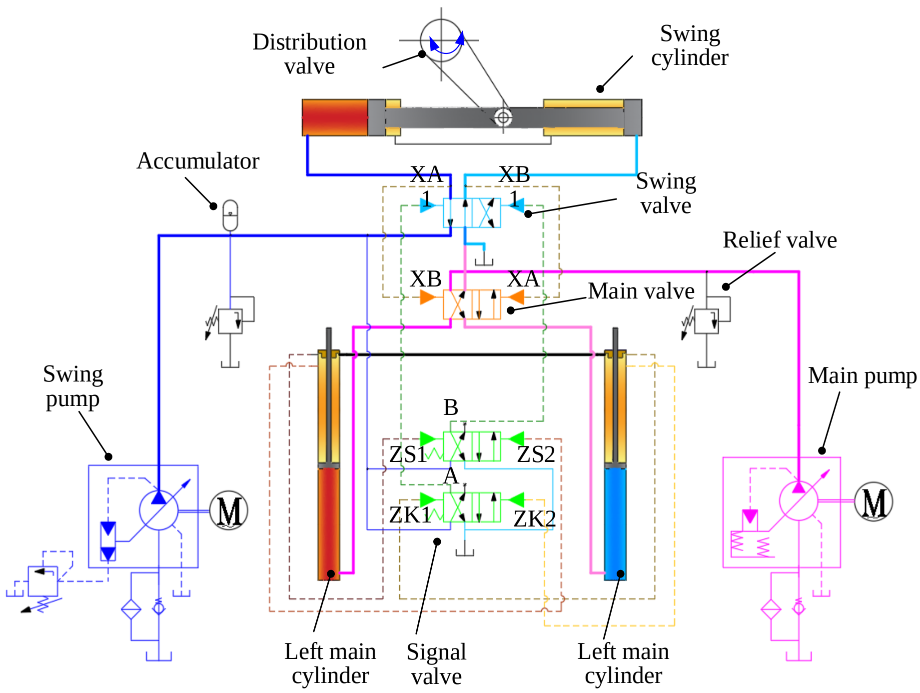

Figure 2. Hydraulic schematic diagram of the CPS.

2.2. Methods

To address the existing problems of the pumping system, the research method shown in Figure 3 is adopted. The process is as follows: establish an accurate simulation model based on the structure of the system and experimental data; use the simulation model to study the operation law of the pumping system and draw the commutation timing diagram; analyze the mechanism of the wear of the spectacle plate and the cutting ring;

put forward the optimization scheme of the commutation timing; and carry out simulation analysis and industrial verification.

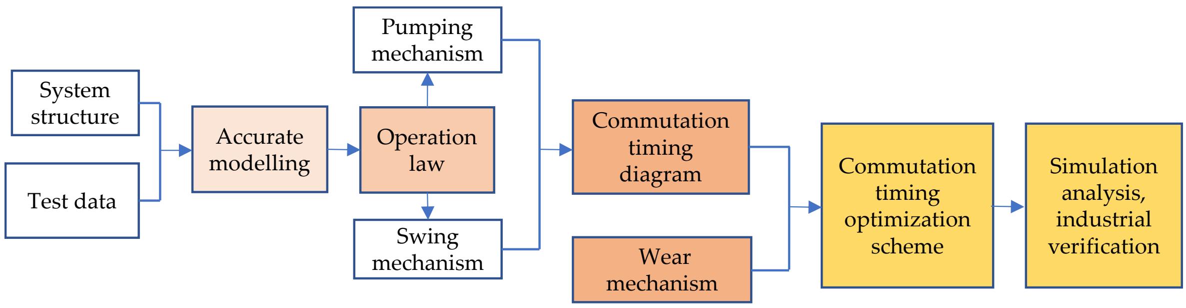

Figure 3. Study flow chart.

2.3. CPS modeling and validation

According to the hydraulic principle of the CPS and the physical structure of the components, the simulation model of the pumping system is built based on the AMESIM platform [23,24], as shown in Figure 4. The simulation parameters of the system are shown in Table 1. The main components of the pumping system are two main pumps with 190 mL/r, a swing pump with 28 mL/r, a main valve, two main cylinders, signal valves, a swing valve, swing cylinders, a damping hole and hydraulic piping.

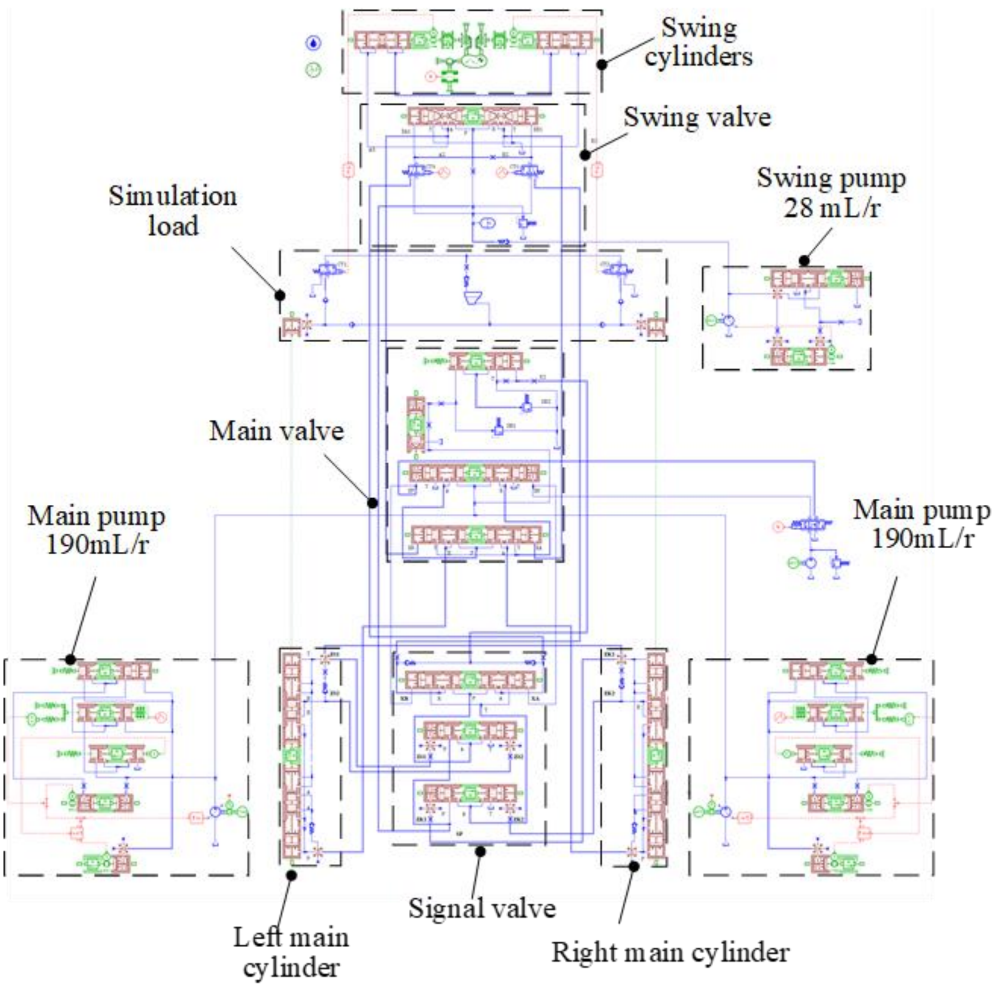

Figure 4. Simulation model of the CPS.

When the pumping system operates, the concrete cylinder sucks and discharges concrete, so high-pressure concrete is the load of the pumping system. In the simulation model, this concrete load is simulated using water passing through the throttle port, and the load model is revised according to the actual tested load. The model of key components and the model of pumping system are verified by experimental data.

Table 1. Simulation parameters of the pumping system.

Component	Parameters
Main cylinder piston/rod/stroke	125/80/2000 mm
Main cylinder effective mass	109.2 kg
Swing cylinder piston/rod/stroke	100/70/179 mm
Swing cylinder effective mass	20 kg
Main pump displacement	190 mL/r
Main pump speed	2200 r/min
Main pump power	120 kW
Cutoff pressure	350 bar
Swing pump displacement	28 mL/r
Swing pump speed	2200 r/min
Setting pressure	85 bar
Main valve diameter/stroke	40/±23.5 mm
Swing valve diameter/stroke	40/48 mm
Signal valve diameter/stroke	4/9.5 mm

Figures 5 and 6 show that the simulation curve and the measured curve have the same change pattern, the same trend and similar values, and the simulation model has a high accuracy of more than 90%, which can reflect the real pumping system. In the next step, the model will be used to study the characteristics of the pumping system to save time and money.

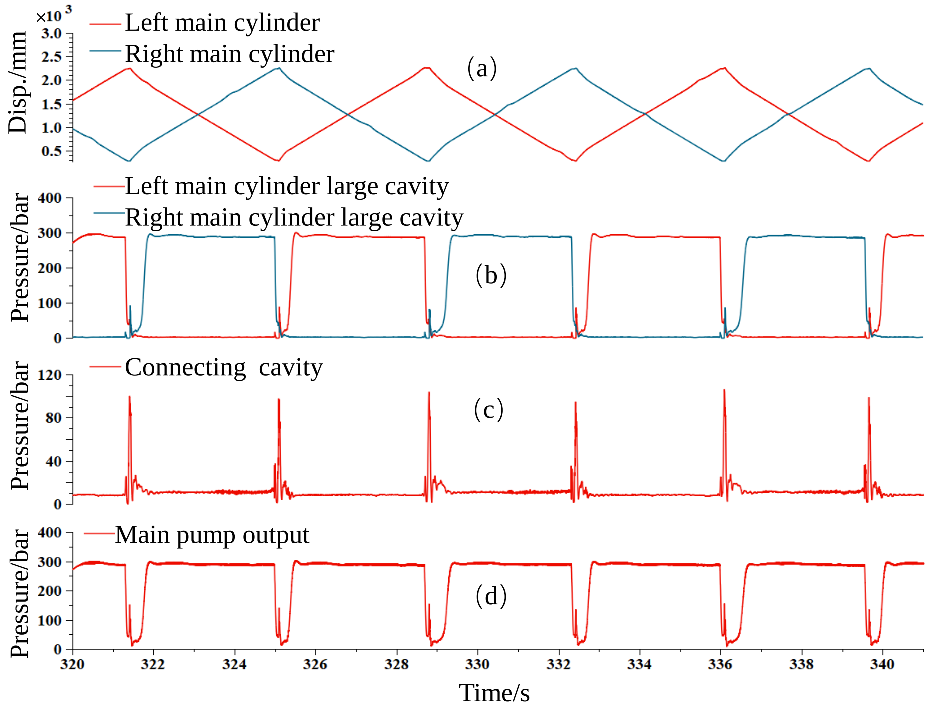

Figure 5. Test curves of the CPS: (**a**) main cylinder displacement, (**b**) large cavity pressure, (**c**) connecting cavity pressure and (**d**) main pump output pressure.

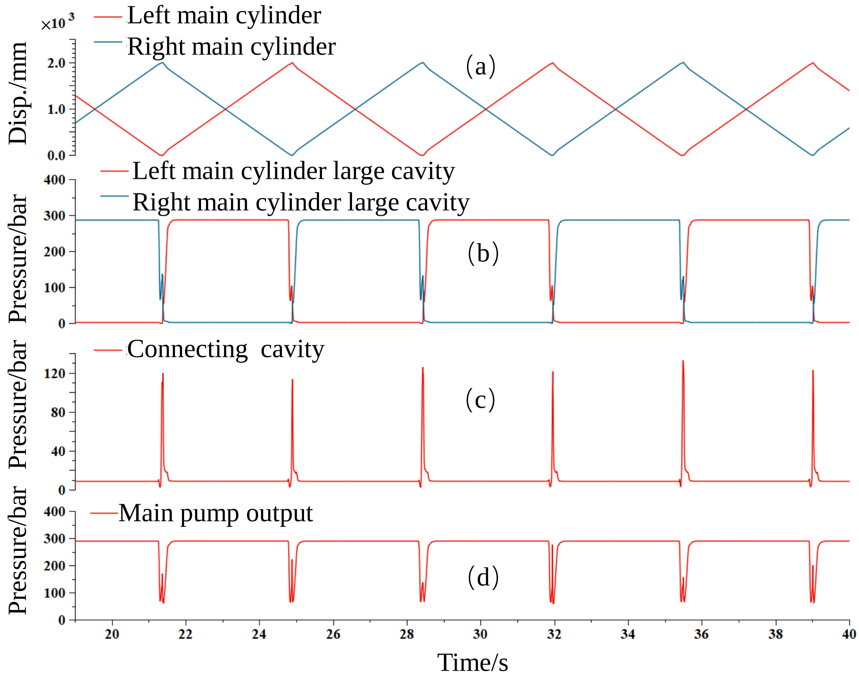

Figure 6. Simulation curves of the CPS: (**a**) main cylinder displacement, (**b**) large cavity pressure, (**c**) connecting cavity pressure and (**d**) main pump output pressure.

3. Results and Discussion

3.1. Operation law of the CPS

3.1.1. Operation law of the pumping mechanism

The movement of the pumping mechanism refers to the reciprocating motion of the left and right main cylinders, which drive the concrete cylinders to suck in and discharge concrete, respectively. Figure 7 shows the pressure curves of the large chambers of the left and right main cylinders and their connecting chambers during the pumping cycle. During the propulsion process, the pressure in the large chamber of the propulsion cylinder (about 288 bar) is much higher than the pressure in the large chamber of the absorption cylinder (about 2.5 bar), and the pressure in the connecting chamber is also very low (about 9 bar). During the main cylinder reversal, the high and low pressures of the two large chambers are exchanged, while the pressure shock in the connecting chamber is larger (about 121–163 bar).

Figure 8 shows the pressure and flow curves of the main pump and relief valve in the pumping cycle. Due to the large load, the main pump works at constant power during the main cylinder advance, the pump pressure is 290 bar and the flow rate is 226 L/min, and the pressure and flow rate of the main pump remain basically the same during the advance. When the main cylinder reverses direction, the relief valve opens and the instantaneous relief flow reaches 960 L/min, at which time the outlet pressure of the main pump drops rapidly and works at the maximum displacement, and its flow reaches 380 L/min.

Figure 9 shows the characteristic of the signal valve in the pumping cycle. After the main cylinder passes the detection point, the control chamber ZK or ZS of the signal valve goes into high pressure, and the signal valve opens rapidly and holds for a period. When the main cylinder changes direction, the signal valve quickly closes. The opening time of the signal valve depends on whether the main cylinder can change direction quickly, but if the signal valve opens and closes quickly, it will be unfavorable for the swing cylinder to change direction.

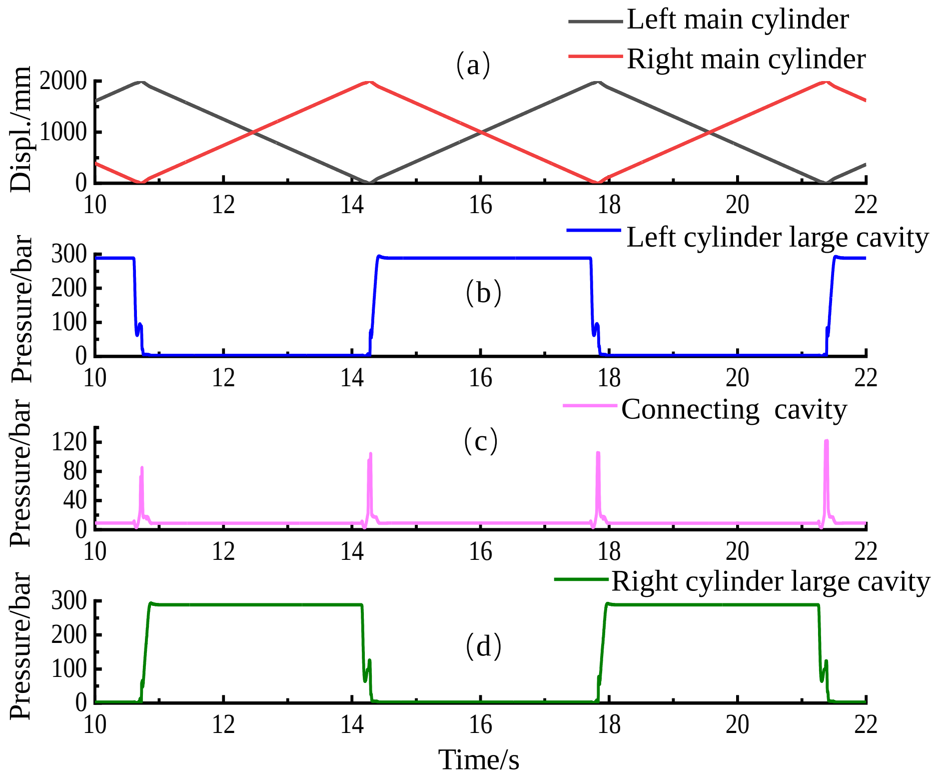

Figure 7. Large cavity pressure of main cylinder and connecting cavity pressure: (**a**) main cylinder displacement, (**b**) left large cavity pressure, (**c**) connecting cavity pressure and (**d**) right larger cavity pressure.

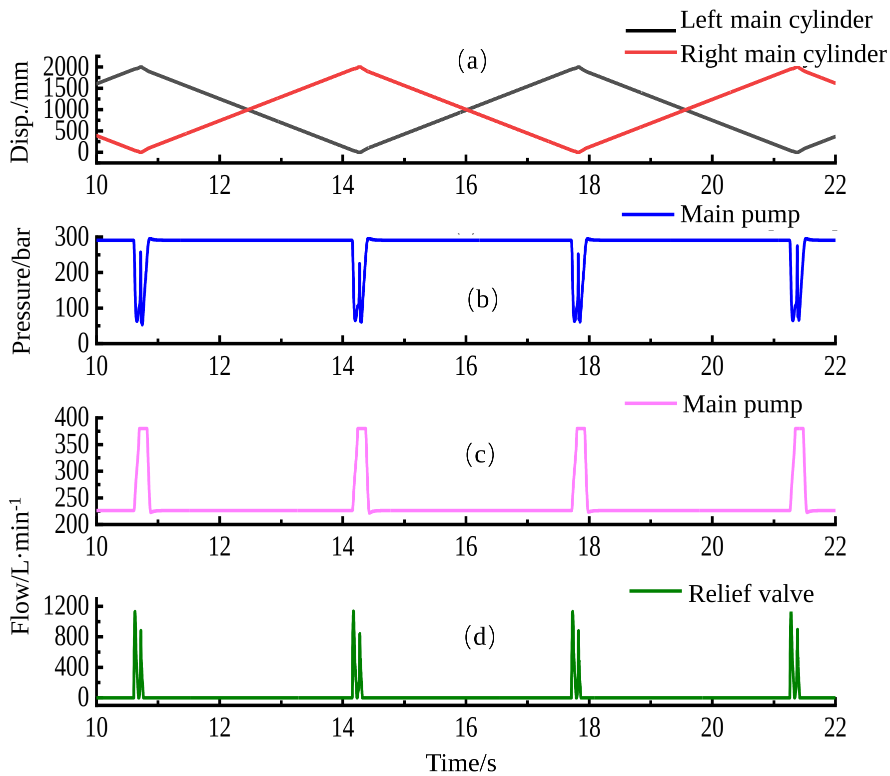

Figure 8. Pressure and flow curves of main pump: (**a**) main cylinder displacement, (**b**) main pump pressure, (**c**) main pump flow rate and (**d**) relief valve flow rate.

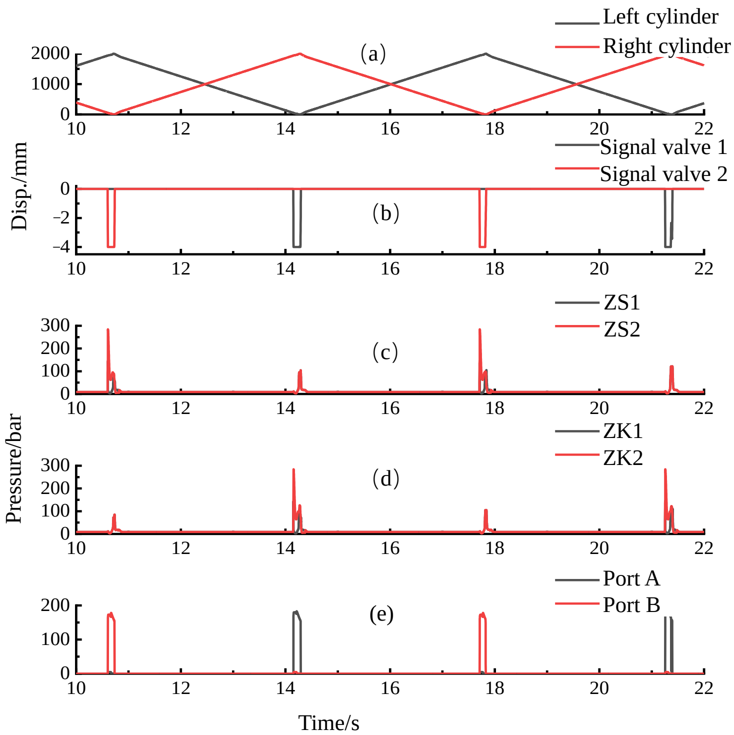

Figure 9. Dynamic characteristic curves of signal valve: (**a**,**b**) main cylinder and signal valve displacement; (**c**,**d**) signal valve control pressure; and (**e**) signal valve output pressure.

Figure 10 shows a graph of the pressure in the two chambers of the main valve during the pumping cycle. The main valve starts to change direction when the piston of the main cylinder passes the detection point. The switching time of the main valve determines the commutation speed of the main cylinder. Here, the switching time of the main valve is about 172 ms and the switching time of the main cylinder is about 120 ms. While the main valve is reversing, the main cylinder is already starting to move in the opposite direction.

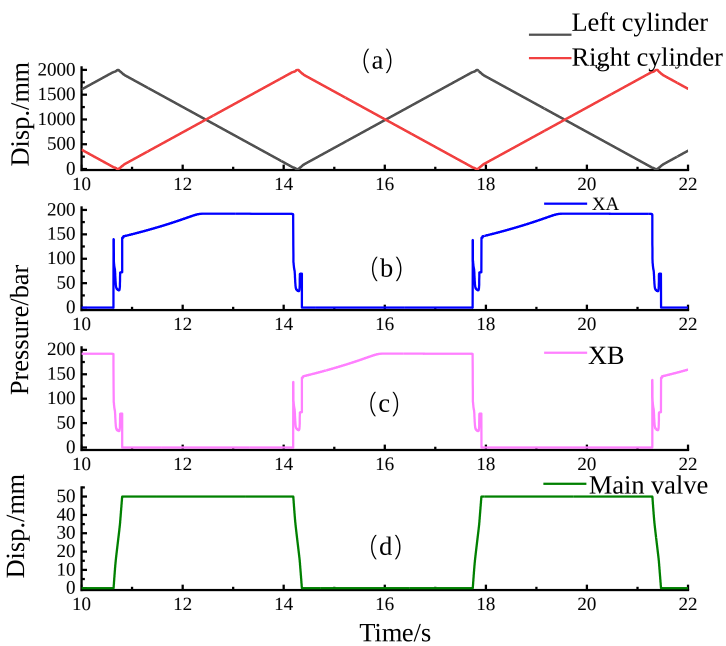

Figure 10. Dynamic characteristic curves of main valve: (**a**) main cylinder displacement; (**b**) and (**c**) main valve control pressure; and (**d**) main valve displacement.

3.1.2. Operation law of swing mechanism

The displacement of the swing valve and the change curve of the pressure of the control chamber in the pumping cycle are shown in Figure 11. The pressure of the two control chambers XA1 and XB1 of the swing valve changes alternately, with high pressure on one side and low pressure on the other side, and the swing valve is driven to change direction by the pressure difference in the control chamber, with a spool displacement of 40 mm and a changeover time of about 80 ms.

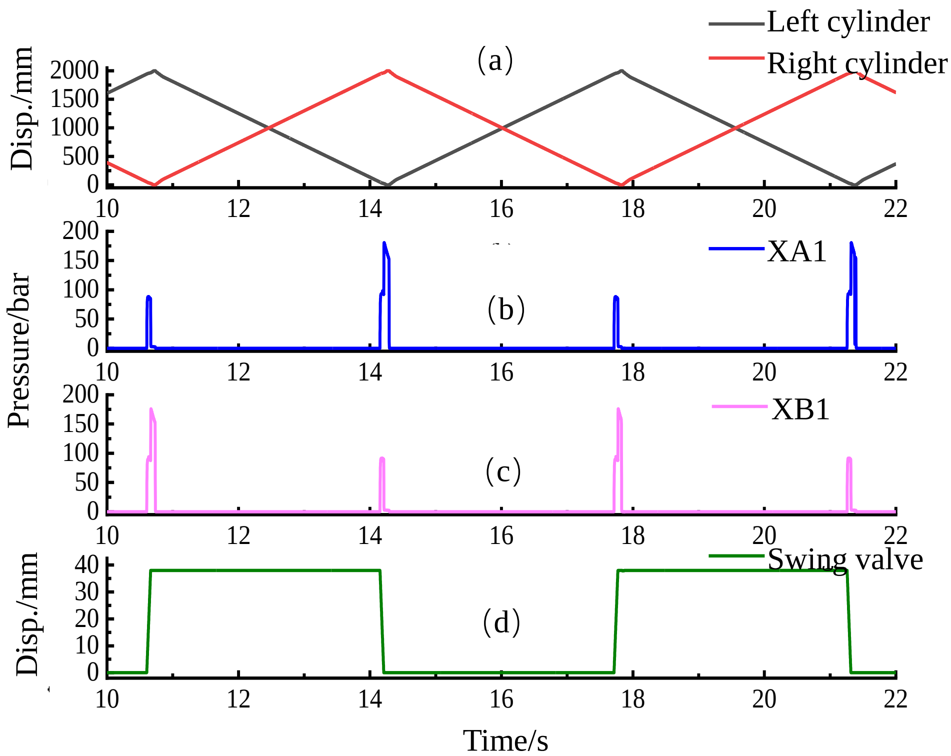

Figure 11. Dynamic characteristic curves of the swing valve: (**a**) main cylinder displacement; (**b**) and (**c**) swing valve control pressure; and (**d**) swing valve displacement.

Figure 12 shows the curves of the stroke of the swing cylinder and the pressure of the left and right buffer chambers. The stroke of the swing cylinder is 197 mm and the commutation time is about 210 ms, of which the buffer time is 60 ms, accounting for 30.9% of the total time. By reducing the buffer time, the reversing time of the swing cylinder can be reduced. When the swing cylinder swings left and right, the pressure of the left and right buffer cavities changes alternately. When the swing is in place, the pressure in the high-pressure chamber is about 190 bar and the pressure in the low-pressure chamber is about 5 bar. At the beginning and end of the swing, there is a pressure shock with a peak of 274 bar. Reducing the buffer time can shorten the changeover time of the swing cylinder.

Figure 13 shows the pressure and flow curves for the swing pump and accumulator. When the swing cylinder is reversed, the pressure of the swing pump drops rapidly and the accumulator is rapidly discharged with a flow rate of 680 L/min, much higher than the flow rate of the swing pump. At the end of the reversal, the swing pump delivers the maximum flow, which is about 55.8 L/min, and the outlet pressure gradually rises, filling the accumulator with liquid. When the pressure rises to 190 bar, charging stops. At this point, the pressure of the oscillating pump is maintained at 190 bar and the flow rate is only 4.7 L/min to replenish the internal leakage of the swing unit. As can be seen, the accumulator provides the main power for the rapid oscillation of the oscillating cylinder, while the main role of the swing pump is to fill the accumulator with liquid.

Therefore, optimizing the parameters of the accumulator can increase the reversal speed of the swinging cylinder.

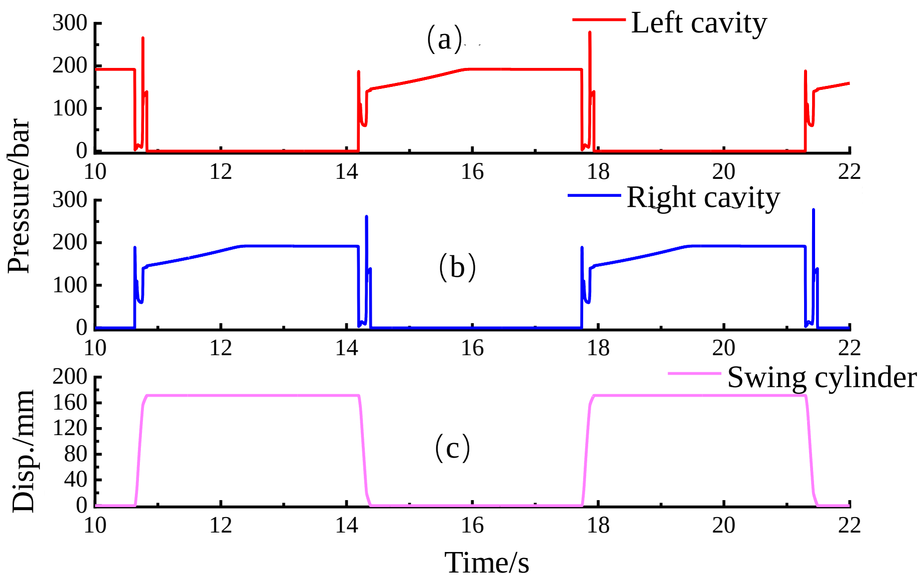

Figure 12. Dynamic curves of swing cylinder: (**a**) left cavity pressure, (**b**) right cavity pressure and (**c**) swing cylinder displacement.

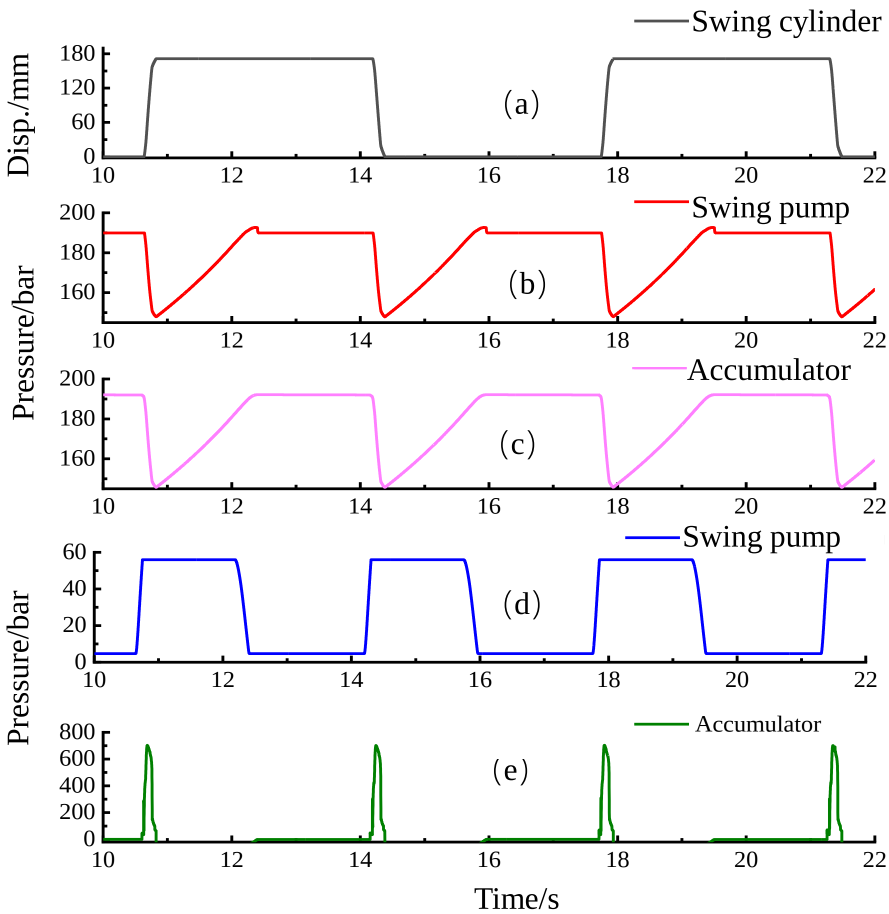

Figure 13. Pressure and flow curves of swing pump and accumulator: (**a**) swing cylinder displacement; (**b**,**c**) swing pump and accumulator pressure; and (**d**,**e**) swing pump and accumulator flow.

3.2. Commutation timing of the CPS

The pumping system achieves continuous pumping through the reciprocating and coordinated action of the pumping and swinging cylinders. It is therefore important to identify the commutation timing of the pumping system in order to achieve high precision and efficiency in pumping.

Figure 14 shows the reversing sequence of the main cylinder, signal valve, swing valve and main valve during the pumping process. The commutation timing of the CPS is characterized as follows:

(1) Sequential, cyclic: The signal valve, swing valve, main valve, swing cylinder and main cylinder are commutated in sequence to form a pumping cycle.

(2) Hysteresis: The main cylinder reversal always lags behind the swing cylinder, which is the inherent characteristic of the hydraulic-controlled pumping system. The timing cannot be changed; we can only change the delay time.

(3) Coupling: The main cylinder reversing and the swing cylinder reversing affect each other; the reversing signal is feedback of each other.

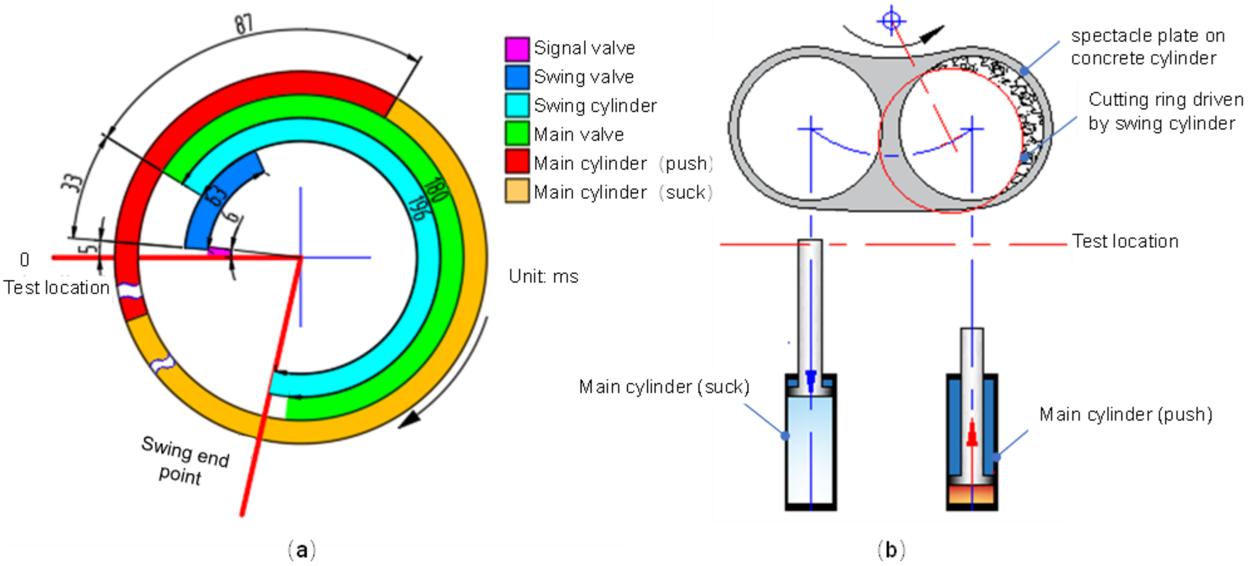

Figure 14. System commutation timing: (**a**) circulation and (**b**) movement.

3.3. Commutation timing optimization

3.3.1. Erosion wear of the CPS

The spectacle plate and cutting ring are key components of the pumping system, with the spectacle plate mounted on the outlet of the concrete cylinder and the cutting ring mounted on the inlet of the distribution valve. When the distributor valve swings, the concrete fluid with high velocity and high pressure flows through the gap between the spectacle plate and cutting ring, causing erosion wear and reducing the life of these components [25–27].

As shown in Figure 15, the mismatch between the commutation timing of the main cylinder and the swing cylinder caused erosion wear on the spectacle plate and cutting ring, resulting in extensive spalling of the metal at the gate, which caused the pumping system to malfunction. Figure 14 also indicates that the erosion wear has a V-shaped trajectory and occurs mainly during the opening and closing phases of the distributor valve, with more severe wear occurring during the closing phase.

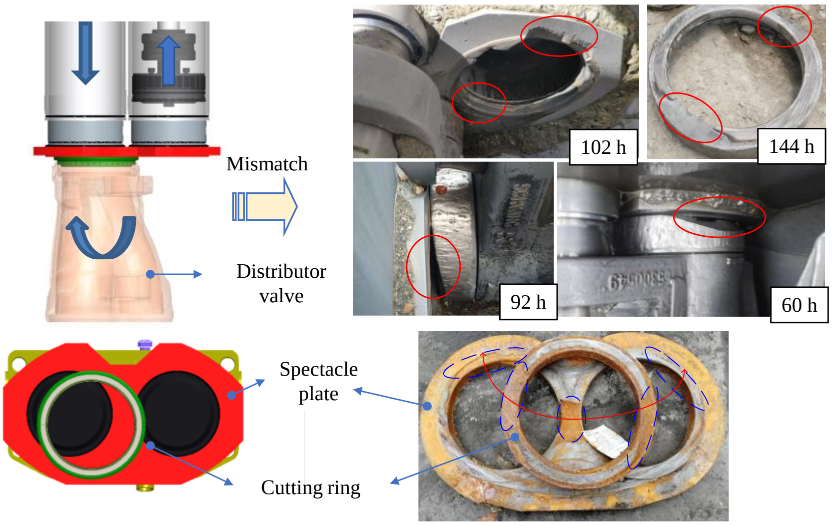

Figure 15. Erosion wear of the CPS.

3.3.2. Optimization scheme of commutation timing

In order to reduce the erosion and wear caused by mismatched reversing timings, the following reversing timing optimization scheme is proposed:

(1) For the main cylinder drive side, reduce the relief pressure once the main cylinder has passed the detection point in order to reduce the shock pressure of the concrete flow and reduce the load on the distribution valve swing.

(2) For the swing cylinder drive side, shorten the swing time, especially the low coasting time during the buffer phase, in order to allow the distributor valve to close quickly.

(3) The more the main cylinder changeover time lags behind the swing cylinder changeover, the less material leakage and the less erosion. Here, the reversing point of the main cylinder is about 2/3 of the swinging reversing interval.

Based on the above optimization suggestions, the specific parameters are shown in Table 2.

The swing time of the distribution valve can be reduced by increasing the volume of the accumulator, increasing the diameter of the valve throttle orifice, increasing the length of the buffer section of the swing cylinder and increasing the diameter of the fast inlet port of the swing cylinder. The relief valve is reduced from 80 bar to 50 bar to reduce the erosion pressure. The parameters before and after optimization are shown in Table 2.

Table 2. Optimization parameters of the CPS.

Parameters	Before Optimization	After Optimization
Acc. volume	10 L	13 L
Acc. charging pressure	100 bar	no change
Swing valve throttle orifice	12 mm	14 mm
Total buffer length	30 mm	no change
Buffer length	15 mm	10 mm
Quick oil inlet hole	6 mm	10 mm
Reversing pressure	80 bar	50 bar

3.3.3. Optimization results

Figure 16 reveals the correspondence between pumping and swing at different stages before and after optimization. There are five stages during pumping:

S1: The swing cylinder (distribution valve) does not move, the spectacle plate and cutting ring overlap, the left main cylinder advances just past the detection side point, pumping high-pressure concrete into the distribution valve, and the right main cylinder sucks concrete from the hopper.

S2: The left main cylinder continues to advance while the distribution valve begins to swing counterclockwise and the faceplate and cutting ring begin to separate.

S3: The main cylinder moves to the end, ready to change direction, and the distributor valve continues to oscillate counterclockwise.

S4: The main cylinder reverses direction, the left main cylinder sucks up the concrete and the right main cylinder pumps the concrete; part of the concrete is pumped into the distributor valve and part of the concrete escapes through the gap between the spectacle plate and the cutting ring into the hopper.

S5: The distribution valve swings into place, the spectacle plate and cutting ring are reunited and the right-hand main cylinder pumps the material normally.

Figures 17 and 18 show the displacement and velocity curves of the main cylinder and swing cylinder before and after optimization. Figures 14 and 15 have a corresponding relationship.

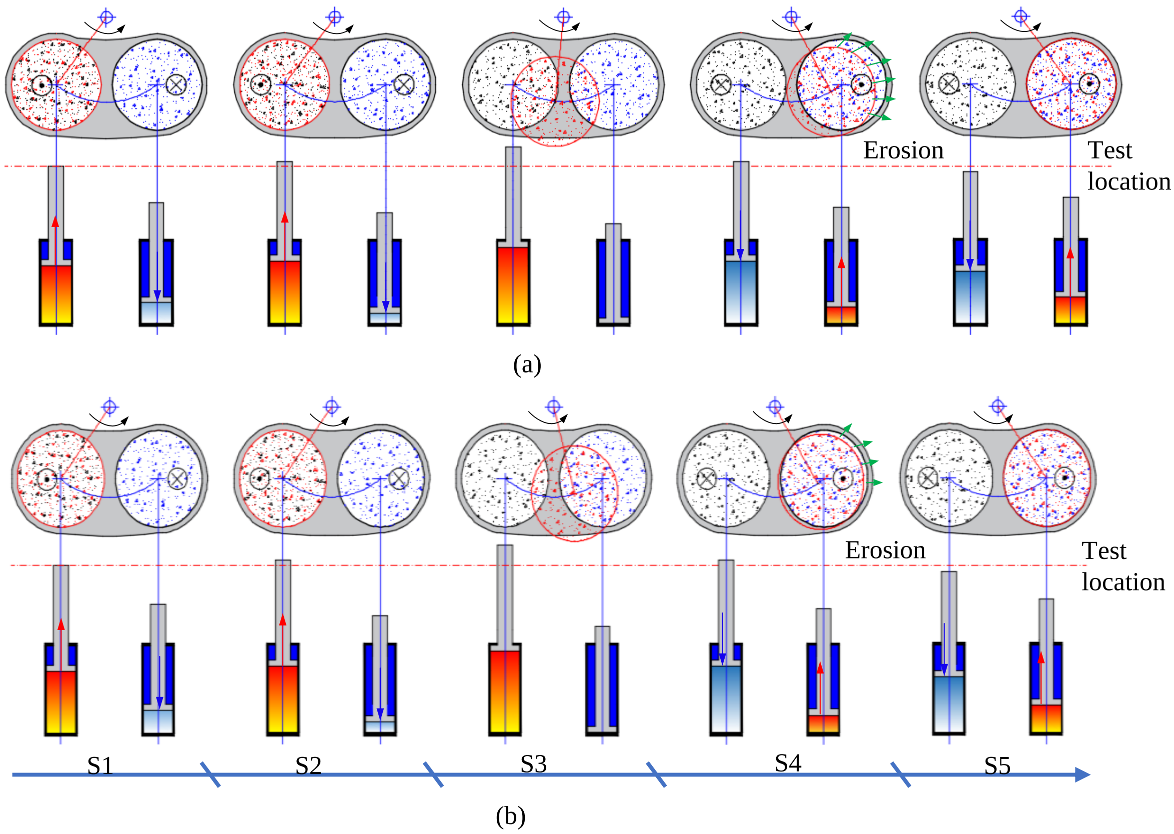

Figure 16. The relationship between pumping and oscillation at different stages: (**a**) before optimization and (**b**) after optimization. (red and orange represent high pressure, dark blue represents medium pressure, light blue represents low pressure, and the arrows represent the direction of motion).

From S2 to S4, the swing cylinder moves at high speed, the distribution valve and main cylinder outlet are separated and then closed and there is a large gap through which the high-pressure concrete leaks into the hopper. The problem with this process is mainly leakage. In fact, there is always leakage during the swing process, so the swing time determines the leakage and system efficiency. Figure 15 shows that after optimization, the swing time is reduced from 196 ms to 155 ms, the main cylinder switching point is delayed from 1/2 to 2/3 of the swing interval and the leakage stroke of the main cylinder is reduced from 128 mm to 69 mm, which effectively improves the pumping efficiency.

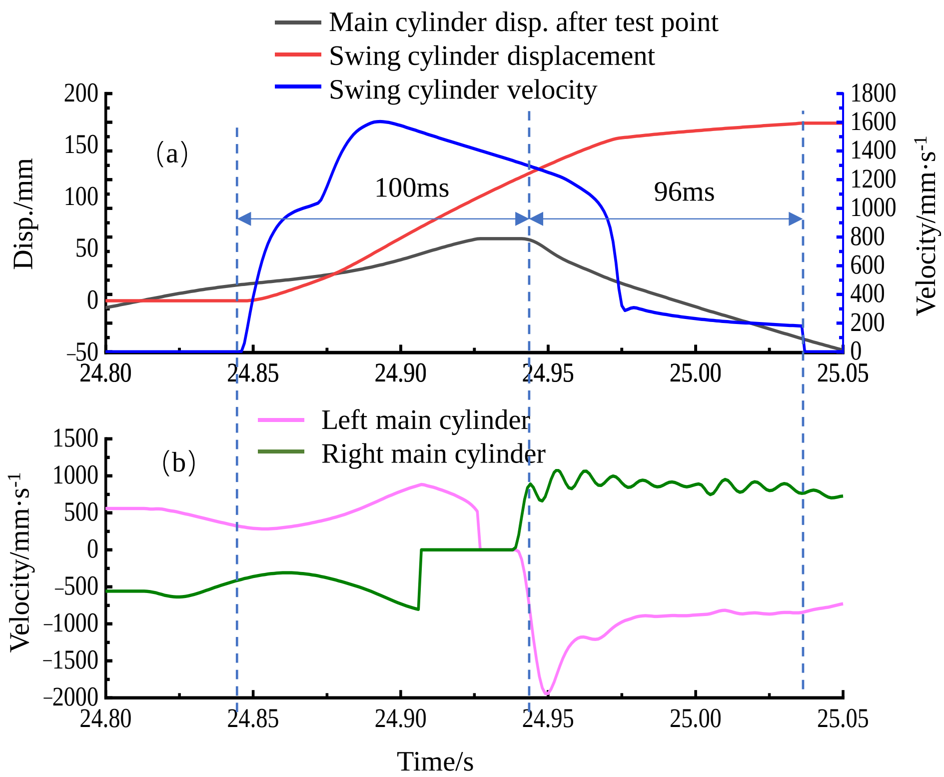

Figure 17. System reversing sequence curves before optimization: (**a**) main cylinder displacement and swing cylinder velocity and (**b**) main cylinder velocity.

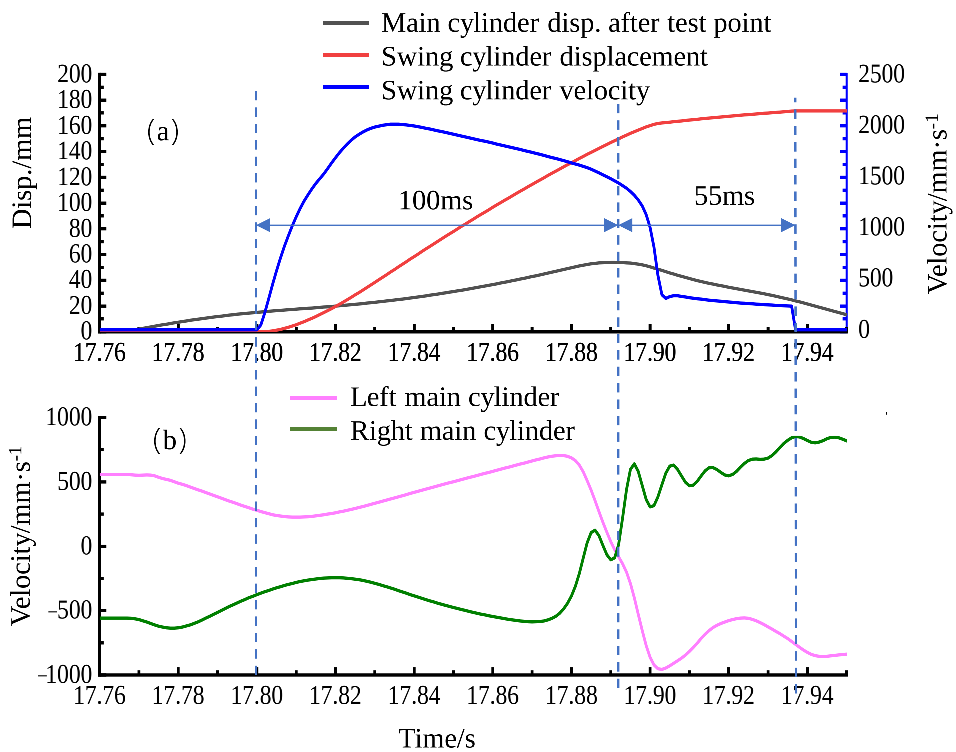

Figure 18. System reversing sequence curves after optimization: (**a**) main cylinder displacement and swing cylinder velocity and (**b**) main cylinder velocity.

From S4 to S5, the swing cylinder slides at low speed and the gap between the face plate and the cutting ring becomes progressively smaller. The high-pressure concrete passes through this gap, causing erosion wear. The slip time at low speed determines the degree of erosion wear. Figure 15 shows that after optimization, the low-speed slip time is reduced from 60 ms to 33 ms, effectively reducing the erosion wear.

The proposed optimization scheme of commutation timing has been proven in the market with a significant increase in the life of wear parts, including a 93% increase in the average life of spectacle plates and a 200% increase in the average life of cutting rings.

4. Conclusions

The pumping system is the core of the concrete pump truck, which delivers high-pressure concrete to the pipeline through the coordinated action of the reciprocating linear motion of the main cylinder and the reciprocating motion of the swing cylinder. The key findings and recommendations are as follows:

(1) This paper establishes an accurate pumping system simulation model. the accuracy is more than 90%, and the simulation model could simulate the actual pumping system. Utilizing this platform could reduce the cost and cycle time of pumping system development.

(2) This study reveals the operation law and inherent characteristics of the pumping system: sequence, hysteresis, coupling and recirculation. There is unsynchronized commutation of the main cylinder and the swing cylinder in the operating process, and the swing cylinder always commutes when the main cylinder advances, which causes shocks and vibrations. The degree of matching of the commutation times determines the pumping efficiency and the life of wear parts.

(3) An optimization scheme for the pumping commutation timing is proposed: reducing the pumping relief pressure of the main cylinder to reduce the swing load, shortening the swing time of the swing cylinder and moving the main cylinder changeover point towards the rear of the commutation interval to reduce erosion wear and the amount of concrete leakage. The solution is market-proven and significantly reduces wear on the cobbler plate and cutting ring and significantly increases pumping efficiency.

Future research will be carried out in the following areas: further optimization of the simulation model to provide model accuracy and optimization of the structure of the pumping system using model simulation instead of experimentation; development of corresponding timing optimization schemes for different pumping systems; and industrial validation.

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