Study of volute cutwater diameter on the structural strength of pump rotor

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Abstract. Based on the Workbench platform, temperature and pressure loads are applied to the rotor system (impeller, pump shaft and impeller nut) in high temperature hot water circulating pump when the medium temperature is 150 °C. The corresponding boundary conditions are defined, and steady-state thermal analysis and static analysis are carried out. The temperature distribution, the equivalent stress and the total deformation of the rotor system is discussed in detail when the volute cutwater diameter is 214mm, 216mm and 218mm. The results show that the deformation of impeller, pump shaft and impeller nut has the maximum value when cutwater diameter is 216mm. With the increasing of cutwater diameter, the minimum temperature and maximum equivalent stress of the impeller decreases gradually. There is an obvious stress concentration in the shaft shoulder which is from bearing fitting section to the maximum shaft diameter.

1. Introduction

High temperature hot water circulating pump is applied in metallurgy, petrifaction, power and other industries during the transmission of high temperature and high pressure medium. The reliability of the long-term operation of the equipment plays a crucial role in the industry-related processes. Compared with the conventional circulating pump, temperature of the medium is high, thus the stability of the rotor will be inevitably affected. As a result, the reliability of high temperature hot water circulating pump poor will be affected[1].

Therefore, the study of the solid structure strength is necessary. But for the pump flow components, the analysis of the stress and deformation is limited to normal temperature and pressure situation. Yang Wang[2] took a one-way fluid-solid coupling method to accurately calculate the stress distribution and deformation of the welding impeller in the flow field. The results show that the impeller has the largest deformation under small flow rate condition. What is more, the deformation decreases first and then increases with the increase of the flow rate. Ruofu Xiao [3] analyzed the stress characteristics and deformation of the hydro turbine blade. He found that the deformation was the important factor of causing difference between the single and the two-way coupling calculation. Nowadays, with the development of computer, structural mechanics, hydrodynamics and numerical heat transfer, the study of heat-fluid-solid coupling problems [4] in the field of high temperature pump has been conducted. FanYu Kong[5, 6] conducted the stress strain analysis of the pump body and impeller on the basis of heat-fluid coupling and fluid-solid coupling methods. The deformation of the solid structure and the stress distribution were obtained and the structural strength of the pump is checked. Liang Dong[7] compared the stress distribution characteristics of structure in two different temperature and pressure conditions during the one-way fluid-solid coupling calculation. The stable
temperature field of the center gear and planet gear is established by FanYu Kong\cite{8} which is based on the heat transform theory.

For high temperature hot water circulation pump, the geometric parameters of the hydraulic model are numerous and the internal flow field distribution of different volute cutwater diameter has been widely studied\cite{9, 10}. But the effect of different volute diameter on the rotor structure strength is little studied. Based on the previous studies, this paper focuses on the influence of the volute cutwater diameter on the rotor strength under different temperature conditions.

2. Research model

In this paper, the design flow rate is $Q = 23.6\text{m}^3/\text{h}$, the head and rotational speed is $H =14\text{m}$ and $n = 1450\text{r} / \text{min}$. The medium is $150\, ^\circ\text{C}$ hot water, the physical parameters are saturated water vapor pressure $p = 476.24\text{kPa}$, the density $\rho = 917\text{kg} / \text{m}^3$, the specific heat capacity $c = 4312\text{J} / (\text{kg} \cdot ^\circ\text{C})$, the thermal conductivity $\alpha = 68.38\, \text{W} / (\text{m} \cdot ^\circ\text{C})$, kinematic viscosity $\mu = 18.63 \times 10^{-5}\text{Pa} \cdot \text{s}$. This impeller is a closed impeller with 5 blades, and its diameter is $209\text{mm}$. The related properties of rotor system material are shown in table 1.

| Components               | Impeller | Nuts       | Pump shaft |
|--------------------------|----------|------------|------------|
| Material                 | QT400-18 | OCr18Ni12Mo2Ti | 35CrMo       |
| Poisson's ratio           | 0.274    | 0.27       | 0.286      |
| Young's modulus (GPa)     | 161      | 193        | 213        |
| Density (kg/m$^3$)        | 7.01×10$^3$ | 8×10$^3$ | 7.87×10$^3$ |
| Thermal expansion coefficient | 1.29×10$^{-5}$ | 1.60×10$^{-5}$ | 1.25×10$^{-5}$ |
| Specific heat capacity (J/(kg-k)) | 5.10×10$^2$ | 5.0×10$^2$ | 4.6×10$^2$ |
| Thermal conductivity (W/(m-k)) | 47       | 16.3       | 44         |

3. Numerical simulation methods

Figure 1. Schematic diagram.
This paper focuses on the structural strength of the rotor system when the volute cutwater diameter is 214mm, 216mm, and 218mm. The rotor parts and fluid domain were modeled by Pro/E software. The flow field was meshed by ICEM, and the flow field inside the pump was simulated by CFX. For steady-state thermal analysis and static analysis, the Mesh module of ANSYS15.0 Workbench is used to divide the mesh.

The internal flow field was calculated by ANSYS CFX15.0. In order to ensure the reliability of numerical calculation, it is necessary to manually establish the physical parameters when the medium temperature is 150 °C in CFX. At the time of calculation, the velocity inlet and the pressure outlet are used, and the RNG k-ε turbulence model is selected. The non-slip boundary is applied to the solid wall, the grid association is GGI. It is necessary to establish the physical properties of the material in the Engineering Data under the Workbench platform.

The pressure load, temperature load and inertial force of the fluid domain can be applied to the solid domain when the data transfer between the flow field analysis module CFX and the thermal fluid-solid coupling analysis module Thermal-Stress is realized. The temperature load is applied to the coupling interface between the rotor system of the high temperature hot water circulation pump and the high temperature hot water, the pump shaft and nut surface in the air are set to convection heat transfer surfaces, the convective heat transfer coefficient selects the Air-Simplified Case; the pressure load and the temperature load are applied to the corresponding parts of the rotor system; Rotational Velocity is applied. To simplify the calculation process, Fixed Support and Standard Earth Gravity are applied to the mounting bearing section.

4. Calculation results and analysis

![Figure 2](image_url)

**Figure 2. Temperatures on the rotor system.**

Figure 2 is the temperature distribution on rotor system when D₃ = 216mm. The front and back shroud of the impeller and the blade are in the high temperature medium, making the impeller overall temperature higher. Since the impeller hub is contact with the pump shaft directly, heat is transferred...
to the low temperature pump shaft, resulting in a low temperature of the hub corresponding position; it is found that the integral pump shaft temperature change is large and the temperature at matching part is the highest, the temperature decreases slowly as the area from the matching surface increases. The overall temperature distribution on the impeller nut is higher, but there is a significant temperature gradient.

Table 2. Temperatures on the rotor system at different volute cutwater diameter

| Rotor system | Cutwater diameter($D_3$) | 214mm | 216mm | 218mm |
|--------------|---------------------------|-------|-------|-------|
| Impeller     | $T_{\text{min}}$ (°C)     | 144.73| 144.54| 144.52|
|              | $T_{\text{max}}$ (°C)     | 150   | 150   | 150   |
| Pump shaft   | $T_{\text{min}}$ (°C)     | 66.64 | 66.688| 66.634|
|              | $T_{\text{max}}$ (°C)     | 149.52| 149.53| 149.53|
| Impeller nuts| $T_{\text{min}}$ (°C)     | 149.34| 149.34| 149.34|
|              | $T_{\text{max}}$ (°C)     | 150   | 150   | 150   |

As shown in table 2, with the increase of the cutwater diameter, the impeller minimum temperature decreases gradually and the decreasing trend decreases gradually; the pump shaft maximum temperature is kept constant and the minimum temperature increases first and then decreases with cutwater diameter increase, its minimum temperature is the smallest when $D_3 = 218$mm; when the cutwater diameter is different, the impeller nut temperature distribution is kept consistent.

Figure 3 is the total deformation of rotor system under the design conditions. The deformation of impeller front shroud deformation is more obvious than the back shroud of impeller and the impeller hub deformation is minimal, the impeller deformation along the outer circumference is not consistent.
due to the asymmetry of the impeller flow and the action of gravity. Due to the bearing support, the pump shaft deformation on the matching part with bearing is zero, but the matching part deformation of the impeller and impeller nut is the largest. And the deformation of the part between pump shaft on the matching part with bearing and the shaft at both ends increased gradually. Because of the high temperature, the coupling between the impeller nut and the pump medium is deformed maximally.

Table 3. Deformation on the rotor system with different volute cutwater diameter

| Rotor system | Cutwater diameter($D_3$) | 214mm | 216mm | 218mm |
|--------------|--------------------------|-------|-------|-------|
|              | $S_{min}$(mm)            | 0.0322| 0.037547 | 0.034776|
|              | $S_{max}$(mm)            | 0.062889 | 0.084882 | 0.071939|
| Impeller     | $S_{min}$(mm)            | 0     | 0     | 0     |
|              | $S_{max}$(mm)            | 0.04711 | 0.059375 | 0.052919|
| Pump shaft   | $S_{min}$(mm)            | 0     | 0     | 0     |
|              | $S_{max}$(mm)            | 0.043176 | 0.053484 | 0.048161|
| Impeller nuts| $S_{min}$(mm)            | 0.055184 | 0.068646 | 0.061534|
|              | $S_{max}$(mm)            | 0.055184 | 0.068646 | 0.061534|

As shown in table 3, when diameter increases from $D_3 = 214mm$ to $D_3 = 216mm$, the deformation of the rotor system became obvious gradually, however continuing to increase, the maximum deformation of the rotor system decreases.

Figure 4. Distribution of equivalent stress on rotor system.

Rotor system equivalent stresses are shown in figure 4. The impeller equivalent stress is relatively small, and impeller shroud equivalent stress changes regularly. The magnitude of the stress varies periodically along the impeller circumference, and the change period is consistent with the number of blades of the impeller; the pump shaft equivalent stress on the matching part about bearing is large relatively. There is an obvious stress concentration in the shaft shoulder which is from bearing fitting.
section to the maximum shaft diameter. Due to the interaction between the pump shaft and the impeller nut, the equivalent stress of the impeller nut on both surfaces is large relatively.

### Table 4. Equivalent stress on the rotor system with different volute cutwater diameter

| Rotor system | Cutwater diameter\((D_3)\) | 214mm | 216mm | 218mm |
|--------------|-----------------------------|-------|-------|-------|
| Impeller     | \(\sigma_{min}\) (MPa)     | 0.013016 | 0.01705 | 0.014358 |
|              | \(\sigma_{max}\) (MPa)     | 5.2446 | 4.6213 | 3.0319 |
|              | \(\sigma_{min}\) (MPa)     | 0.000415 | 0.00046656 | 0.00040052 |
| Pump shaft   | \(\sigma_{min}\) (MPa)     | 0.07852 | 0.78671 | 0.075195 |
|              | \(\sigma_{max}\) (MPa)     | 24.293 | 24.942 | 24.635 |
| Impeller nuts| \(\sigma_{min}\) (MPa)     | 291.42 | 294 | 274.34 |
|              | \(\sigma_{max}\) (MPa)     | 24.293 | 24.942 | 24.635 |

As shown in table 4, the maximum equivalent stress of the impeller is reduced significantly as cutwater diameter increases. When the cutwater diameter increases from \(D_3 = 214\text{mm}\) to \(D_3 = 216\text{mm}\), the pump shaft maximum equivalent stress is increased slightly, and the pump shaft maximum equivalent stress is reduced obviously when \(D_3 = 218\text{mm}\). The change of cutwater diameter has little effect on the equivalent stress of the impeller nut.

### 5. Conclusion

- The deformation of rotor system are the largest when \(D_3 = 216\text{mm}\), however the maximum deformation are the smallest when \(D_3 = 214\text{mm}\).
- With the increase of the cutwater diameter, the minimum temperature and the maximum equivalent stress of the impeller decreases gradually, while the influence of different cutwater diameter on the steady thermal analysis of impeller nut is very small.
- The equivalent stress of the pump shaft is large, there is an obvious stress concentration in the shaft shoulder which is from bearing fitting section to the maximum shaft diameter. The maximum equivalent stress in the model with \(D_3 = 218\text{mm}\) is small relatively, so the model is safe.

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