Optimization Design and Numerical Investigation on Ball Valve of High Pressure Coal Slurry Pump

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Abstract. The charging flow rate fluctuation of the coal slurry pump was caused by the ball valve. In this study, the reconstruction was established to increase the circulation area surrounding the valve ball, the valve limiter was redesigned. The numerical simulation of the structure and performance of the ball valve is carried out with the new limiter structure, getting the flow resistance and the operational parameters. The simulation results showed that the new limiter can effectively eliminate the flow fluctuation caused by the old limiter, the reform was successful to bring huge economic benefits to the plant.

Keywords: High pressure coal slurry pump; Ball valve; Limiter; Numerical simulation.

1. Introduction

High pressure coal slurry pump as an important process equipment is commonly used in various industries such as metallurgical, fertilizer, petrochemical, coal chemical, iron and steel, environmental protection and others [1]. In the process of industrial production, the failure of the ball valve at the inlet and outlet often affects the stable operation of the coal slurry pump, resulting in huge economic losses [2-3]. During the operation of the coal slurry pump, the most critical problem is the flow fluctuation. The excessive flow fluctuation leads to the abnormal ratio of the coal slurry and the oxygen, which may cause the interlock shutdown and the explosion that leads to the major accident loss. In this study, we have analysed the structure and performance of the ball valve at the inlet and outlet of the high pressure coal slurry pump, improved the design of ball valve limiter and completed the flow field simulation of the ball valve at the inlet and outlet of the high-pressure coal slurry pump, and then verified whether it can effectively eliminate the flow fluctuation.

2. Performance Analysis and Structure Improvement of Coal Slurry Pump Ball Valve

2.1. The Characteristic Parameters of Ball Valve

In this study, the pump uses a double ball lift check valve with an inner diameter of 290mm, as shown in Figure 1. The working medium of the coal slurry pump is coal water slurry, with the solid mass fraction of 59%–68%, the density is 1265kg/m³, the maximum operating temperature is 90°C, the maximum particle diameter is 3mm, the pH is 7–9, and the viscosity is 600–3000mPa·s.
2.2. The Performance Parameters of Ball Valve

2.2.1. The Flow Resistance Coefficients. The flow resistance coefficients of the valve are usually expressed by the flow resistance coefficients of the valve, which is dependent on the structure, shape and relevant dimensions of the valve flow passage parts. The fluid resistance is mainly concentrated in the valve seat, valve ball, limiter, ball valve barrel and other parts. To a certain extent, the pressure loss of the valve is equal to the sum of the pressure losses of each part of the valve, that is

$$\zeta = \zeta_1 + \zeta_2 + \zeta_3 + \cdots + \zeta_n \tag{1}$$

Where $\zeta_1$, $\zeta_2$, $\zeta_3$, $\zeta_n$ are the resistance coefficients of each part.

2.2.2. The Discharge Coefficient. Refer to relevant data, and the calculation formula is that

$$K_v = q_v \sqrt{\frac{\rho}{10\Delta p}} \tag{2}$$

Where $q_v$ is valve flow, $\rho$ is the density, and $\Delta p$ is valve pressure drop.

2.3. The Improvement of Ball Valve Limiter

The limiter is used to limit the valve ball’s stay position and lift height when the valve is opened. If the circulation area of the limiter is too small, the circulation capacity will be too small to meet the production demand. The Figure 2 show the structure sketch of a ball valve limiter before and after improvement. It is based on the original limiter, with most of the materials removed, and only four evenly distributed arc surface legs are reserved for limiting. Compared with the original limiter, it greatly increases the flow area and has stronger flow capacity.
2.4. Performance Analysis
The flow resistance coefficient and flow coefficient of the ball valve with the original and the improved new limiter are summarized in Table 1. It can be seen that the flow resistance coefficient of the improved ball valve is smaller and the flow coefficient is larger than that of the improved ball valve, especially when the ball valve is closed. It is proved that the improved limiter is beneficial to eliminate the flow fluctuation, which is consistent with the actual application.

Table 1. Summary of flow resistance coefficient and flow coefficient of ball valve with the original and improved new type limiter.

| Limiter     | Flow resistance coefficient(open) | Discharge coefficient(open) | Flow resistance coefficient(close) | Discharge coefficient(close) |
|-------------|-----------------------------------|------------------------------|-----------------------------------|------------------------------|
| The original| 24.31                             | 3998.7m³/h                  | 9.31                              | 6453.4m³/h                  |
| The improved| 23.91                             | 4002.8m³/h                  | 4.04                              | 9788.9m³/h                  |

3. Numerical Simulation

3.1. CFD Method
Computational fluid dynamics (CFD) which is a new discipline developed on the basis of fluid mechanics and computer science [4-5]. By establishing computer algorithm and combining with the ability of computer fast calculation, the approximate solution of fluid control equation can be obtained. In commercial software of Fluent, the standard $k-\varepsilon$ model has become the main tool in engineering flow field calculation since it was proposed by Lauder and Spalding. This model is widely used in industrial flow field and heat exchange simulation for enormous computing capacity and simple solution [6]. So we choose it to simulate the inner flow field of the ball valve limiter in this paper.

3.2. Boundary Conditions
Before the flow field analysis of the limiter, the fluid inlet and outlet are set as follows: the inlet is below the valve ball, and the outlet is above the valve ball. The fluid flows in through the inlet and out through the outlet. Meanwhile, the inlet pressure is set as 0.22-0.23MPa, the outlet pressure is set as 6.5-6.6MPa and the coal slurry temperature is 45-55°C.

3.3. Simulation Data

3.3.1. Velocity. It can be seen from the Figure 3 that the flow velocity around the valve ball is about 1.69m/s, the maximum flow velocity is about 1.13m/s before the optimization of the model. After the optimization, the flow velocity around the valve ball is about 47.2m/s the maximum flow velocity is about 94.3m/s, the flow velocity of coal slurry is greatly increased, and some large particles of coal...
slurry can be carried away. Before the transformation, the coal slurry flows out from around the valve ball, and after the transformation, it flows out from the top of the valve ball.

![Figure 3](image1.png)

**Figure 3.** The distributions of velocity (left is original and right is after improvement).

3.3.2. **Kinetic Energy.** It can be seen from **Figure 4** that the turbulent kinetic energy of the coal slurry inflow position under the valve ball is about 400K before the model optimization, and the turbulent kinetic energy is reduced to about 300K after the model optimization indicating that the impact on the valve ball is reduced.

![Figure 4](image2.png)

**Figure 4.** The distributions of kinetic energy (left is original and right is after improvement).

3.3.3. **Pressure.** It can be seen from the **Figure 5** that the upper part of the limiter bears the same level of higher pressure, and the maximum pressure is about 6.55MPa. After the model optimization, the pressure in most areas is about 5.92MPa and the high-pressure area is significantly reduced. It indicates that the impact load on the surface of the valve ball is dispersed effectively, it shows that the ball valve can withstand more force.

![Figure 5](image3.png)
Figure 5. The distributions of pressure (left is original and right is after improvement).

Through the optimization design of the limiter structure, the simulation results show that the velocity, the turbulent kinetic energy, the pressure around the valve ball can be reduced, which shows that the impact on the valve ball and the surrounding area is greatly reduced, so as to prolong the service life of the ball valve and improve the flow performance of coal slurry in the valve.

3.4. Experiment

After flow field simulation new limiter was installed in the pump of the laboratory for slurry medium test with the test time of 2h. During the whole test process, the slurry flow and current are stable (as shown in Figure 6, the up three curves from top to bottom respectively represent the slurry flow fluctuation at three monitoring points, and the last curve represents the current fluctuation). It shows that the coal slurry flow is in a stable state without fluctuation, which is in line with the expected results. After stopping the pump when we disassemble and check the one-way valve, there is no residual coal slurry inside it as shown in Figure 7.

Figure 6. Monitor chart of slurry flow and current

The experiment result shows that the new limiter is successful, which can improve the performance of the valve, prolong the service life of the valve and ensure the safety of the operation of the coal slurry pump.

4. Conclusions

At present, the improved new limiter proposed for high-pressure coal slurry pump has been verified in the above, which can effectively eliminate the flow fluctuation of high-pressure coal slurry pump so as to ensure stable operation. However, there are still other problems after the transformation, such as hose rupture, ball valve wear and so on, which will also affect the stable operation of the pump, and further follow-up research is needed to do about it.
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References
[1] Kmar S, Gandhi B K, Mohapatra S K. Performance Characteristics of Centrifugal Slurry Pump with Multi-Sized Particulate Bottom and Fly Ash Mixtures[J]. Particulate Science & Technology, 2014, 32(5):466-476.
[2] WONG G S, GILMAN H H, Davis O E. Development of a High-Pressure, Centrifugal Slurry Pump[J]. Chemical Engineering Progress, 1979, 75(12):58-65.
[3] Sunil C, Singh S N, Seshadri V. Experimental Study of Erosion Wear in a Centrifugal Slurry Pump Using Cori sles Wear Test Rig[J]. Particulate Science & Technology, 2012, 30(2):179-195.
[4] Qingang, Xiong. CFD simulation of biomass thermochemical conversion: Model development, practical application and experimental validation[J]. Renewable Energy, 2020, 147(Pt 1).
[5] Kiran, Ramadan Ahmed, Saeed Salehi. Experiments and CFD modelling for two phase flow in a vertical annulus[J]. Chemical Engineering Research and Design, 2020, 153.
[6] Lan Yu, Lianjie Zhang. Large Finite Element Analyse Software ANSYS[J]. Application of Science and Technology, 2000, (6): 11-15.