NUMERICAL SIMULATION AND OPTIMIZATION OF SOLID-LIQUID TWO-PHASE FLOW IN A BACK-SWEPT AXIAL FLOW PUMP

by

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The simulation study is proposed to analyze the wear property of the axial flow pump using the sewage as medium. Different axial flow pumps are designed with different back-swept angles, of which are 40°, 65°, and 90°. Numerical simulation results showed the relationship between solid volume fraction and back--swept angle on the pressure/suction surface, as well as the particle diameter. To validate the correctness of numerical investigation, the result of the 65° backswept blade model was compared with a sludge axial flow pump in sewage treatment plant, which showed fair agreement with the simulated results.

Key words: back-swept blade, axial flow pump, solid-liquid two-phase flow, blade wear

Introduction

The axial flow pumps are widely used in China's urban sewage treatment. Nowadays, impeller design of the axial flow pump is based on the premise of water medium, which is different from the actual work environment. It leads to serious problems of wearing of the pump impeller and the blockage of the runner channel in practical operation [1]. Experiments conducted by Gu *et al.* [2] showed that back-swept blades agitator with three blades had good performance of cutting, cycling characteristics, and mass transferring. Xia *et al.* [3] tested and optimized the impeller of the diving mixer (flow booster), the design of which was based on the airfoil lift, had a high anti-winding function. Hurault *et al.* [4] analyzed the influence of the back-swept blades on flow inside of the axial flow fan and the radial velocity was improved when the back-swept blades were used. Larwood and Zuteck [5] found that the backswept blade could reduce the dynamic loads on the blade after their investigation of the load and dynamic performance on the fan with back-swept blades.

Currently, mixture model is mostly applied to simulate the solid-liquid two-phase flow in pumps [6], however the mixture model is based on the two-phases which are both continuous phase. Literature involved numerical simulation of solid-liquid two-phase flow in pumps less used particle model [7]. There will be a good accuracy using the particle model, of which one phase is continuous phase and the other phase is dispersed phase [8]. Geiss *et al.* [9] investigated the influence of a dispersed phase on the turbulence properties of a continu-

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ous phase. Virdung and Rasuson [10] used particle imaging velocimetry to evaluate liquid and solid velocities and turbulence levels in the developing region of a confined jet which is compared with those from numerical simulations using the mixture, dispersed, and per-phase realizable k- ε models.

This paper aims at discussing and solving the wearing problem of axial flow pump blades in steering pond of waste water treatment plant with design of back-swept angle of blade. The numerical investigation of the solid-liquid two-phase flow, based on particle model, is conducted to obtain the methodology to reduce blade wearing of axial flow pump.

Geometric model and numerical method

The governing equations of steady-incompressible flow inside the pump can be regarded as continuity equation and momentum equation:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho \overline{u_i u_j}}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_j} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \overline{u_i}}{\partial x_j} - \partial \rho \overline{u'_i u'_j} \right)$$
(2)

where \overline{p} and $\overline{u_i}$ are time average pressure and velocity component, respectively, and $\rho \overline{u'_i u'_j}$ – the Reynolds stress.

Particle model is used to simulate dispersed solid phase of the continuous liquid phase. Gidaspow drag force equation between solid and liquid phases:

$$D_{\alpha\beta} = \frac{3}{4} \frac{C_D}{d} \gamma_\beta \rho_\alpha \left| U_\beta - U_\alpha \right| (U_\beta - U_\alpha)$$
(3)

$$C_D = r_c^{-1.65} \max\left(\frac{24 + 3.6r_c^{0.687} \operatorname{Re}^{0.687}}{r_c \operatorname{Re}}, 0.44\right) \quad \text{when} \quad r_c > 0.8$$
(4)

$$\frac{3}{4} \frac{C_D}{d} \gamma_\beta \rho_\alpha \left| U_\beta - U_\alpha \right| = \frac{150(1 - r_c)^2 \mu_c}{r_c d_p^2} + \frac{7(1 - r_c)\rho_c \left| U_c - U_d \right|}{4d_p} \quad \text{when} \quad r_c < 0.8 \tag{5}$$

where $D_{\alpha\beta}$ [Nm⁻³] is the drag of particles on continuous phase per unit volume, d, and d_{ρ} [m] are the average particle diameter, respectively, γ_{β} , and r_c [%] – the particle and continuous phase volume fraction, respectively, ρ_{α} , and ρ_c [kgm⁻³] – the continuous phase density, U_{β} , U_d , U_a , and U_c [ms⁻¹] – the particle and continuous phase velocity, and μ_c [Pa·s] is the continuous phase viscosity.

An ordinary axial flow pump blade was used as the prototype in fig. 1(a). The backswept angle of leading edge is θ . The arc radius, *R*, of leading edge is 100 mm, and other parameters of the blade are not changed, which is showed in fig. 1(c). The θ of prototype blade and back-swept blades are 0° and 40°, 65°, 90°, respectively.

Mesh and boundary conditions

The hexahedral mesh were used in inlet pipe, impeller, guide vane, support plate, and outlet flow channel. Grid mesh number independent inspection has been done, so as to control the effect of the grid number within 5% for the pump performance parameter. The





Figure 1. Geometric model of prototype blade and back-swept blade; (a) prototype blade, (b) back-swept blade, (c) the front view of back-swept blade and prototype blade

grid number of inlet pipe, impeller, guide vane, support plate, and outlet flow channel are 240000, 1540000, 670000, 210000, and 190000, respectively, shown in fig. 2

Similar grid number of prototype axial flow pump is used for the back-swept axial flow pump. Then numerical simulation is done with the same medium and boundary conditions are set to be the same as the prototype axial flow pump. On the basis of previous simulation which only the water is set as the medium, solid phase is added using particle model to numerically simulate two-phase flow of internal flow



Figure 2. Computational domain and grid of prototype blade axial flow pump

field in the axial flow pump. For continuous flow, the standard k- ε turbulence model is used. For the discrete particle phase, discrete phase zero equation model is used. Gidaspow drag model is adopted to deal with interphases drag force and simulation accuracy is set to $5 \cdot 10^{-5}$.

Results and discussion

Hydraulic external characteristics

The axial flow pump model is located in a closed test loop facility at the National Fluid Machinery Laboratory, Jiangsu University, Zhenjiang, China, shown in fig. 3. The pump model was designed to include a transparent casing. It consists of the impeller, guide



Figure 3. View of the axial flow pump model

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vane diffuser, shaft, and bearing box. Pump head and efficiency are significantly reduced when the blades are back-swept. The larger the back-swept angle turns, the lower the head and efficiency are. Experimental and simulated values are close when the flow rate of the prototype axial flow pump close to the design flow point. The data is nearly equal for experimental and simulated values of the prototype axial flow pump under the design condition.

Impact of back-swept angle on flow in impeller

At the design flow point, the particle volume fraction is set as 10% and the particle diameter is 0.3 mm. Figures 4 and 5, respectively, show the solid phase volume distribution on the pressure side and suction side of the prototype blade and back-swept blades.



Figure 4. Distribution of solid volume fraction on pressure surface of prototype blade and back-swept blade

As fig. 4 shows, solid particles on the pressure side are mainly close to the trailing edge of the blade. It can be explained that particles enter inside of the impeller with a certain axial velocity and velocity difference in the circumferential direction between solid particles and blades leads to the collision in the process of motion of the solid particles when passing through the impeller. Therefore, the solid volume fraction close to the leading edge of blades is obviously less than the trailing edge.

Figure 5 shows that solid phase volume fraction of the prototype blade on the suction side is less than that on the pressure side, while it concentrates on the hub side of the leading edge and the trailing edge of the 40° back-swept blade. There are still a large number of solid particles close to the tip side of the trailing edge on the suction surface of the 60° back-swept blade. However, for the 90° back-swept blade, the solid phase volume fraction on the suction side is obviously less.



Figure 5. Distribution of solid volume fraction on suction surface of prototype blade and back-swept blade

Impact of particle diameter on the flow of back-swept blade impeller inside

In order to study the impact on the flow of the particle diameter, in the design flow, the solid-liquid two-phase flow in axial flow pump with the 65° back-swept blade was calculated under four different conditions, where the solid volume fraction is set to 10% and particle diameters are 0.1, 0.3, 0.5, and 0.8 mm, respectively.

As is shown in figs. 6 and 7, the solid volume fraction on the pressure surface increases with the particle diameter, and solid particle spreads around, which indicates that the larger the diameter of the solid particle becomes, the more easily the solid particle can touch the pressure surface of the blade. However, on the suction surface of the blades, with the particle diameter increases, the solid volume fraction close to the hub side of the leading edge increases significantly. The solid volume fraction on the suction surface is the smallest when the particle diameter is 0.3 mm.



Figure 6. Distribution of solid volume fraction on pressure side of 65° back-swept blade with different particle



Figure 7. Distribution of solid volume fraction on suction side of 65° back-swept blade with different particle

Contrast of the wear situation and the simulation results for the back-swept blade

To verify the simulation results of the back-swept blade, the practical wear situation of a 65° back-swept blade axial flow pump used for sludge return in Nanjing Jiangxin Island, Nanjing, China, sewage treatment plant is compared with the numerical results.

The operating environment of the back-swept blade axial flow pump is complex, and the particle volume fraction and particle diameters are not uniform. Figure 8 shows the contrast between the practical wear situation of the back-swept blade and the simulated results, in which the particle diameter is 0.3 mm and solid volume fraction is 10%. It is noted

that the practical wear situation on the pressure surface is consistent with the solid phase volume fraction of the 65° back-swept blade, and the wear is serious where the solid volume fraction is large. The solid particle erosion close to the blade tip of the pressure surface is serious, which throughout the blade and damage the suction surface of the blade. However, the solid phase volume fraction on suction side of the 65° back-swept blade is not consistent with the practical wear situation, and it may be the impact of serious cavitation on the suction surface.



Figure 8. Swept blade wear and distribution of solid volume fraction; (a) pressure surface, (b) suction surface

Conclusion

The practical wear situation on the pressure surface is consistent with the solid phase volume fraction of the 65° back-swept blade, while the inconsistency on the suction surface might because of the impact of serious cavitation. For blade with large back-swept angle, the radial flow is the main factor for the solid phase distribution on the pressure surface, while the back-swept angle will be the main factor for the solid phase distribution with small back-swept angle; For the 90° back-swept blades, the solid phase distribution on both the pressure side and suction side are uniform and fewer, which can effectively avoid severely local wear, increase the service life of the impeller and improve the operation reliability of the pump.

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