Analysis of silt abrasion of the impeller ring in a centrifugal pump with J-grooves

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Abstract: The water flow and movement of silt in a prototype double-suction centrifugal pump was simulated using an Euler-Lagrange multiphase flow model. J-Grooves were adopted to protect the impeller ring from silt abrasion. The influence of J-grooves on the silt concentration and pump efficiency was analyzed. The results show that the radial component of the relative velocity around the impeller ring is too low to move the silt out of the spacing between the impeller plate and the casing. The high silt concentration around the impeller ring is the major contributor to silt abrasion of the impeller ring. The J-grooves induce two strong vortices, which increase the radial component of the relative velocity of water and reduce the silt concentration around the impeller ring, but additional friction losses are introduced and the pump efficiency is decreased. Optimization of the number and shape of J-grooves decreases losses in the efficiency of the pump, and effectively protects the impeller ring. Case 4 was found the most effective configuration in this study.

1. Introduction

The double-suction pump is widely used for pumping irrigation in the Yellow River irrigation district because of its large flow rate and high head, but the silt concentration in the Yellow River is so high that the flow passage components of the pump are easily worn. The impeller ring is usually the most seriously affected by silt abrasion. Its lifetime is only one-third of the impeller. Silt abrasion occurring in hydraulic machinery is a problem for users and designers, and consequently is the subject of considerable research. Liu et al. [1] studied the movement rule of solid particles in a single-suction centrifugal pump using high-speed photography. Yoshiro and Kazuyuki [2] studied silt abrasion of different coating materials. CHEN et al. [3] analyzed the reason for the different appearance of damage at different positions on the hydrofoil. Most research has focused on the silt abrasion of the blade, while neglecting the impeller ring. Kurokawa et al.[4] and Saha et al.[5,6]proposed shallow grooves, named "J-Grooves", mounted on the casing wall of turbo-machinery in the pressure gradient

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direction of the main flow, as a countermeasure to various abnormal flow phenomena. For the present problem, it is believed that the J-groove is an effective method for suppressing silt abrasion of the impeller ring, because the J-groove can increase the radial component of the relative velocity of water, which helps to reduce the silt concentration around the impeller ring.

In recent years, as a new powerful and effective research tool, computational fluid dynamics (CFD) has been widely used in the flow of pumps [7, 8], and it has become an effective and accurate tool in pump design for engineering applications [9-11]. In this study, the water flow and movement of silt in a prototype double-suction centrifugal pump was simulated using an Euler-Lagrange multiphase flow model. J-Grooves were adopted to suppress silt abrasion of the impeller ring in the double-suction centrifugal pump. The influence of the shape and number of J-grooves on silt abrasion of the impeller ring was analyzed.

2. Numerical simulation method

2.1. Mathematical model

The three-dimensional Reynolds-averaged Navier-Stokes equations for incompressible flow are as follows [12]:

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

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

Considering the rotating flow inside the pump impeller, the RNG \( k - \varepsilon \) model, which is effective for strongly rotating flow, was adopted in this simulation [13].

The Euler-Lagrange multiphase flow model was used to simulate silt motion; it can describe the interaction between silt and water and the collision of silt particles and its governing equation takes the form [14]:

\[
\frac{d\bar{u}_p}{dt} = F_D (\bar{u} - \bar{u}_p) + \frac{\bar{g} (\rho_p - \rho)}{\rho_p} + \bar{F}
\]

The silt concentration in the flow passage is obtained when the silt concentration in the inlet and outlet is balanced. The Euler-Lagrange multiphase flow model can describe not only the interaction between silt and liquid but also the collision of silts. The silt concentration around the impeller ring is the major contributor to silt abrasion of the impeller ring. This was chosen as the major performance indicator for optimizing the J-grooves.

All simulations were conducted using Fluent 14.0 software. The SIMPLEx algorithm was used for the pressure-velocity coupling [15]. The second-order upwind difference scheme was used for the momentum, turbulent kinetic energy, and dissipation rate equations. The mass flow rate was defined at the inlet and the static pressure at the outlet. The roughness heights of the hub and casing were also considered [16]. The sliding mesh model was used to simulate the rotor-stator interaction in the pump.
2.2. Physical model

The computational domain is the flow passage from the inlet to the outlet, including the impeller and volute as shown in Figure 1. The diameter of the impeller was 0.765 m, the rated speed was 960 rpm, and there were 8 blades. The structures of the impeller are shown in Figure 2. The unstructured mesh was used to form the discrete computational domain for the double-suction centrifugal pump because of their complicated geometry. There were about 3,000,000 mesh cells in total.

![Figure 1. 3D perspective view of the double suction pump](image1)

![Figure 2. 3D perspective view of the impeller](image2)

The operating conditions of the prototype double-suction centrifugal pump and silt are as follows in Table 1.

| Table 1. Operating conditions of pump and silt |
|-----------------------------------------------|
| Discharge                                    | $Q=0.95 \text{ m}^3/\text{s}$ |
| Total head                                   | $H=71.0 \text{ m}$ |
| Rotational speed                             | $n=960 \text{ rpm}$ |
| Silt concentration                           | $C=2.832 \text{ kg/m}^3$ |
| Silt diameter                                | $d=0.031 \text{ mm}$ |

For the given boundary conditions, the computational head of the prototype pump is $H = 71.82 \text{ m}$, and the error was only 1.15 %. Therefore, the mathematical model and boundary conditions were acceptable.

3. Results and discussion

3.1. Prototype pump

The outer surface of the impeller plate and a section $S_1$ were chosen to analyze the water flow and movement of silt in the gap between the impeller plate and the casing as shown in Figures 3 and 4. Figure 4 shows the silt concentration on the impeller plate (units: kg/m$^3$), the silt concentration around
the impeller ring was obviously higher than the mean concentration in the water, which was the primary cause for rapid silt abrasion of the impeller ring. Figure 5 shows the velocity of water flow in section S1. It was found that the water flowed into the gap, forming two long vortices. Figure 6 shows the relative velocity on the impeller plate. The radial component of relative velocity on the impeller plate was small. It can be concluded from Figures 5-6 that the silt particles can be easily deposited at the impeller ring and were difficult to extract, which resulted in a high silt concentration around the impeller ring.

3.2. J-Grooves
The main reason for silt abrasion of the impeller ring was the high concentrations of silt particles around the impeller ring. According to the research in Reference 5, as shown in Figure 7(a), J-grooves were designed in the impeller plate. As shown in Figure 7(b), $a$ is the dip angle of the groove, $h$ is the depth, $b_1$ is the width of lower edge and $b_2$ is the width of upper edge. Four different cases are listed in Table 2.
Figure 7. Schematic view of the J-Groove

Table 2. Specifications of J-Grooves

| J-Groove | Case 1 | Case 2 | Case 3 | Case 4 |
|----------|--------|--------|--------|--------|
| Number   | 70     | 35     | 35     | 35     |
| $a$ [°]  | 45     | 45     | 30     | 30     |
| $h$ [mm] | 5      | 5      | 5      | 5      |
| $b_1$ [mm] | 20    | 40     | 40     | 40     |
| $b_2$ [mm] | 20    | 40     | 40     | 55     |

In Case 1, there were 70 J-grooves. Figure 8 shows the silt concentration on the impeller plate. The silt concentration on the impeller plate was relatively higher than that in Figure 4, but the silt concentration around the impeller ring was almost zero. Figure 9 shows the velocity in section S1. Figure 10 shows the relative velocity on the impeller plate.

It can be seen from Figures 9 and 10 that the J-grooves induced two shorter and stronger vortices in the gap between the impeller plate and the casing, and the radial component of the relative velocity was obviously increased. The silt particles were prevented from reaching the area around the impeller ring and the removal of silt particles in the gap between the impeller plate and the casing was easier.

The pump efficiency dropped by 4.21%. It can be easily understood that the J-grooves increased the roughness of the impeller plate and the friction losses increased accordingly. It can be concluded that the J-grooves had the effect of a dynamic seal and the impeller ring was protected from silt abrasion. The presence of J-grooves also led to additional friction losses and pump efficiency decreased. Therefore, the number and shape of the J-grooves needed to be optimized.
In Case 2, the number of J-grooves was reduced to 35 and the width of the lower edge and upper edge of the J-groove was increased to 40 mm. The silt concentration and the relative velocity on the impeller plate for Case 2 are shown in Figures 11 and 12. It can be seen that the silt concentration on the impeller plate changed a little, and the radial component of the relative velocity on the impeller plate was also low. However the pump efficiency for Case 2 dropped by 3.50 %. The silt concentration and the pump efficiency were thus unacceptable. It was concluded that the shape of the J-groove needed to be optimized to achieve acceptable silt concentration and pump efficiency.
In Case 3, the dip angle was decreased to 30°. Figures 13 and 14 show the silt concentration and the relative velocity on the impeller plate for Case 3. In Figure 13, the silt concentration on the impeller plate near the J-grooves was increased and the area where the silt concentration around the impeller ring was nearly zero enlarged. Figure 14 shows that the radial component of the relative velocity obviously increased, which made for efficient silt extraction. The pump efficiency for Case 3 dropped by 3.55%. The combined effect for Case 3 was an improvement.

To reduce the friction losses caused by the J-grooves, the shape of the J-grooves in Case 4 was optimized on the basis of Case 3. The width of upper edge \( b_2 \) was expanded to 55 mm. The results of Case 4 are shown in Figures 15 and 16. It can be seen in Figure 15 that the silt concentration on the impeller plate changed a little but the silt concentration around the impeller ring still remained about zero. In Figure 16, the radial component of the relative velocity only changed a little compared with...
Case 3, so the capacity for carrying silts was maintained. The pump efficiency for Case 4 dropped by 3.11%, which was an improvement on Case 3.

The analysis results show that the J-groove was effective in protecting the impeller ring from silt abrasion. The pump efficiency loss can be reduced by reducing the number of J-grooves. In this simulation, optimization of the number and shape of the J-grooves was conducted. Case 4 was considered acceptable in protecting the impeller ring from silt abrasion and keeping friction losses low.

4. Conclusions
The water flow and movement of silt in a prototype double-suction centrifugal pump was simulated using an Euler-Lagrange multiphase flow model. J-Grooves were designed in the impeller plate to protect the impeller ring from silt abrasion. Four different cases were simulated and analyzed. The results show:

1. The J-Grooves induced two short and strong vortices which formed a dynamic seal and prevented the silt particles from reaching the area around the impeller ring.

2. The J-groove was effective in increasing the radial component of the relative velocity of water and reducing the silt concentration around the impeller ring, but additional friction losses were also introduced which decreased pump efficiency.

3. With the optimization of the number and shape of the J-grooves, Case 4 was considered the most effective for protecting the impeller ring from silt abrasion and maintaining pump efficiency.

Acknowledgment
This work was supported by the National Natural Science Foundation of China (No.51422906).

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