The stress analysis of a heavy liquid metal pump impeller

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Abstract. Lead-based coolant reactor is a promising Generation-IV reactor. In the lead-based coolant reactor, the coolant is liquid lead or lead-bismuth eutectic. The main pump in the reactor is a very important device. It supplies force for the coolant circulation. The liquid metal has a very large density which is about ten times of the water. Also, the viscosity of the coolant is small which is about one sixth of the water. When the pump transports heavy liquid, the blade loading is heavy. The large force can cause the failure of the blade when the fatigue stress exceeds the allowable stress. The impeller fraction is a very serious accident which is strictly prohibited in the nuclear reactor. In this paper, the numerical method is used to simulate the flow field of a heavy liquid metal pump. The SST k-ω turbulent model is used in the calculation to get a more precise flow structure. The hydraulic force is obtained with the one way fluid solid coupling. The maximum stress in the impeller is analyzed. The stress in the liquid metal pump is compared with that in the water pump. The calculation results show that the maximum stress of the impeller blade increases with increase of flow rate. In the design of the impeller blade thickness, the impeller strength in large operating condition should be considered. The maximum stress of the impeller blade located in the middle and near the hub of the leading edge. In this position, the blade is easy to fracture. The maximum deformation of the impeller firstly increase with increase of flow rate and then decrease with increase of flow rate. The maximum deformation exists in the middle of the leading edge when in small flow rate and in the out radius of the impeller when in large flow rate. Comparing the stress of the impeller when transporting water and LBE, the maximum stress is almost one-tenth of that in the LBE impeller which is the same ratio of the density. The static stress in different medium is proportional to the pressure distribution because a large percentage of the total stress is caused by hydraulic pressure.

1. Introduction

Fusion and fission energy are the important ways recognized so far to solve the energy crisis problems [1][2][3][4][5]. Lead-based coolant reactor is a promising Generation-IV reactor. In China, Chinese LEAd-based research Reactor (CLEAR) was selected as the reference reactor in the first phase of CAS ADS project (“strategic priority research program” named “the future of advanced nuclear fission energy system-ADS transmutation system”) [1][6][7][8][9][10].

In the lead-based coolant reactor, the coolant is liquid lead or lead-bismuth eutectic. The main pump in the reactor is a very important device. It supplies force for the coolant circulation. The liquid metal has a very large density which is about ten times of the water. Also, the viscosity of the coolant is small which is about one sixth of the water. When the pump transports heavy liquid, the blade
loading is heavy. So the stress is much higher compared with transporting water. The structure analysis is necessarily.

In the previous studies, CFD method is already successfully used in the stress calculation of hydraulic machineries. Chen Xiangyang et al. [11] calculated the blade stress considering the thermal stress of a coolant reactor pump. Tang Xuelin et al. [12] studied the bulb tubular pump impeller stress and deformation in different flow conditions to check the impeller strength. In Sambhrant Srivastava et al.’s [13] study, the stress analysis was carried out to optimize blade shape. Gao Yongjiang et al. [14] studied the dynamic stress in different flow conditions. It is shown that under small flow condition the dynamic stress is the largest because of the large pressure fluctuation. Li Liuyang et al.’s [15] studies also showed that the dynamic stress has a considerable amplitude compared with the static stress. Xiao Ruofu et al. [16] studied the dynamic stress of a Francis turbine runner at high heads and low loads under which condition the largest dynamic stress occurred. The dynamic stress can not be ignored to the blade’s micro-cracks. Wang Zhengwei et al. [17] also found the actual dynamic stress in transient process is much larger than experienced value and is the main reason to the premature cracks. And also there are other valuable studies [18][19]. These studies have important engineering values for the pump design and operation. And also It is proved the numerical method be a valid and economical method. It can be used to analyze the impeller stress of a heavy liquid metal pump.

There are two ways of fluid-solid coupling methods. The first one is the double way coupling. The deformation of the solid will be transferred to the fluid zone. It is usually considered when the large deformation occurred, such as in the wind turbine. For the studied pump, since the size is not so large and the deformation is not so obvious. The influence of the blade deformation to the flow field is ignored in this study. So a one-way coupling method is used in the calculation. In this paper, the flow field in a mixed pump is simulated. The pressure is exerted to the blade and the structural characteristic is analyzed.

2. Computational model

2.1. Physical model

The studied pump is a centrifugal pump with 7 blades. The physical model is shown as follows. The numerical model consists of the impeller, diffuser, casing, front and back clearance, inlet and outlet pipe.

![3-D model of the impeller](image)

*Figure 1. 3-D model of the impeller*

2.2. Mesh

Structure mesh was applied to the impeller and the diffuser. Near the blade wall boundary, the mesh was refined to guarantee that the $y^+<30$ near the wall. The total number of the mesh cells is about 2.66 million. For the solid zone of the impeller, unstructured grid with fine size was meshed in workbench.
3. Numerical method

3.1. Boundary conditions
For the fluid domain, the velocity inlet and pressure outlet boundary conditions were set. The blade surface was set as fluid solid interface. The impeller zone was rotational domain. The rotation of the impeller is realized by rotating reference frame method. No slip wall was set for the hub and shroud.

For the solid domain, the fixed support condition is set to the rotating surface. Centrifugal force was applied to the impeller. Pressure in the impeller surfaces from the fluid computational results is exerted.

3.2. Control functions
The continuity and momentum conservation function is shown as follows:

\[
\frac{\partial u_i}{\partial x_i} = 0
\]

\[
\rho \frac{\partial (u_i u_j)}{\partial x_i} = -\frac{\partial p^*}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_i \partial x_j}
\]

The SST k-w model is shown as follows:

\[
\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta' k w + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma_i \mu_i) \frac{\partial k}{\partial x_j} \right]
\]

\[
\frac{\partial w}{\partial t} + U_j \frac{\partial w}{\partial x_j} = \alpha S^2 - \beta w^2 + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma_i \mu_i) \frac{\partial w}{\partial x_j} \right] + 2(1 - F_i)\sigma w^2_2 \frac{1}{w} \frac{\partial k}{\partial x_i} \frac{\partial w}{\partial x_i}
\]

\[
\mu_i = \frac{\alpha_i k}{\max(\alpha_i w, SF_2)}
\]

The meanings of the parameters can refer to ANSYS Fluent 14 help.

3.3. Numerical methods
The simulation work was conducted with Fluent 14, which contained plenty of physical models. SIMPLEC algorithm was used as a relationship between velocity and pressure corrections to enforce mass conservation. The second order upwind scheme was used to discrete the convective terms. The stress analysis is performed with Workbench static structure analyze. One-way fluid-solid coupling

![Figure 2. Mesh](image)

(a) impeller flow channel structural mesh  (b) refined mesh in the boundary  (c) Solid mesh
method is used. The pressure load calculated by hydraulic computation is transferred to the impeller solid domain.

4. Results and discussions

4.1. Steady performance

The following equations defined the dimensionless head and flow rate parameter of the pump. In these equations, the subscript 0 stands for the head and flow rate in nominal condition.

\[
H' = \frac{H}{H_0} \\
W' = \frac{W}{W_0}
\]

Experiments were conducted with water in room temperature. The steady state pump performance was compared between numerical results and experimental results, as shown in Figure 3. In the small flow rate, the experimental results and the numerical results fit well, while in larger flow rate, the numerical results decreases more gentle and slowly. On the contrary, the efficiency curve fits well in large flow rate. The differences are mainly caused by the inlet boundary condition and the physical model. In numerical simulation, the inlet velocity distribution is idealistically uniform.

![Figure 3. Comparison between numerical and experimental results](image)

4.2. Stress analysis in different flow rate

In the stress analysis, the material properties are shown as follows:

| Material             | Structural steel |
|----------------------|------------------|
| Young Modulus        | $2 \cdot 10^{11}$ Pa |
| Poisson Ratio        | 0.3              |
| Density              | 7850 Kg/m$^3$    |
| Thermal expansion    | $1.2 \cdot 10^{5}$ $/^\circ C$ |
| Yield stress         | $2.5 \cdot 10^8$ N/m$^2$ |

The Von Mises stress is calculated to evaluate the strength of the impeller. Von Mises stress is often used in determining whether an isotropic and ductile metal will yield when subjected to a complex loading condition. The Von Mises stress is directly related to the deviatoric strain energy term. The Von Mises yield criterion suggests that the yielding of material begins when the second deviatoric stress invariant $J_2$ reaches a critical value.
\[ J_2 = k^2 \]  
(8)

Where \( k \) is the yield stress of the material in pure shear.

\[ k = \frac{\sigma_y}{\sqrt{3}} \]  
(9)

Figure 4 shows the stress of the impeller of the LBE pump in different flow rate. The maximum stress located at the middle of the blade inlet edge as well as blade near the hub. The maximum stress increases linearly with increase of the flow rate. But as increase of the flow rate, the stress distribution in the blade is getting more uniform and the stress gradient in the blade is getting smaller. Comparing the stress caused by centrifugal force and hydraulic pressure, the stress caused by centrifugal force is very small compared with that caused by hydraulic pressure. The centrifugal stress keeps the same in different flow conditions while the hydraulic stress increased with increase of flow rate. And the total stress is less than the sum of centrifugal stress and the hydraulic stress.

Figure 5 shows the deformation of the impeller of LBE pump in different flow rate. The deformation distribution is different from that of the stress. The maximum deformation changes with flow rate. In small flow rate, the maximum deformation located at the middle of the blade inlet edge, in accordance with the stress distribution. With increase of flow rate, the deformation distribution changes. The deformation increases with increase of the impeller radius. In large flow rate, the maximum deformation located at the out radius of the impeller.

Calculate the deformation in centrifugal force and hydraulic pressure separately. The same conclusion can be drawn with the stress analysis. The deformation caused by hydraulic force is much larger than that caused by centrifugal force. And also the total deformation is less than the sum of centrifugal deformation and the hydraulic deformation.
4.3. Comparison of different medium

With the same non-dimensional flow rate, as we already know from results shown in Figure 3, the non-dimensional head is very close. Since the density of the lead bismuth is 10 times of that of water, the hydraulic pressure load exerted to the blade of the water pump is also much smaller than that of the LBE pump. From Figure 6(a), Figure 7(a) and Figure 8(a), the maximum stress is almost one-tenth of that in the LBE impeller. The deformation variation with flow rate is also in the same tendency with LBE pump. When transporting LBE, the stress increases in a large range in different flow rate. So when designing a LBE impeller, the maximum operating flow rate should be considered as the design condition to guarantee the impeller strength.

Figure 5. Deformation contour in different flow rate (LBE), Unit: m

Figure 6. Stress and deformation comparison (0.6Q₀)
5. Conclusions

In this paper, the impeller stress of a LBE pump is analyzed and compared with a water pump. The following conclusions can be drawn from the study.

1) The maximum stress of the impeller blade increases with increase of flow rate. In the design of the impeller blade thickness, the impeller strength in large operating condition should be considered. The maximum stress of the impeller blade located in the middle and near the hub of the leading edge. In this position, the blade is easy to fracture.

2) The maximum deformation of the impeller firstly increase with increase of flow rate and then decrease with increase of flow rate. The maximum deformation exists in the middle of the leading edge when in small flow rate and in the out radius of the impeller when in large flow rate.

3) Comparing the stress of the impeller when transporting water and LBE, the maximum stress is almost one-tenth of that in the LBE impeller which is the same ratio of the density. The static stress in different medium is proportional to the pressure distribution because a large percentage of the total stress is caused by hydraulic pressure.

For further studies, the dynamic stress in transient and unsteady condition will be studied since the large pressure and pressure fluctuation. The two-way coupling method could be used to evaluate the influence of the structure deformation to the hydraulic and mechanical performance. And also, the impeller stress in multi-physical fields considering thermal stress are also need further study.

6. References

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