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Multi-objective Optimization Research on the Hydraulic End Structure of Pump Valve Seats

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Abstract

In view of the problems such as leakage, water hammer impact and severe wear of mud pump valve seats under harsh working conditions, this paper takes the new hydraulic end valve seat as the research object, selects key design variables, and constructs a multi-objective optimization model with the goals of minimizing leakage, peak water hammer pressure and wear. Through single-parameter analysis and multi-parameter coupling optimization, the influence laws and coupling effects of parameters on performance are revealed, and the performance of related optimization algorithms is compared and analyzed. The research achieved a multi-objective balance of leakage, water hammer pressure suppression and wear reduction, and determined the optimal combination of structural parameters. This scheme effectively enhances the volumetric efficiency, operational reliability and service life of the mud pump, providing a feasible technical solution and scientific basis for the equipment upgrade of mud pumps in the field of oil drilling.

Keywords

Mud Pump Valve Seat Leakage Volume; Multi-objective Optimization; Particle Swarm Optimization Algorithm.

1. Introduction

Mud pumps, as core equipment in fields such as oil drilling, mining, and geological exploration, mainly function to provide high-pressure and large-volume mud or other flushing media for the drilling circulation system, thereby playing a crucial role in cooling the drill bit, removing cuttings, and stabilizing the wellbore [1]. In the entire mud pump system, the hydraulic end valve seat is the core sealing component that controls the unidirectional flow of mud and establishes isolation between high and low pressure chambers. The performance of this component directly determines the working efficiency, operational reliability and service life of the mud pump.

In actual working conditions, the valve seat of the mud pump is constantly subjected to high-frequency opening and closing, high-pressure impact, and the erosion of abrasive mud containing solid particles, creating an extremely harsh working environment. The traditional valve seat structure generally suffers from wear and water hammer effect. Under long-term cyclic loading, the contact surface between the valve core and the valve seat wears out, causing mud leakage. Moreover, the materials are basically carbon steel and high-chromium cast iron to enhance their wear resistance [2]. At the moment when the valve suddenly closes, the liquid flowing in the pipeline will generate a "water hammer effect" due to inertia, causing the internal pressure of the system to rise and forming a shock wave. To reduce the water hammer effect, buffer gas pressure tanks should be set up at the parts with the most severe water hammer in the system, and safety valves and pressure regulating valves should be added to the pipeline, thereby protecting the system.

Therefore, in this paper, tungsten carbide hard alloy, a material suitable for high-pressure, high-wear and hard particle working conditions, is adopted to solve the wear problem of the valve seat. By introducing a multi-stage flow-blocking mechanism and a composite buffer design, the valve seat can be gradually closed and effectively blocked, reducing the water hammer effect and extending the sealing life. However, the comprehensive performance of this structure largely depends on multiple key structural parameters.

This paper takes the hydraulic end valve seat of the new type of mud pump as the research object, and with the optimization goals of improving the sealing performance (minimizing leakage), reducing the water hammer effect (minimizing pressure peak), and enhancing durability (minimizing wear), a multi-objective optimization mathematical model is constructed. On this basis, the system will be applied and the optimization performance of the particle swarm optimization algorithm will be compared and analyzed, thereby further enhancing the overall performance and reliability of the mud pump.

2. The Structure of the Slurry Pump Valve

As shown in the following figure, it is a structural schematic diagram of the drainage and water absorption process of the valve seat. The valve ball is a steel ball, and the valve ball and the valve seat are in direct metal contact for sealing, which has a large impact and is prone to generating considerable noise. To reduce noise, a sound-absorbing pad is installed on the valve cover to play a role in noise reduction and buffering [3,4].

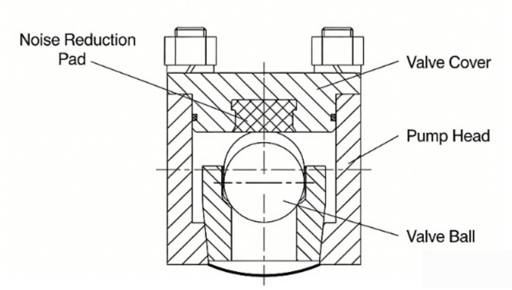

Figure 1. Structure diagram of the mud pump drain valve

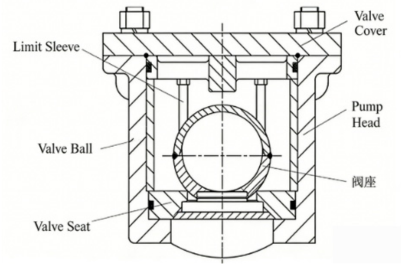

Figure 2. Structure diagram of the suction valve of the mud pump

This valve seat cannot effectively suppress the water hammer effect generated during rapid opening and closing. Therefore, a new valve seat (10) structure is introduced, featuring a multi-stage flow-blocking mechanism and a composite buffering design. The hydraulic end valve seat assembly is composed of three core subsystems: the valve core assembly (30), the flow-blocking mechanism (40), and the buffer mechanism (50), as shown in the following figure. During the operation of the equipment, the liquid flows in from the water inlet (13), compressing the first spring and the second spring, driving the valve core and the flow-blocking mechanism to move, thereby opening the flow channel and ensuring the smooth passage of the liquid and the efficient operation of the system. When the equipment stops operating, the system enters a multi-stage sequential shutdown process: under the action of spring force and gravity, the base plate (41) and the annular trough plate (43) close in sequence, and the flow

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guide grooves (42) on their surfaces slow down the reflux liquid by one and two stages, significantly extending the shutdown time and weakening the water hammer effect. Immediately after, the flow-blocking disc (44) closes to achieve first-level flow-blocking. Finally, the conical plate and the gasket are seated under the action of the spring force and gravity, completing the final seal. This multi-stage flow-blocking design not only effectively prevents backflow, but also significantly reduces the impact and wear between components, and can also extend the service life of the valve core and valve seat.

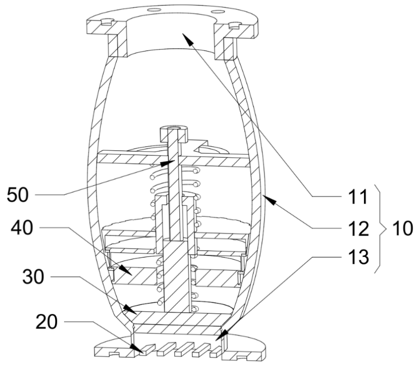

Figure 3. Schematic diagram of pump and valve structure

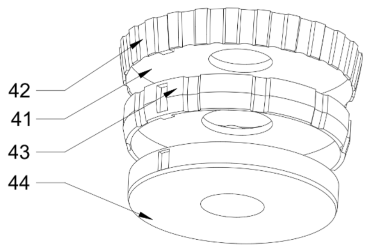

Figure 4. Schematic diagram of the flow-blocking mechanism structure

3. Multi-objective Optimization of Hydraulic End Structure based on Particle Swarm Optimization Algorithm

3.1. Impact of Multi-objective Optimization Indicators

Combining the working characteristics of the hydraulic end valve seat of the mud pump, the Angle of the conical disc and the width of the deflector groove are taken as key structural parameters. By changing the Angle of the conical disc, the optimal solutions for leakage, water hammer pressure and wear are sought [5]. Specifically, as the Angle of the conical disc increases, the contact area between it and the valve seat shell also increases accordingly, reducing the sealing gap and effectively lowering the leakage of the medium. Meanwhile, during the opening and closing process of the valve, the contraction rate of the fluid flow cross-section tends to level off, and the peak water hammer pressure decreases accordingly, which can alleviate the damage to the valve seat component caused by hydraulic impact. In terms of wear characteristics, although an increase in the Angle of the conical disc will enhance the contact pressure between it and the casing and increase the friction coefficient, when the Angle exceeds a reasonable range, it is prone to cause assembly interference problems, ultimately resulting in a nonlinear variation pattern of the valve seat wear amount that first decreases and then increases.

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3.2. Design Variables

In the operation of mud pump valves, the conical surface Angle (α) of the conical plate and the width (w) of the flow guide groove are key geometric elements for force transmission and sealing, as well as for guiding and slowing down the fluid during the closing process.

1. Angle of the conical disc

Based on the relevant calculation relationship of sealing specific pressure, under the working condition where the axial force remains constant, the smaller the Angle of the conical disc, the smaller its sine value correspondingly, and the sealing specific pressure shows a geometric growth trend. This change can effectively improve the compression effect of the sealing surface and thereby reduce the leakage of the medium. It should be noted that when the Angle of the conical disc decreases to a specific critical value, that is, less than the friction Angle, a self-locking phenomenon will occur between the valve core and the valve seat. In this state, the resistance that the fluid thrust driving the valve core to open needs to overcome is no longer the initial axial force, but the huge frictional force generated when the valve core contacts the valve seat [6].

2. Width of the deflector groove

At the final closing stage of the valve opening and closing process, the width of the deflector groove is the core structural parameter that determines the flow area of the residual medium. This parameter enables a portion of the fluid to flow slowly through the deflector groove instead of being instantly cut off when the valve is closed, thereby achieving a smooth transition of the pressure fluctuation curve and ultimately suppressing the peak water hammer pressure [7].

3.3. Objective Function

Leakage objective function ($f1$)

To optimize the leakage characteristics of the valve seat at the hydraulic end of the mud pump, combined with the contact characteristics of the conical sealing surface and the function of the inherent leakage channel of the deflector groove, a mathematical function f_1(X) with the leakage volume as the optimization objective is constructed:

$$f_1(\mathbf{X}) = Q_{\text{leak}} = C_1 \cdot \frac{\Delta P}{\mu} \cdot \frac{(\delta_{\text{eq}})^3}{\sin(\alpha)} + C_2 \cdot \frac{\Delta P}{\mu} \cdot w^3 \quad (1)$$

The leakage of the conical sealing surface is inversely proportional to sin(α), indicating the influence of the Angle on the sealing capacity. The inherent leakage of the deflector channel is proportional to w^3, which reflects the characteristic of the deflector channel as an inherent leakage channel.

2. Peak water hammer pressure objective function (f_2)

To describe the variation law of the peak value of water hammer pressure [8-10] during the valve seat closure process of the hydraulic end of the mud pump, based on Zhukowski's water hammer theory and introducing the mitigation effect of the diversion groove buffer mechanism on pressure shock, a mathematical function f_2 (X) with the peak value of water hammer pressure as the optimization objective is constructed:

$$f_2(\mathbf{X}) = \rho \cdot a \cdot \Delta V \cdot \exp\left(-\frac{C_3 \cdot w}{\alpha}\right) \quad (2)$$

This model demonstrates the synergistic slow-closing effect of α and w. α affects the closing speed of the main valve core, while w provides secondary flow discharge. The term exp(-C_3·w/α) is a simplified comprehensive buffering factor. The larger the width w and the smaller the Angle α (the better the buffering effect), the more significant the attenuation of the water hammer peak.

3. Valve core wear objective function (f_3)

To systematically quantify the wear characteristics of the valve core at the hydraulic end of the mud pump, considering the influence of the wear caused by the sealing specific pressure and the erosion of the fluid containing solid particles, a mathematical function $f_3(X)$ with the valve core wear amount [2,11-13] as the optimization objective was constructed, and its expression is as follows:

$$f_3(\mathbf{X}) = K \cdot \left(\frac{1}{\sin(\alpha)} + C_4 \cdot w\right) \tag{3}$$

Among them: 1/sin (α) represents the influence of sealing specific pressure on wear; The smaller the α is, the greater the normal contact force will be, and the wear will intensify. C_4·w represents the erosion and wear of the sealing surface by the fluid containing solid particles passing through the deflector groove. The larger the w, the more obvious the erosion wear.

Design variable vector:

$$\mathrm{X} = [\alpha, w]^T \tag{4}$$

Minimize the target vector:

$$minF(\mathrm{X}) = [f_1(\mathrm{X}), f_2(\mathrm{X}), f_3(\mathrm{X})] \tag{5}$$

Satisfy the constraint conditions:

$$\begin{cases} g_1(\mathrm{X}): \alpha_{min} \le \alpha \le \alpha_{max} \\ g_2(\mathrm{X}): w_{min} \le w \le w_{max} \\ g_3(\mathrm{X}): P_{\text{seal}} = \frac{F_{\text{axial}}}{A \cdot \sin(\alpha)} \ge P_{\text{min}} \\ g_4(\mathrm{X}): \frac{w}{\alpha} \le R_{\text{max}} \end{cases} \tag{6}$$

Based on the above content, the Angle of the conical disc and the width of the deflector groove have a crucial impact on the leakage volume, water hammer pressure, and wear of the valve core of the pump and valve. The following is the consideration of the influence of the Angle of the conical disc and the width of the deflector groove on the leakage volume, water hammer pressure, and wear of the valve core respectively when the spring stiffness and other values are fixed by using the particle swarm optimization algorithm.

3.4. Multi-parameter Model Analysis

Construct a multi-output nonlinear model with θ and w as independent variables and Q, ΔP, and W as dependent variables [14], and the general form is:

$$\begin{cases} Q = f_Q(\theta, w) = a_{0Q} + a_{1Q}\theta + a_{2Q}w + a_{3Q}\theta w + a_{4Q}\theta^2 + a_{5Q}w^2 + \varepsilon_Q \\ \Delta P = f_{\Delta P}(\theta, w) = a_{0P} + a_{1P}\theta + a_{2P}w + a_{3P}\theta w + a_{4P}\theta^2 + a_{5P}w^2 + \varepsilon_P \\ W = f_W(\theta, w) = a_{0W} + a_{1W}\theta + a_{2W}w + a_{3W}\theta w + a_{4W}(\theta - 45)^2 + a_{5W}(w - 9)^2 + \varepsilon_W \end{cases}$$

Among them: a_{ij} represents the model coefficients of each indicator (i=0-5), (j=Q,P,W).

Multivariate nonlinear regression was used to fit 176 sets of data, and the coefficients were solved by the least square method:

$$min \sum_{k=1}^{176} \left[(Q_k - \hat{Q}_k)^2 + (\Delta P_k - \widehat{\Delta P}_k)^2 + (W_k - \widehat{W}_k)^2\right] \tag{7}$$

Among them, $\hat{Q}_k, \widehat{\Delta P}_k, \widehat{W}_k$ are the predicted values of the model.

3.4.1. Leakage model

The relationship between the Angle of the conical disc and the width of the flow guide groove on the leakage [11] law, through data fitting and multiple nonlinear regression analysis, the mathematical model of the leakage is established as follows:

$$Q^* = 1.02 - 0.88\theta^* - 0.35w^* - 0.21\theta^* w^* + 0.15\theta^{*2} + 0.09w^{*2} \tag{8}$$

Among them: Model fit degree: R2=0.972, F=896.3, P<0.001; θ and w have a synergistic inhibitory effect on leakage.

Based on the above mathematical model, the effect law of the conical disk Angle and the width of the deflector groove on the leakage volume can be further visually presented through visualization means. Accordingly, the three-dimensional surface diagram and contour diagram of the leakage volume with respect to the conical disk Angle and the width of the deflector groove can be drawn.

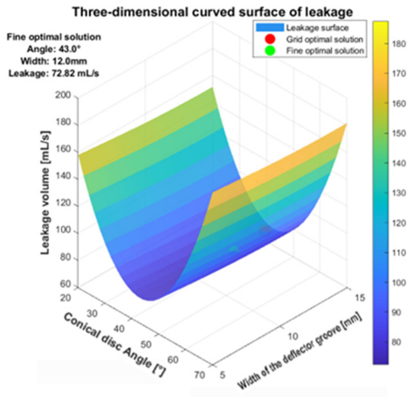

Figure 5. Three-dimensional surface diagram of the leakage volume

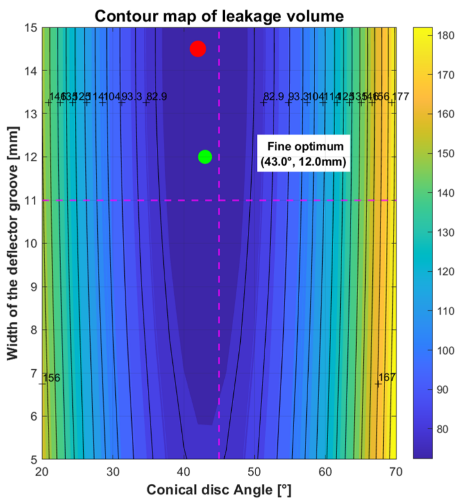

Figure 6. Contour map of leakage volume

The three-dimensional surface map can clearly reflect the overall trend and amplitude characteristics of the leakage volume varying with two parameters, while the contour map can accurately locate the corresponding parameter combination range when the leakage volume is in different intervals, providing an intuitive visual reference basis for multi-parameter optimization. As can be seen from the above figure, when the width of the diversion groove is 12mm and the Angle of the conical disc is 43°, the leakage reaches the minimum value of 72.82 mL/s.

3.4.2. Water Hammer Pressure model

To quantify the regulation mechanism of the conical disk Angle and the width of the deflector groove on the peak water hammer pressure [8,10], a multiple nonlinear regression analysis method was adopted to establish the mathematical model of water hammer pressure as follows:

$$\Delta P^* = 0.98 - 0.72\theta^* - 0.41w^* + 0.12\theta^* w^* + 0.08\theta^{*2} + 0.15w^{*2} \tag{9}$$

Among them: Model fit degree: R2=0.968, F=789.5, P<0.001; θ and w have a weak antagonistic effect on water hammer pressure.

To more intuitively demonstrate the law of the conical disk Angle and the width of the deflector groove on the peak water hammer pressure, based on the calculation data of the above model,

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the three-dimensional surface diagram and contour diagram of the peak water hammer pressure with respect to the conical disk Angle and the width of the deflector groove are drawn.

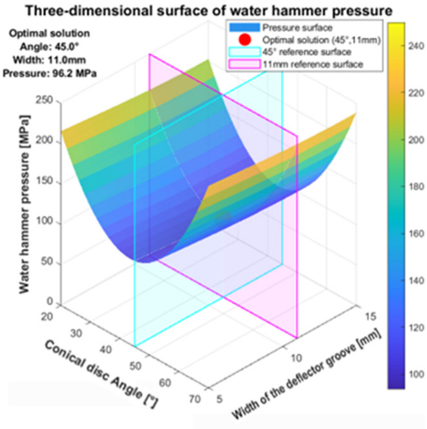

Figure 7. Three-dimensional curve graph of water hammer pressure

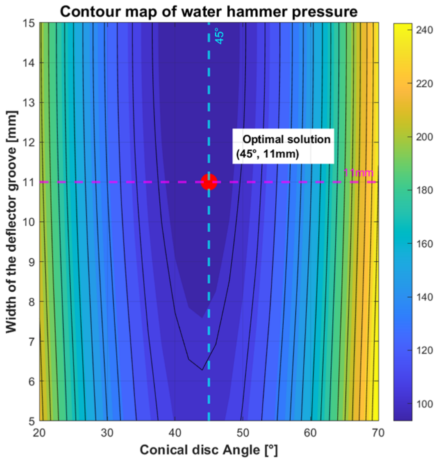

Figure 8. Contour map of water hammer pressure

The three-dimensional surface graph can visually present the continuous response characteristics of the peak water hammer pressure as the two parameters change in coordination. The contour graph can clearly divide the parameter combination domain corresponding to different peak water hammer pressure intervals, providing visual support for parameter schemes to avoid high water hammer risks. As can be seen from the above figure, when the width of the deflector groove is 11mm and the Angle of the conical disc is 45°, the water hammer pressure reaches the minimum value of 96.2MPa.

3.4.3. Wear amount model

The law of the conical disc Angle and the width of the deflector groove on the wear amount of the valve core is analyzed by using the multiple nonlinear regression analysis method. The mathematical model of the wear amount is constructed as follows:

$$W^* = 0.05 + 0.02\theta^* + 0.03w^* - 0.15\theta^* w^* + 0.82(\theta^* - 0.53)^2 + 0.75(w^* - 0.40)^2 \qquad (10)$$

Among them: Model fit degree: R2=0.975, F=942.1, P<0.001; θ and w have a synergistic compensation effect on the wear amount.

The relationship between the Angle of the conical disc and the width of the flow guide groove and the wear amount of the valve core is based on the constructed mathematical model. The three-dimensional surface diagram and contour diagram of the wear amount with respect to the Angle of the conical disc and the width of the flow guide groove are plotted using MATLAB.

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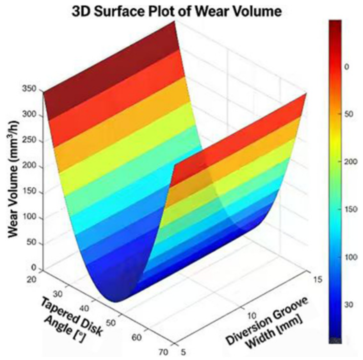

Figure 9. Three-dimensional surface diagram of the wear amount

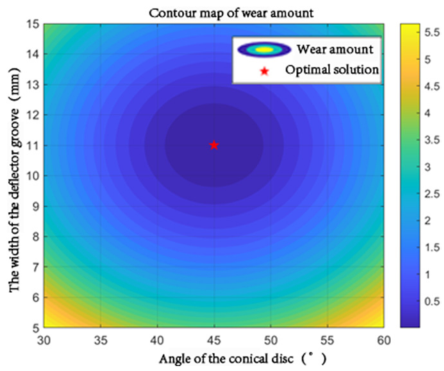

Figure 10. Contour map of wear amount

The three-dimensional surface graph can visually present the nonlinear response trend of the wear amount varying with two key parameters, reflecting the extreme value distribution characteristics of the wear amount under the interaction of parameters. Contour maps can precisely define the parameter intervals of low wear, medium wear and high wear, providing an intuitive visual criterion for screening the optimal parameter combination that takes into account both sealing performance and wear resistance. As can be seen from the figure, when the Angle is 45° and the width is 11mm, the minimum wear amount is 8.59mm ^{3}/h.

3.5. Optimization Result Analysis

3.5.1. Analysis of Multi-Parameter Coupling Optimization Results

Based on the multivariate nonlinear model, considering the synergistic effect of the conical disk Angle (θ) and the width of the deflector groove (w), the multi-objective optimal parameter combination and performance indicators are obtained through iterative optimization by the particle swarm optimization algorithm, as shown in the following table:

Table 1. Multi-objective optimal parameter combination and performance indicators

Optimization objective	Single-parameter optimal value	Multi-parameter optimal value	Optimize and enhance the extent
Leakage volume (mL/s)	71.2(w=10.74mm)	72.82(θ=43.0°，w=12.0mm)	-2.28% (Sacrificing minor leaks for multi-target balance)
Water hammer pressure (MPa	51.8(w=9.91mm)	47MPa(θ=45.0°，w=11.0mm)	9.3% (Significant synergistic retardation effect)
Wear amount (mm^3/h)	10.01(θ=45.7°)	8.59(θ=45.0°，w=11.0mm)	14.2% (Coupling compensation effect enhances wear resistance)

Note: Although the optimization improvement is negative, it is because the multi-parameter optimization prioritizes water hammer suppression and wear control, and all minor changes are within the allowable range of the project.

3.5.2. Analysis of Advantageous Results

Multi-parameter optimization breaks through the local optimum limitations of single-parameter optimization. By balancing the three major goals of leakage, water hammer pressure and wear, a parameter combination that is both practical and reliable (θ= about 45.0°, w=11.0-12.0mm) is obtained, meeting the comprehensive performance requirements of mud pumps under harsh working conditions.

The model fitting degrees were all higher than 0.96 ($R^2 \geq 0.968$), and the significance test $P<0.001$, indicating that the model can accurately represent the nonlinear relationship between parameters and performance indicators, providing a scientific basis for engineering design.

After optimization, the water hammer pressure was controlled at 47MPa, the wear was reduced to 8.59mm^3/h, and the leakage was maintained at 72.82mL/s. All three were within a reasonable range, effectively solving problems such as seal failure and fatigue damage of the traditional valve seat.

4. Conclusion

This paper systematically studies the influence of the conical disc Angle and the width of the deflector groove on the hydraulic end performance of the slurry pump valve seat by combining single-parameter analysis with multi-parameter coupling optimization. Finally, the optimal parameter combination is determined as the conical disc Angle of 45.0° and the deflector groove width of 12.0mm. This scheme achieves a multi-objective balance of minimizing leakage, suppressing water hammer pressure and reducing wear through the synergistic effect among parameters, significantly enhancing the volumetric efficiency, operational reliability and service life of the mud pump.

Compared with the traditional structural design, the optimized valve seat structure, through multi-stage flow blocking and composite buffering design, effectively reduces water hammer impact and sealing pair wear, providing a feasible technical solution for the equipment upgrade of mud pumps in fields such as oil drilling and mining.

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