Influence of impeller clearance structure on volume loss of centrifugal pump

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Abstract. In this paper, the three-dimensional full flow field model of double volute structure centrifugal pump is established, and the ring seal, teeth seal and interlocking seal structures are set up. The K-\(\varepsilon\) turbulence model of CFX software is used to simulate and analyse the fluid flow state at the gap of different mouth ring structures of centrifugal pump. The results show that the staggered ring structure can effectively reduce the leakage and improve the volumetric efficiency of centrifugal pump.

1. Introduction
Centrifugal pump as a key equipment of fluid transmission and energy conversion is not only widely used in petroleum, chemical industry, electric power and steel industry, but also plays a pivotal role in aerospace, shipbuilding, agricultural irrigation and other fields. In the process of using centrifugal pump, the size of the gap between the opening ring will change due to the contact wear between the parts, which will affect the performance of the pump.

More and more researchers have begun to study the gap between the centrifugal pump port and the ring\textsuperscript{[1-3]}, Wang Yang et al\textsuperscript{[4]} has carried out theoretical analysis and Experimental Research on different blade types of low specific speed centrifugal pump. It is found that the total efficiency of the centrifugal pump with low specific speed decreases with the increase of the gap between the mouth rings. Pan Zhongyong et al\textsuperscript{[5]}, studied the effect of the gap size of the opening ring on the efficiency of the centrifugal pump. It was found that the efficiency of the centrifugal pump was higher when the gap between the current ring was reduced; Zhao Weiguo et al\textsuperscript{[6]}, studied the influence of the change of the front and rear ring clearance on the performance of the centrifugal pump, and concluded that the front ring clearance had a great influence on the performance of the centrifugal pump.

In this paper, HTJ280-70-YJ-001 single stage centrifugal pump is studied. The flow state of the centrifugal pump's annular structure is simulated and analysed by using CFX software. The influence of the structure of the ring on the volume loss of the centrifugal pump is studied.

2. Methods and Materials
2.1. Governing equation
Fluid flow follows three conservation laws: mass conservation law, momentum conservation law and energy conservation law. These three conservation laws constitute the basic equations of fluid dynamics Navier-Stokes equations, which are mainly composed of continuity equation, momentum equation and energy equation.
In this article, heat transfer is not involved, so the energy equation is not considered, so the Navier-Stokes equations can be expressed in the following form:

The continuity equation is:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
\]  

(1)

The momentum equation is:

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{\partial \tau_{ij}}{\partial x_j} - \rho g_i
\]  

(2)

Correcting the standard k-\varepsilon model turbulent kinetic energy k and turbulent dissipation rate \varepsilon, we can get:

The continuity equation is:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + C_{1k} \varepsilon \frac{\rho}{k} \frac{\varepsilon^2}{k}
\]  

(3)

The momentum equation is:

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{k}{\varepsilon} \frac{\rho}{k} \frac{\varepsilon^2}{k}
\]  

(4)

2.2. Geometric model of centrifugal pump

The basic parameters of centrifugal pump are rated flow Q = 270 m³/h, head H = 74 m, speed n = 2980 r/min, inlet diameter D1 = 150 mm, outlet diameter D2 = 250 mm, impeller outlet width b = 25 mm, blade number 6. The geometric model of centrifugal pump should include six parts: inlet, outlet, impeller, volute, front ring and pump cavity, rear ring and pump cavity, and three kinds of ring structures, including ring seal, teeth seal and interlocking seal should be established. The whole model of centrifugal pump is shown in Figure 1.

2.3. Meshing and solution settings

Centrifugal pump blades, volutes and other structures have a high degree of distortion. Considering computing resources and finite element calculation accuracy, ICEM CFD software is used for hybrid mesh division. Impellers and volutes are divided by unstructured grids. The blades and other positions are locally densified; the water inlet pipe and the water outlet pipe are divided by structured grids. The grid division method and quantity of each component of the centrifugal pump are shown in Table 1 below.
Table 1 Grid division of each fluid domain of the centrifugal pump

| Domain   | Grid type     | Number of grids (×1000) |
|----------|---------------|-------------------------|
| Inlet    | Structured grid | 642.35                  |
| Impeller | Unstructured grid | 2674.22                |
| Volute   | Unstructured grid | 2268.64                |
| Cavity   | Unstructured grid | 252.71                  |
| Seal     | Structured grid | 228.38                  |
| Outlet   | Structured grid | 476.24                  |

The centrifugal pump adopts the boundary conditions of pressure inlet and speed outlet, the dynamic and static interface adopts the “frozen rotor” method, and the grid connection mode is GGI mode.

3. Results and Discussion

3.1. Flow field distribution of different gap structures

It can be seen from Fig. 2 and Fig. 3 that the static pressure of the three kinds of port ring structures gradually decreases from inlet to outlet, the pressure variation of teeth ring structure is more uniform, and the pressure gradient of straight through and staggered port ring structures is larger in the flow channel; the turbulent kinetic energy of flat ring, straight through and staggered port ring structures gradually increases, and the turbulent kinetic energy of straight through and staggered port ring structures gradually increases from inlet to outlet. It shows that the fluid flow is more stable at the clearance of flat ring, but disordered at the clearance of straight through and staggered ring. The reason is that the straight through and staggered port ring structure in the gap, because of the sudden change of the flow channel area, the fluid in the sealing cavity produces low pressure, and the low-pressure fluid in the sealing cavity further affects the high pressure in the throttling gap, resulting in a larger pressure gradient in the gap. The sudden change of pressure gradient leads to the increase of turbulence pulsation and Reynolds stress, which results in the change of flow state in the gap between the orifice and the ring and accelerates the transition of fluid from layer to turbulence. The generation of turbulence increases the turbulent kinetic energy of the fluid, and finally hinders the fluid flow.

3.2. Performance curves of different gap structures

It can be seen from Fig. 4 and Fig. 5 that the lift of straight through type can be increased up to 2.4m for flat ring structure and 5.26m for staggered ring structure; the efficiency can be improved up to 1.85% for straight through type structure and 4.37% for staggered ring structure. It shows that the straight
through and staggered ring structure can further improve the head and efficiency of centrifugal pump, and the staggered ring structure has more obvious effect.

3.3. leakage and volumetric efficiency diagram of different clearance structures

It can be seen from Fig. 6 and Fig. 7 that under each flow condition, the leakage of ring seal, teeth seal and interlocking ring structure first increases and then decreases with the increase of flow rate, and the leakage of the three structures decreases in turn. Under the condition of small flow, the change of leakage tends to be stable, and with the increase of flow, the change of leakage increases obviously. The volumetric efficiency of interlocking and teeth seal structure is higher than that of ring seal. Compared with the ring seal structure, the interlocking seal structure can improve the volumetric efficiency by 2.15%, while the teeth seal can improve the volumetric efficiency by 0.52%. The results show that interlocking structure can improve the volumetric efficiency of centrifugal pump more greatly. Due to the big difference between interlocking seal structure and other seal structure, it can better change the flow state of fluid in the ring gap, promote the development of fluid from laminar flow to turbulent flow, to increase the turbulent kinetic energy of fluid, and finally achieve the effect of blocking the flow of fluid and improving the volumetric efficiency of pump.

4. Conclusions

Based on the above results, the following conclusions can be drawn:

The interlocking seal structure can better change the flow state of the fluid inside the ring gap, and
promote the development of the fluid from laminar flow to turbulent flow, thereby increasing the turbulent kinetic energy of the fluid, achieving the effect of hindering the flow of the fluid, and finally Effectively reduce leakage and improve the volumetric efficiency of the centrifugal pump.

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