Fluid-structure coupling analysis of inlet ball valve on pumped-storage power station under extreme conditions

Chang Liu, Jianzhong Zhou¹, Ran Duan, Ye Liu and Yanxi He

School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

¹ E-mail: jz.zhou@hust.edu.cn

Abstract. While pumped storage power stations (PSPSs) provide clean energy, they are also facing many problems of safe operation. Inlet ball valves bear the brunt of the impact and disturbance from upstream pressure pipeline under extreme conditions on PSPSs. Artificially change the wicket gate and ball valve closing laws can improve the extrems of key indicators. However, the internal flow field in ball valves is complex, and the internal flow field interacts with the external structure. The performance impact studied only by the indicators of the ball valve inlet and outlet is far from enough. In this study, three-dimensional flow field simulation of an inlet ball valve on PSPS was carried out, and the Realizable $k$-$\varepsilon$ turbulence model was selected to simulate the pressure and velocity changes of the flow field inside the ball valve under load rejection conditions. Based on the theory of fluid-structure coupling and CFX dynamic grid, the response characteristics of the ball valve mechanical structure after being subjected to transient flow field were studied, the distribution of related performance parameters of the structure was obtained, and the mechanism that causes stress, strain and total deformation was analyzed. This study found that the ball valve structure is significantly affected by the three-dimensional transient flow of water under extreme conditions of load rejection. The safety of the ball valve can be enhanced by setting expansion joints and strengthening the base.

1. Introduction

As a clean and environmental energy source, hydropower energy has gradually emerged as the main source of energy in some countries and regions. The pumped storage power stations (PSPSs) not only have the functions of hump-modulation, trough-stuffing and stabilization of the power system, but also can further improve the utilization efficiency of hydraulic energy and achieve the effect of energy saving and environmental protection. Ball valves are located at the head of the water inlet of the pumped turbines on PSPSs, which are responsible for cutting off the water flow in the maintenance and hydraulic regulation of the units. When the PSPSs are in extreme conditions such as load rejection and wicket gate refusal to move, the ball valve should be closed in time to prevent water pressure from damaging the pumped turbine. However, the drastic changes in the flow field during the closing process of the moving water cause strong vibrations, accompanied by vortices, water hammer, and cavitation. Studying the influence of the flow field on the ball valve structure under extreme working conditions will help to understand the turbulence evolution mechanism of the fluid more deeply, and can also avoid the operation accident caused by the damage of the mechanical structure.

There have been many studies on the visualization of the flow field during the closing and opening of the ball valve. Tao et al. [1] used dynamic pressure experiment and numerical simulation methods
to study the flow coefficient and pressure distribution of the internal flow field of the V-Sector Ball Valve. Chern et al. [2] used particle tracking flow visualization (PTFV) method to study the flow field performance when the ball valve is closed in the field test state. Cui et al. [3] conducted experiments and numerical simulations on the opening and closing process of the ball valve, and characterized the internal flow field performance by monitoring point pressure changes and flow field distribution. Martins et al. [4] used the Realizable k-ε turbulence model to calculate the water hammer pressure in the pipeline when the ball valve was closed, analyzed the pressure fluctuation changes, and realized the visualization of the flow field in the valve. Saha et al. [5] studied the flow field changes of the compressible liquid in the pressure regulating and shut-off valve, and further analyzed the surface force change of the core under different pressure settings. Qian et al. [6] analyzed the flow characteristics and pressure changes of compressible superheated steam in a pressure reducing valve. This method can intuitively observe the flow field and the change characteristics of related parameters in the ball valve, but there is no further analysis of the mechanism for these changes.

There are some researches on the influence of design parameters and opening-closing methods on the flow field in the valve. Lin et al. [7] studied the influence of the core angle on the internal flow and cavitation in the globe control valve. Qian et al. [8, 9] conducted computational fluid dynamics (CFD) research on the different opening methods of the pilot-control globe valve (PCGV), designed the best displacement characteristic curve of valve core, and further studied the effects of orifice on the internal pressure difference in a PCGV. Moujaes et al. [10] used STAR-CD software to simulate and compare the internal flow field characteristics of flanged ball valves with different Reynolds number fluids.

In addition, there are several studies on the design of novel ball valve structures through flow field calculations. Zhang et al. [11] calculated the percentage characteristic of the V-shaped ball valve through numerical simulation, and optimized the design size of the valve core. Chen et al. [12] designed a special ball valve with ultra-high adjustable ratio based on the Artificial Fish Swarm Algorithm (AFSA), and verified it by CFD.

However, the above studies have analyzed the normal opening-closing process of the ball valve, and there are few studies on the more intense transient process. At the same time, the opening-closing process of the ball valve is a process of interaction between the flow field and the structure, and the deformation of the solid and the transient change of the fluid are indispensable [13]. Therefore, in this paper, commercial software Fluent was used to visualize the flow field of the ball valve in the dynamic water closing process under load rejection conditions, and the finite element analysis (FEA) of the fluid-structure coupling in the ball valve was realized in ANSYS Workbench 17.0.

This study has the following innovations:
1) Using dynamic mesh theory to visualize the fluid in the process of load rejection with ball valve dynamic closure;
2) Calculating the effect of transient flow on the operating performance of the ball valve through transient fluid-structure coupling, and analyze the dynamic response of the structure;
3) The change mechanism of transient flow under extreme conditions was analyzed, and safety measures to improve the structure of the ball valve were proposed.

2. Fluid-structure coupling theory
The fluid medium involved in this study is a general compressible Newtonian fluid, which can be described by the fluid governing equation. The mass conservation equation and momentum conservation equation are as follows:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]  
(1)
\[
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} - \mathbf{t}) = \mathbf{f}_e
\]  
(2)

According to the solid governing equation, the plastic solid conservation equation is derived from Newton’s second law:
\[
\rho_s \mathbf{d}_s = \nabla \mathbf{\sigma}_s + \mathbf{f}_s
\]  
(3)
The governing equations are also applicable to the fluid-structure coupling analysis, which is embodied in the fundamental conservation law of the fluid-structure coupling interface. Among the fluid and solid parameters, the shear stress \( \tau \), displacement \( d \), heat flow \( q \), and temperature \( T \) are all equal or conserved, which is reflected in the basic governing equations of fluid-structure coupling:

\[
\begin{align*}
\tau_f &= \tau_s, \\
d_f &= d_s, \\
q_f &= q_s, \\
T_f &= T_s.
\end{align*}
\]

It is rewritten according to the general form of the control equation, using each parameter matrix as a variable, solved by the given parameters and initial conditions and boundary conditions, and the fluid-structure coupling calculation is performed by a direct solution method. The governing equations of fluid and solid are solved jointly in a unified solver, namely

\[
\begin{bmatrix}
A_f & A_s \\
A_f & A_s
\end{bmatrix}
\begin{bmatrix}
\Delta X_f \\
\Delta X_s
\end{bmatrix} =
\begin{bmatrix}
B_f \\
B_s
\end{bmatrix}
\]

(5)

3. Establishment of fluid-structure two-phase model

The basic parameters of the ball valve are shown in Table 1. Unigraphics NX 12.0 was used to establish the physical model (PM) of the inlet ball valve of the PSPS in China, and the Boolean operation was used to obtain the PM of the ball valve water body. Tiny structures were ignored in the modeling process to improve the efficiency and reliability of simulation calculation. The basic structure diagram is shown in Figure 1. The ball valve structure of the solid phase was mesh in Workbench to obtain the corresponding FEM. The structured grids were adopted for upstream and downstream extensions and middle flanges of the ball valve, while the unstructured grids were adopt for the upstream and downstream valve bodies and ball-trunnion connections. This grid division method can take the accuracy and efficiency of calculation into account. The liquid phase of water body in ball valve was meshed to obtain the FEM in the commercial software ICEM 17.0, and the structured grids adopted for complete water body.

**Table 1. Basic parameters of the ball valve.**

| Parameter                                | Value |
|------------------------------------------|-------|
| Nominal diameter of upstream connecting flange/ \( D_1 \) (mm) | 2100  |
| Nominal diameter of downstream connecting flange/ \( D_2 \) (mm) | 2100  |
| Design pressure of valve body/ \( P_d \) (MPa)          | 8.7   |
| Test pressure of valve body/ \( P_t \) (Mpa)            | 12.5  |
| Ball valve opening and closing time/ \( t \) (s)         | 40-100|

![Figure 1. Establishment of ball valve simulation model.](image-url)
Before the numerical analysis, the grid independence test was carried out. We set up 5 groups of fluid phase grids and solid phase grids, and carried out steady-state analysis. The steady-state analysis was carried out when the spool was rotated for 10s. The inlet pressure on the ball valve and the stress on the inlet flange of the ball valve were compared with different grid densities, the analysis results are shown in the Figure 2.

![Figure 2. Grid independence test: (a) fluid phase grid; (b) solid phase grid.](image)

According to the grid independence test, the final selected mesh model should balance the calculation accuracy and efficiency. The solid phase FEM selected in this study has a total of 2,514,320 meshes, and the mesh quality is above 0.45. The liquid phase FEM has a total of 1,264,883 meshes, and the mesh quality is above 0.5. The two-phase FEM meets the calculation accuracy requirements.

In the solid phase model, the material properties of the parts need to be set. Since the materials involved are all plastic materials, the yield stress can be converted into allowable stress. The material parameters are shown in Table 2.

| Part name             | Yield strength/ MPa | Allowable strength/ MPa |
|-----------------------|---------------------|-------------------------|
| Ball                  | 351                 | 219                     |
| Trunnion              | 379                 | 237                     |
| Upstream valve body   | 380                 | 238                     |
| Downstream valve body | 398                 | 249                     |
| Upstream intermediate flange | 361             | 226                     |
| Downstream intermediate flange | 328         | 205                     |
| Upstream extension flange | 341             | 213                     |
| Downstream extension flange | 390             | 244                     |
| Bearing bush          | 773                 | 483                     |

4. Transient analysis of flow field

4.1. Initial parameter setting

We simulated the transient flow field changes inside the ball valve under load rejection conditions in Fluent. When choosing a turbulence model for transient flow field analysis, the $k$-$\varepsilon$ double equation extended from Euler’s equation was often used to describe the turbulent flow field. The Realizable $k$-$\varepsilon$ turbulence model derives the dissipation rate from the mean square error of the vortex motion, which can more accurately predict the divergence rate of the flat jet, and is well adapted to the rotating flow. Therefore, the Realizable $k$-$\varepsilon$ turbulence model was used to simulate the turbulence analysis of the ball valve when the moving water was closed. The pressure-based solver was selected, and the
second-order upwind discrete format was adopted to obtain higher-precision simulation results. The SIMPLEC algorithm was selected, the sub-relaxation factor was set to 1, and the standard wall function was used near the wall.

To simulate the rotation of the ball in the transient process of the ball valve, the flow field calculation domain used the dynamic grid function in Fluent, and the angular velocity of the ball instantaneous rotation was set by writing user-defined-function (UDF) scripts [14, 15]. In this study, the linear motion shut-off law was selected, the closing time is 62s, which was consistent with the operation in the actual project, and the speed was set to 0.024,54 rad/s. According to the measured of a PSPS in Jiangxi Province, China, the flow rates through the ball valve inlet under the load rejection conditions when the wicket gate refuses to move were calculated through the numerical simulation model of the one-dimensional method of characteristic (1D-MOC), and they were regarded as the boundary condition of three-dimensional CFD [16]. This calculation adopted the boundary conditions of mass-flow-inlet and pressure-outlet, and used UDF script to realize the instantaneous change of parameters. Taking into account the rotation speed of the ball valve, the calculation time step was selected as 0.1s, and each step was iterated 25 times.

Knowing the overflow of the ball valve, we calculated the flow velocity of the upstream extension section of the ball valve, took the upstream extension section velocity and the downstream extension section pressure as known conditions, and compared the upstream section pressure monitored by the sensor when the ball valve is closed. The calculated values of numerical simulation were compared to verify the correctness of the model. As shown in Figure 3, it can be seen that the change trends of the test result and the numerical simulation result are basically the same, and it can be seen that the simulation result has a high degree of credibility.

![Figure 3. Comparison of simulation results and test results.](image)

### 4.2 Fluid analysis results

After iterative calculation, the visualization information of the internal flow field of the ball valve was obtained. Figure 4 depicts the contour of pressure and flow velocity magnitude on the vertical meridian surface of the ball valve. We can see that when the ball valve is just beginning to close, the overall pressure is relatively stable, and only a higher pressure occurs inside the valve cavity between the body and the ball (see Figure 4(a)-4(d)). With the continuous decrease of the opening degree, the water flow from the upstream lashes the wall of the ball, resulting in a greater water hammer pressure, and then the pressure oscillation is reflected back to the upstream, interacting with the upstream flow, and it will easily trigger upstream pipeline vibration. At the same time, because the streamlines enter the ball from the upstream extension section with a larger flow area, the flow area suddenly decreases. Jet-flow is generated on one side of the ball channel and vortex is generated on the other side to form a low-pressure area (see Figure 4(e)-4(h)). After the valve body is further closed, the flow rate reduces rapidly and the internal pressure gradually decreases. However, there are more vortex disturbances at the junction between the ball and the upstream and downstream extensions, downstream extensions and the valve cavity, forming several low-pressure areas, which not only affect stability of the flow.
field, but also damage structure of the ball valve by vibrations and cavitations [16] (see Figure 4(i)-4(l)).

5. Fluid-structure coupling analysis
The parameter distribution of the flow field inside the ball valve obtained by Fluent was regarded as the force acting on the solid phase, which was embodied as the value and distribution field of the stress, strain and deformation of each part of the ball valve. In this study, the CFX module in ANSYS Workbench was used to simulate the fluid-structure coupling of the ball valve, and the overall structure of the ball valve and the frequently switching ball-trunnion part was analyzed.

![Image](attachment:image.png)

**Figure 4.** Contours of pressure and velocity magnitude on ball valve meridian surface: (a) pressure $t=0$s; (b) velocity magnitude $t=0$s; (c) pressure $t=5$s; (d) velocity magnitude $t=5$s; (e) pressure $t=15$s; (f) velocity magnitude $t=15$s; (g) pressure $t=25$s; (h) velocity magnitude $t=25$s; (i) pressure $t=35$s; (j) velocity magnitude $t=35$s; (k) pressure $t=45$s; (l) velocity magnitude $t=45$s.

5.1. Initial condition setting
In ANSYS CFX, the UDF script was used to set the rotation angle of the ball structure to correspond to the rotation of the water body, and the fluid calculation result was applied to the structure model through the loading mode. The effect is shown in Figure 5. The fixed support constraint was imposed on the position of the ball valve pedestal, and the frictionless support constraint was imposed on the connection between the upstream and downstream extension flanges and the upstream and downstream pipelines. After the loading conditions were completed, the transient calculation of the ball valve dynamic closure can be performed to obtain the liquid-solid two-phase action of the ball valve under this condition. To verify the accuracy of the fluid-structure coupling model, the valve body in the full-open state was calculated in steady calculation, and the maximum equivalent stress value was calculated to be 0.8527MPa. According to the single-phase strength calculation report of ball valve based on the field measurement and tests, the equivalent stress in the full-open state is 0.8732MPa, and the relative error of the two-phase coupling experiment is only 2.3%, so the fluid-structure coupling model met the accuracy requirements.

5.2. Fluid-structure coupling analysis results
Since the structure of the ball valve is symmetrical and the load is evenly distributed in the circumferential direction, half of the ball valve was used for the result analysis. The change curve of
the global maximum value of equivalent stress, equivalent strain and total deformation obtained by transient calculation is shown in Figure 6. According to the curve in the Figure 6, the ball valve has a higher stress, strain and deformation before about 25s after it starts to close, and it is in a more dangerous state at this stage. After 25s, with the gradual decrease of the flow rate, the influence of the fluid on the structure gradually decreases, and the stress, strain, and deformation decrease rapidly. The stress and strain values have extremum values at 5s and 20s, while the total deformation values have extrems at 5s and 15s. Therefore, we selected 0s, 5s, 15s and 20s as the key points to further research the structure simulation of the ball valve.

![Figure 5](image5.png)  
**Figure 5.** Application diagram of fluid-solid coupling boundary conditions of ball valve.

![Figure 6](image6.png)  
**Figure 6.** Variation curve of the global maximum value of parameters.

Figures 7 shows the stress contours of the overall structure of the ball valve and valve shell at key points. At 0s, the overall stress level is low, the stress distribution is uniform, and the higher stress is distributed at the valve cavity between the valve and the shell. The connecting part of the shell and the trunnion is affected by the jet-flow from the upstream middle section, and the circumfluence is generated at the trunnion part, which eventually forms a higher stress (see Figure 7(a)-7(b)). At 5s, and 15s, the maximum values are distributed at the pedestal of the valve body, where it is fixedly connected to the base plate. When the flow passes through, due to the unbalanced fluid pressure distribution along the vertical direction and the pipeline direction, it will herein produce squeeze and twist (see Figure 7(c)-7(f)). At 20s, the maximum equivalent stress appears at the connection of the foundation plate, which value is 8.0435 MP, but it is much smaller than the yield stress of the material at this position, namely 380 MPa (see Figure 7(g)-7(h)), which indicates that the strength of the ball valve meets the requirements during the dynamic water closing process.

The separately analyses of the equivalent stress contours of the ball-trunnion structure, which are added multiple probes at 20s, and analyzed the maximum value distribution, are shown in Figure 8. According to the stress contours of the ball-trunnion structure, the larger value of stress is located near the valve body on both sides of the trunnion except for the full-open state, which is generally ring-shaped or crescent-shaped. It reaches the maximum at 20s, which is 1.6842 MPa. The impact force, and the greater shear stress are generated at this location. The maximum stress is much smaller than the yield stress of the valve material, but the stress concentration may cause fatigue damage to the surface material.
Figure 7. Equivalent stress contours of the ball valve: (a) general assembly t=0s; (b) shell t=0s; (c) general assembly t=5s; (d) shell t=5s; (e) general assembly t=15s; (f) shell t=15s; (g) general assembly t=20s; (h) shell t=20s.

Figure 9 depicts the equivalent strain contours of the half of the ball valve cut apart by the meridian surface. We can know that the stress and strain results are similar, and the maximum value still exists at an angle of 70°, which is a dimensionless unit value of 4.127e-5 (see Figure 9(d)). It should be noted that in the overall process of load rejection, the larger stress and strain on the downstream pipeline of the ball valve are not at the jet-flow position behind the ball, but the impact force of the fluid accumulates to the pedestal and is transmitted to the downstream. Expansion joints should be set between the downstream body and downstream pipelines, which can effectively compensate for the axial, lateral and angular force deformation of the absorption pipeline, while absorbing equipment vibration and reducing the impact of equipment vibration on the pipeline.
Figure 8. Equivalent stress contours of ball-trunnion part: (a) t=0s; (b) t=5s; (c) t=15s; (d) t=20s.

Figure 9. Equivalent strain contours of half of the ball valve: (a) t=0s; (b) t=5s; (c) t=15s; (d) t=20s.

6. Conclusions
Based on the flow field simulation and the fluid-structure coupling analysis of the ball valve on PSPS, the interaction between the liquid and solid phases under extreme conditions was studied, and the key indicators of the ball valve dynamic water closing strength were calculated. In the process of load rejection and dynamic water closing, the overall equivalent stress reaches its maximum value at 20s. It is located at the pedestal and is less than the allowable stress of the upstream valve body, indicating that the overall structure of the ball valve meets safety requirements. The ball-trunnion part meets the strength requirements, but frequent rotation at this position may cause fatigue damage; In the working state of the ball valve, that is, full-open state, the main cause of stress is the drastic current size change at the seal ring, which is susceptible to trigger upstream and downstream pressure fluctuations, and even self-excited vibration. Through the study of the ball valve dynamic water closing process under load rejections, this paper further clarifies the influence of the ball valve structure on the flow field movement, and obtains the vulnerable parts through analysis, which has certain reference value for the ball valve design and safe operation.

Nomenclatures

| Symbol | Description |
|--------|-------------|
| $A_{ff}$ | Single system matrix of the flow field |
| $A_{fs}$, $A_{sf}$ | Two-phase matrix of fluid-structure coupling |
| $A_{ss}$ | Single system matrix of the solid region |
| $B_f$ | External force of the flow field |
| $B_s$ | External force of the solid region |
| $\mathbf{d}$ | Displacement |
| $\ddot{\mathbf{d}}_s$ | Local acceleration of the solid region |
| $\mathbf{f}_f$ | Volume force vector |
| $f_s$ | Volume force |
| $k$ | Number of iterations |
| $q$ | Heat flow |
| $\rho$ | Density |
| $\sigma$ | Cauchy stress |
| $\tau$ | Shear stress |
| $\nu$ | Flow velocity |
| $\nabla$ | Vector differential operator |
Acknowledgement
This work was supported by the National Key R&D Program of China (Grant No. 2016YFC0402205 & Grant No.2016YFC0401910).

References
[1] J Tao, et al. 2020 An Experimental and Numerical Study of Regulating Performance and Flow Loss in a V-Port Ball Valve Journal of Fluids Engineering 2 142
[2] M Chern, C Wang and C Ma 2007 Performance test and flow visualization of ball valve Experimental Thermal and Fluid Science 6 31
[3] B Cui, et al. 2017 Influence of opening and closing process of ball valve on external performance and internal flow characteristics Experimental Thermal and Fluid Science 80
[4] Martins N, et al. 2016 CFD modeling of transient flow in pressurized pipes Computers and Fluids 126
[5] Saha B, et al. 2014 Dynamic simulation of a pressure regulating and shut-off valve Computers & Fluids 101
[6] Qian J, et al. 2017 Flow rate analysis of compressible superheated steam through pressure reducing valves Energy 135
[7] Lin Z, et al. 2015 Effect of Cone Angle on the Hydraulic Characteristics of Globe Control Valve Chinese Journal of Mechanical Engineering 3 28
[8] Qian J, et al. 2014 CFD analysis on the dynamic flow characteristics of the pilot-control globe valve Energy Conversion and Management 87
[9] Qian J, et al. 2016 Effects of orifice on pressure difference in pilot-control globe valve by experimental and numerical methods International Journal of Hydrogen Energy 41 41
[10] Moujaes S and R Jagan 2008 3D CFD Predictions and Experimental Comparisons of Pressure Drop in a Ball Valve at Different Partial Openings in Turbulent Flow Journal of Energy Engineering 1 134
[11] Zhang H, G Wang and Q Zhao 2017 Design Optimization of V-sector Ball Valve Core IOP Conference Series: Earth and Environmental Science 3 267
[12] Chen S, H Xu and Z Zhao 2021 Modeling and optimization of novel ball valve with high adjustable ratio International Journal of Pressure Vessels and Piping 190
[13] Wang D, Bai C and Mao Y 2018 Study on fluid-solid coupling dynamic characteristics of dump flooding pipeline under different openings of ball valves Chinese Journal of Applied Mechanics 1 35
[14] Srikanth C and C Bhasker 2009 Flow analysis in valve with moving grids through CFD techniques Advances in Engineering Software 3 40
[15] Z Zou, F Wang and L Wang 2018 Study on unsteady flow field of butterfly valve in startup process of pressure-driven water diversion system in pumping station Chinese Journal of water conservancy 6 49
[16] Wen F, Y Cheng and W Meng 2018 Dynamic hydraulic characteristics of a prototype ball valve during closing process analysed by 3D CFD method IOP Conference Series Earth and Environmental Science 1 163