Design and Analysis about Top Entry Structure of Manual Ball Valve for Nuclear Power Stations

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Abstract. The structure features and working principle of top entry manually ball valve for nuclear power stations were introduced. The contact between the ball and stem, as well as the contact between regulating rod and seat were considered, and stress analysis was conducted to the two pairs of components mentioned using finite element software Ansys. The analysis results show that the key parts of the ball valve are reliable under the design conditions, can meet the design requirements of the ball valve and have good practical value in practice.

1. Overview
Ball valves are widely used in petroleum and natural gas pipelines, as well as oil production, refining, petrochemical, chemical, chemical fiber, metallurgy, electric power, nuclear power, food and papermaking equipment.

Due to the particularity of environmental conditions and system operation conditions, the common ball valve for nuclear power stations requires a high performance. Using top entry structure, it is not necessary to remove the ball valve from the line when servicing or replacing the seat, so it is easy to inspect and maintain the ball valve. In general, the top entry structure adjusts the seat position with a wedge or threaded seat on the outside [1]. However, the peripheral wedge will increase the external leakage point and reduce the sealing reliability, while the threaded seat will be easily killed in the large diameter valve and the service life will be shortened. In view of the above situations, a reliable top entry structure of manual ball valve is designed in this paper.

2. Structural design
In this paper, the top entry manually ball valve adopts fixed structure. It has the characteristics of small open and close torque, small valve seat deformation, seating stable performance, as well as long service life, and mainly consists of valve body, ball, seat, regulating rod, upper stem, lower stem and bonnet, as shown in FIG.1. The inlet and outlet nominal diameter of ball valve is DN150mm. The design pressure is 5.0MPa and the design temperature is 180℃. The valve ball is made of a whole ball structure and is processed into a straight channel. The ball is connected to the upper and lower stem, and the valve can be opened and closed by rotating the axis perpendicular to the valve channel. The upper stem and the ball have a connection plate, and the connecting plate is fixed by connecting pins and balls. A disc spring is arranged on the back of the seat to provide pretension. The valve body has four holes in it. After the regulating rod is placed in the four holes, it can be adjusted by adjusting the regulating rod to the valve seat. The schematic diagram of the regulating rod and the valve seat is...
shown in FIG. 2. The valve ball can be easily loaded or removed when the cylindrical surface of the rod is adjusted to the valve seat surface.

1. Valve body 2. Lower valve stem 3. Valve ball 4. Valve seat 5. Connection plate 6. Regulating rod 7. Upper valve stem 8. Valve bonnet 9. Limit block 10. Handle

FIG 1. Schematic diagram of the top entry manually ball valve for nuclear power stations

1. Regulating rod 2. Valve seat 3. Valve body

FIG 2. Schematic diagram of the regulating rod and the valve seat

The valve seat is made of a v-shaped outer circle, which is designed to be inclined with the contact part of the regulating rod, reducing the pressure on the regulating rod and the valve seat contact surface to increase the service life effect. In addition, the design of the v-shaped outer circle makes it easy to remove the valve seat from the valve body when the valve seat is removed.

3. Material selection
The main body material of top entry manually ball valve for nuclear power stations is stainless steel, mostly valve body, ball, valve seat, valve stem, valve bonnet and other parts adopt austenitic stainless steel material, and the regulating rod or is under the pressure rating of the valve stem material, choose high strength of 17-4PH or FXM stainless steel, the sealing material using PEEK and soft sealing material, such as polymer polyethylene.

The design temperature of the ball valve is 180℃. For conservative estimates, the material properties at 200℃ are chosen in the calculation analysis and evaluation process. The material properties for main components of the ball valve at 200℃ are shown in table 1.
Table 1. Property parameters of each metal part [2] [3]

| Part name     | Material | Elasticity modulus (MPa) | Density (kg/m³) | Poisson's ratio | Tensile strength Su(MPa) | Yield strength Sy(MPa) |
|---------------|----------|--------------------------|------------------|-----------------|--------------------------|-----------------------|
| Ball          | 316L     | 1.84E5                   | 7980             | 0.29            | 429                      | 121                   |
| Valve seat    | F316L    | 1.84E5                   | 7980             | 0.29            | 429                      | 121                   |
| Regulating rod| 630      | 1.84E5                   | 7780             | 0.29            | 907                      | 680                   |
| Valve stem    | 630      | 1.84E5                   | 7780             | 0.29            | 907                      | 680                   |

4. Design calculation

4.1. Ball calculation
The maximum pressure edge of the ball is on the inner diameter of the seat channel in contact with the sphere when the ball is closed.

If the spherical surface of the cavity part of the seat is considered as a flat disk with uniform load, and simple conservative calculation was carried out on the ball, the ball of the maximum stress should be followed:

\[ S_q = 3 \times P \times d_1^2 \times \left( \frac{3}{\mu} + 1 \right) / \left( \frac{32}{\mu} \times t^2 \right)^{[4]} \]  

Thereinto:

\( S_q \) — The maximum stress (MPa) of the ball, should be less than the stress intensity of the ball material;
\( P \) — Medium pressure (MPa);
\( d_1 \) — Valve seat inner diameter (mm);
\( \mu \) — Poisson's ratio;
\( t \) — The average wall thickness of the ball in the valve seat inner diameter (mm).

4.2. Regulating rod calculation
When the ball is installed or taken out, the regulating rod will be subjected to torque. If the torque is too large, the regulating rod will not withstand and fracture, and finally the ball will not be removed. Therefore, it is necessary to calculate the torsional stress of the minimum cross section of the regulating rod:

\[ \tau = \frac{T}{W} \]  

Thereinto:

\( \tau \) — The torsional stress (MPa) subjected to the minimum cross section of the regulating rod, should be less than the maximum allowable stress of the regulating rod material;
\( T \) — Torque (N•mm) for the regulating rod;
\( W \) — The torsional cross section coefficient, for hexagonal section, \( W = 0.5413R^3 / 2 \), \( R \) is the radius of circumscribed circle of hexagon.
5. Finite element analysis

5.1. Finite element analysis of the ball
The ball valve is a fixed ball valve. The ball rotates freely along the axis of rotation, and is restricted in the direction of the flow channel. When the ball valve is closed, the force of the fluid acting on the sphere is transmitted to the bearing, it won't make the ball move to the valve seat, so the valve seat will not bear too much pressure, while the ball will bear the pressure of the prevave fluid. Therefore, the stress analysis of the ball valve seal pair is mainly to investigate the strength and deformation of the ball. In the closed state, the ball is affected by the pressure of the medium, and the thin wall of the ball is prone to deformation. When the deformation exceeds 0.0001DN, the sealing performance of the ball valve will be affected.

The ball of the ball valve is discretized using three-dimensional solid element solid187. In the finite element model, the model includes 132034 elements and 187658 nodes. The finite element model of the ball is shown in FIG.3.

FIG 3. Finite element model of the ball

The ball material is 316L stainless steel and the maximum allowable stress of the material is 114Mpa. After setting the parameters of the ball valve model in Ansys, constraints are imposed on the model. Using contact analysis technique in Ansys, the contact area between the ball and the stem is fixed by friction. The ball and the valve stem are contacted by establishing the Targe170 and Conta174 contacts to simulate the friction between the ball and stem. After applying the pressure of the fluid medium at one end of the ball, the computational model is calculated, and the stress distribution contour and deformation contour of the ball are shown in Fig.4.

In the stress distribution contour of the ball, the stress is mainly concentrated in the contact part of the ball and the stem. The maximum equivalent stress is 39.16Mpa, which is far below the maximum allowable stress 114Mpa of the ball. In the deformation contour of the ball, the deformation amount is mainly generated at the pressure end of the ball, and the maximum deformation is 0.0136mm, less than 0.0001DN=0.0001*150=0.015mm. To sum up, the design of the ball meets the design requirements.
5.2. Finite element analysis of regulating rod and seat

During the design process, the strength of the regulating rod must be considered. If the pretension force is too large, the regulating rod can’t bear the greater torque and may lead to fracture, which cause the ball cannot be removed. The finite element model of the regulating rod and seat consists of 180654 elements and 242165 nodes. The finite element model of the regulating rod and seat is shown in FIG.5.

For regulating rod and valve seat for the analysis of finite element mesh model, also adopts the Ansys contact analysis of the technology, regulating rod and the valve seat by establishing Targe170 and Conta174 contact between the method of processing, simulation of the regulating rod and the valve seat. The material of the regulating rod is 17-4PH martensitic stainless steel (630) and the maximum allowable tensile stress is 276Mpa. After setting the parameters of the model material in Ansys, the constraint is applied to the model. In the body of the rod, a preload is applied on the back of the valve body and a torque is applied to the regulating rod. After the calculation, it is necessary to apply 50N·m torque to the regulating rod to overcome the pretension to adjust the seat position. After applying all the loads, the calculation model is calculated, and the stress and deformation contour of the regulating rod are obtained, as shown in FIG. 6.
a) Stress contour of the regulating rod b) Deformation contour of the regulating rod

FIG 6. Stress and deformation contour of the regulating rod

In the stress distribution contour, the stress mainly concentrated in the regulating rod and the seat contact area, the maximum equivalent stress is 379.54Mpa, due to the particularity of the regulating rod structure, the stress concentration will not affect the performance of regulating rod and can be neglected, and the intensity of regulating rod hexagonal side can directly affect the regulating rod to work properly, so only need to consider the hexagonal side strength. In the stress distribution contour, the maximum equivalent stress of the hexagonal end is 230.36Mpa, which is less than the maximum allowable stress 276Mpa of the regulating rod. In the deformation cloud diagram, the deformation quantity is mainly concentrated on the regulating rod hexagonal end, and the maximum deformation is 0.107mm. To sum up, the design of the regulating rod meets the design requirements.

6. Conclusion
1) By setting the contact and coordination of the regulating rod and the seat, it provides a high reliability and good performance top entry structure for the ball valve;
2) The contact stress analysis of the ball valve ball and the stem of the manual ball valve of nuclear power is analyzed, and the analysis results show that the stress and deformation of the ball are less than the allowable value and meet the design requirements;
3) Analysis of the contact stress of the manual type ball valve regulating rod and seat for nuclear power, and the results show that the stress and deformation of the regulating rod are less than the allowable value and meet the design requirements;
4) Provide reliable reference basis for the manufacture of top entry ball valves, and the experience of nuclear power operation in several years proves that it has good practical value in practice.

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