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Research Article

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Dynamics and Wear Analysis of Hydraulic Turbines in Solid-liquid Two-phase Flow

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Abstract: To solve unstable operating and serious wearing of a hydraulic turbine in its overflow parts under solid-liquid two-phase flow, a particle model software and an inhomogeneous model in CFX are used to simulate the hydraulic turbine to understand the wearing of overflow parts and the external characteristics under the solid-liquid two-phase flow. Eleven different conditions at different densities and concentration have been calculated. The simulation results show that the volume distribution of solid particles is larger at the turn of the volute and nose end, resulting in the serious wear in this area. Due to uniform flow at the butterfly edge of volute under solid-liquid two-phase flow, the wear at the entrance of guide vane, the inlet of the blade and the outlet in the shroud is more serious than in other sections. Meanwhile, the collision between the solid phase particles and the overflow components is more intense under solid-liquid two-phase flow in the rotor which can lead to cavitation especially in the outlet and shroud of the blade. In addition, with the increase of density and concentration of solid particles the inlet and outlet pressure difference gradually rises, causing the efficiency loss of the hydraulic turbine.

Keywords: Solid-liquid two-phase flow; Francis turbine; Numerical simulation; Particle model; Inhomogeneous model; Wear

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1 Introduction

In recent years, with the rapid development of industry, hydropower, as a clean renewable energy, occupies an increasingly important position. As the core component of a hydropower station, the hydraulic turbine has been paid more attention by researchers and also has encountered many problems during its development. Most rivers in China have a large sediment content, especially in the Yellow River Basin where the annual sediment intake is as high as 1.6 billion tons. This can lead to serious sediment wear for the hydraulic turbine under solid-liquid two-phase flow. Deep or shallow grooves on the surface will occur when the sediment particles flow through the overflow component, causing certain damage to the overflow parts, and the interruption of the blade will occur in serious cases. Meanwhile, due to the movement of sand particles in the hydraulic turbine, it will bring problems such as performance degradation, vibration, cavitation erosion, and so on, which will seriously affect the stability of turbine [1, 2]. Therefore, it is a critical to study the internal flow of the turbine in the sediment-laden flow and the wear of its overflow component.

For quite a long time, the research on hydraulic machinery mainly concentrates on real experiments, modelling test and numerical calculations. The numerical method is a newly developed way with the development of the computer technology which has high reliability and visualization, and the Computational Fluid Dynamics (CFD) plays an important role in the study of hydraulic machinery internal flow and its dynamic characteristics. In recent years, the research on the operation of water turbines under clean water has been very specific and in-depth [3–6]. For solid-liquid two-phase flow [7] and wear of hydraulic machinery, the researchers mostly focus on the dynamic characteristics of centrifugal pumps and a lot of experiments have been completed. Zhang Y. *et al.* [8, 9] studied the influence of the solid phase property on hydraulic transport performance and the distribution of solid particles in the pump channel, then analyzed the characteristics of internal flow field. Wang J. *et al.* [10, 11] used a CFX particle model to simulate the centrifugal pump in solid-liquid two-phase flow and the simulation results provided a basis for analyzing the wear of the overflowing parts, and then the reliability of particle model was also verified. Huang J. *et al.* [12] simulated a Francis turbine under a small opening condition by Fluent software and the wear of the turbine was obtained, moreover, the simulation results were consistent with the experimental results of the real turbine.

In the present research, researchers mainly take the mixture model as the main research method. The particle model is also used to study the solid-liquid two-phase flow, but its application to the turbine simulation has rarely been reported [13–15]. In this paper, the particle model and the inhomogeneous model are used to simulate and analyze the solid-liquid two-phase flow of the HL240 turbine using the ANSYS-CFX fluid analysis software. The wear of solid particles for the flow parts of hydraulic turbines under solid-liquid two-phase flow and the law of sediment flow inside the turbine are analyzed. Meanwhile, the external characteristics of the turbine under the state of solid-liquid two-phase flow are analyzed, which provides an important reference for the abrasion mechanism of the turbine in the solid-liquid two-phase flow.

2 Calculation Control Equations

2.1 Solid-liquid two-phase flow equations

In the calculation of solid-liquid two-phase flow, the governing equations of solid-phase and liquid phase are considered respectively, and the continuous equation for liquid-phase turbulence is

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho_f u_{fj}\right) = S_f \tag{1}$$

Where ρ_f is the density of liquid phase, u_{fj} is the velocity component of liquid phase, and x_j is Cartesian coordinate.

The continuous equation shows that the mass of the fluid flowing into any section should be the same as the mass of the fluid flowing out of any other section at the same time in a continuous medium with constant density.

The momentum equation is

$$\frac{\partial\left(\rho_f u_{fj}\right)}{\partial t} + \frac{\partial\left(\rho_f u_{fj} u_{fi}\right)}{\partial x_i} = -\frac{\partial p_f}{\partial x_i} + \frac{\partial \tau_{fij}}{\partial x_i} + \rho_f g_i + F_{fdi} + u_{fi} S_f - \frac{\partial\left(\rho_f \overline{u'_{fj} u'_{fi}}\right)}{\partial x_i} \tag{2}$$

The momentum equation indicates that the magnitude of the total external force acting on the object is equal to the change rate of the momentum of the object acting in the direction of the force.

The time-average equations of solid phase are

$$\frac{\partial\left(\rho_P\right)}{\partial t} + \frac{\partial\left(\rho_P u_{Pi}\right)}{\partial x_j} = S_P - \frac{\partial\left(\overline{\rho'_P u'_{Pj}}\right)}{\partial x_j} \tag{3}$$

$$\frac{\partial\left(\rho_P u_{Pi}\right)}{\partial t} + \frac{\partial\left(\rho_P u_{Pj} u_{Pi}\right)}{\partial x_j} = \rho_P g_i + F_{Pdi} + u_{Pi} S_P - \frac{\partial}{\partial x_j}\left(\rho_P \overline{u'_{Pj} u'_{Pi}} + u_{Pj}\overline{\rho'_P u_{Pi}} + u_{Pi}\overline{\rho'_P u'_{Pj}} + \overline{\rho'_P u'_{Pj} u'_{Pi}}\right) \tag{4}$$

2.2 Drag force equations

In the simulation, the particle model in the CFX fluid analysis software is used to simulate the flow law of the sediment containing medium in the hydraulic turbine. The Gidaspow model is used for the drag force between the solid and the liquid phases, and the equation is expressed as [16]

$$D_{\alpha\beta} = \frac{3}{4}\frac{C_D}{d}\gamma_\beta \rho_\alpha \left|U_\beta - U_\alpha\right| \left(U_\beta - U_\alpha\right) \tag{5}$$

When r_c>0.8,

$$C_D = r_c^{-1.65} \max\left(\frac{24}{r_c \mathrm{Re}}\left(1 + 0.15 r_c^{0.687} \mathrm{Re}^{0.687}\right), 0.44\right) \tag{6}$$

When r_c<0.8,

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

Where $D_{\alpha\beta}$ is the drag force of solid particles in unit volume of continuous phase, C_D is the drag coefficient, d_P is the mean diameter of solid particles, γ_β is the volume fraction of solid particles, R_e is the Reynolds number, r_C is the continuous phase volume fraction, ρ_f is the static pressure in the liquid phase, g_i is the acceleration of gravity, ρ_α and ρ_c are the continuous phase densities, U_β and U_d are particle velocities, U_α and U_c are the velocities of the continuous phase, and μ_c is the continuous phase viscosity.

3 Numerical Simulation

3.1 Francis turbine model

The HL240 turbine is chosen as the research object under the 24° opening condition. The design head of this turbine is 45m, the runner diameter is 1m, the unit rotational speed is 72r/min, and the unit flow rate is 1.05m^3/s. The full channel model of the turbine including spiral casing, guide vane, runner and draft tube is established using Solidworks. Then according to its different structure, the tetrahedral structure grid and hexahedral unstructured grid are used to divide the model. Theoretically, the result of numerical simulation will be gradually reduced with the increase of mesh number, until it disappears [17]. But considering the relationship between the computing performance and the computational time, the number of grids should be controlled in a certain range. Finally, based on the grid independence, the number of meshes is 4 295 627, the number of nodes is 1 457 503. The 3-D calculation model diagram of Francis turbine full flow path is depicted in Figure 1.

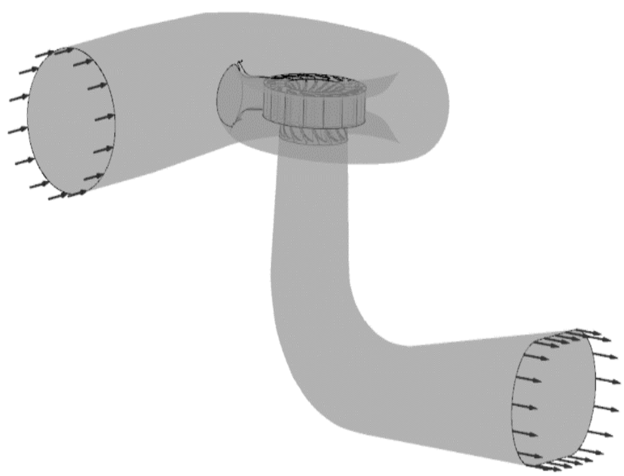

Figure 1: Full channel of flow field model of the Francis turbine

3.2 Numerical calculation

To study the flow and wear of the Francis turbine in solid-liquid two-phase flow, the Ansys flow field analysis software CFX module is adopted. Due to the complexity of the actual problem, it is not easy to realize in the simulation. In order to facilitate the analysis of the flow state of solid particles in the turbine, the following assumptions are made. (1) The liquid phase in the hydraulic turbine medium is an incompressible continuous fluid, the solid phase is discrete term, and the physical property of the two-phase is constant. (2) The particle diameter is homogeneous, the shape is spherical, and the effect of phase change is not considered. (3) The solid-liquid two-phase flow in the turbine is steady flow. (4) The collision loss of solid particles in turbine is not considered.

3.3 Experimental method

To explore the effect of solid phase properties on the dynamic characteristics and internal wear of hydro-turbine under solid-liquid two-phase flow, the following simulation test scheme is developed, and the influence of different solid states in the turbine is obtained through the analysis of different concentrations and densities. The different densities are: the particle concentration is 5% and the diameter is 0.1mm. Six kinds of working conditions including 1.5g/cm^3, 2.0g/cm^3, 2.3g/cm^3, 2.5g/cm^3, 2.8g/cm^3, 3.0 g/cm^3 are simulated. The different concentration: the particle density is 2.5g/cm^3 and the diameter is 0.1mm.

4 Simulation results and analysis

In this paper, the particle model in the ANSYS-CFX software is adopted. Firstly, the conditions with 5% particle concentration, 2.5g/cm^3 density and 0.1mm diameter is analyzed, emphasizing wear of the over-flow components such as volute, guide vane and blade. Secondly, the influence of particle properties such as concentration and density on the external characteristics of the Francis turbine is analyzed to reveal the complex flow mechanism inside the turbine under solid-liquid two-phase flow.

4.1 Wear analysis

4.1.1 Spiral casing

Figure 2 shows the volume fraction distribution of solid particles when the particle concentration is 5%, the density is 2.5g/cm^3 and the diameter is 0.1mm. As can be seen from the diagram, at the entrance of the spiral case to the inlet section, the solid particles do not cause wear to the wall, and the worn parts mainly occur at the turn of the volute with the wear at the nose end of the volute being the most serious. When the water flows through the turning place in solid-liquid two-phase flow, the solid particles accumulate here due to the inertia, abrading the volute wall especially in the volute nose end and this is where the particles reach the highest concentration. Another reason is that the flow velocity and the solid particle velocity at the nose end are higher than other parts which may increase the silt abrasion in this area.

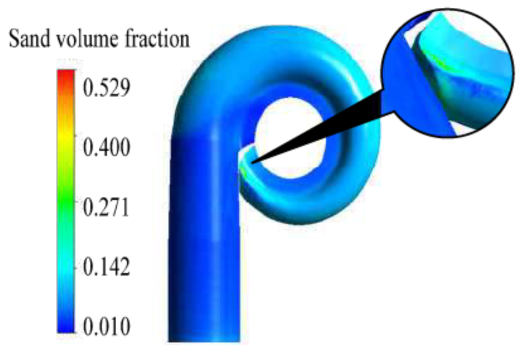

Figure 2: Volume fraction distribution of solid particles at the wall

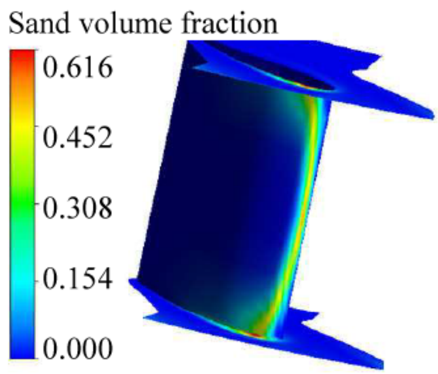

Figure 3: Volume fraction distribution of solid particles in guide

4.1.2 Guide vane

Figure 3 and Figure 4 show the distribution of the particle volume fraction of the guide vane and the velocity streamline distribution of solid particles at different blade span respectively. It can be seen from Figure 3 that the distribution of the volume fraction at the inlet of active guide vane is larger so the wear situation is more serious. The distribution shows the trend of increasing from middle to both sides and the volume fraction distribution is the largest in the hub and shroud. Meanwhile, it can be observed from Figure 4 that the flow state of solid particles is more uneven than that in the middle of the guide vanes near the hub and shroud, which leads to serious abrasion here. This is because when the water flows through the volute into the guide vanes, the flow state of the volute is uneven near the butterfly. The solid particles at the entrance of the guide vane have a serious impact and as the solid particles have a large volume fraction here this produces a lot of wear and tear to the guide vane at inlet. At the same time, due to the viscous flow, the liquid phase flows along the wall of the active guide vane, while the solid particles do not generate some wear for the active guide vane pressure surface and

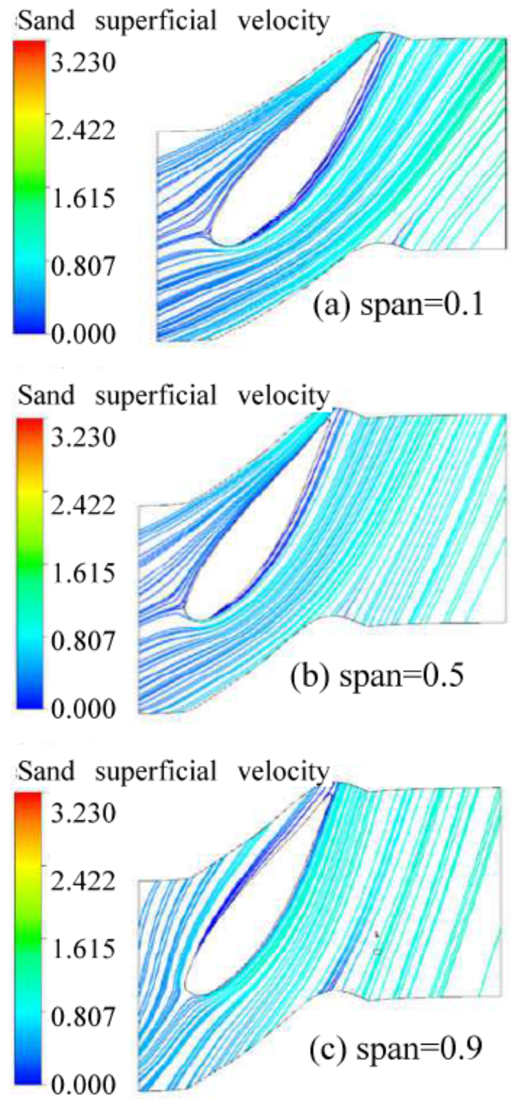

Figure 4: Flow velocity distribution of solid particles at different blade spans direction in guide vane

the suction surface. This result is also consistent with the one obtained in the literature [18, 19].

In the study on the wear condition of the runner blades, the analysis is carried out with a solid particle concentration of 5%, density of 2.5g/cm^3 and a diameter of 0.1mm. Figure 5 shows the distribution of the solid particle volume fraction at different sections of the runner blades. It can be seen from the figure, whether close to the hub or the shroud, the blade inlet volume fraction is relatively large and the impact of solid particles is also serious here, thus causing more abrasion for the blade. However, in the suction surface of the blade, the volume fraction distribution of solid particles is low, therefore there is no wear on the suction surface of the blade. The solid particles in the pressure surface of the volume fraction distribution grow

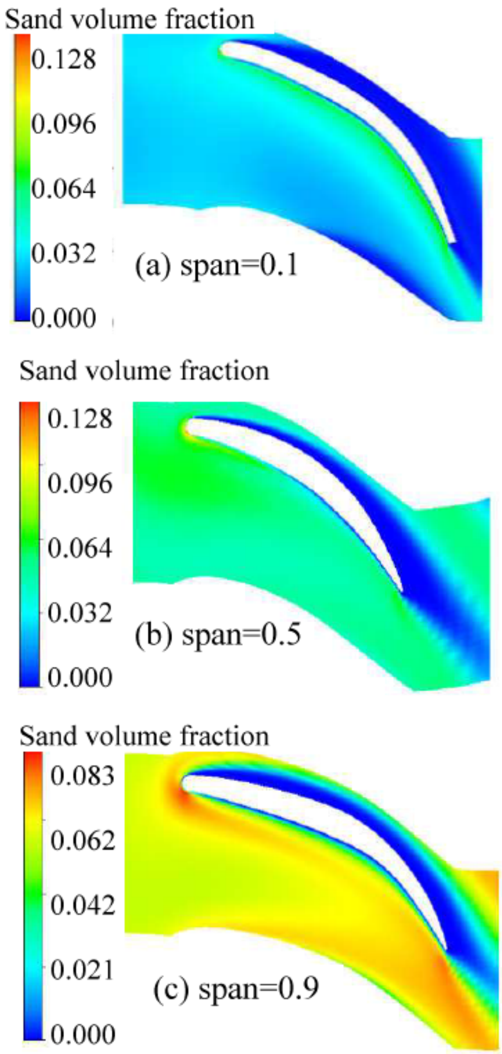

Figure 5: Volume fraction distribution of solid particles at different blade span directions

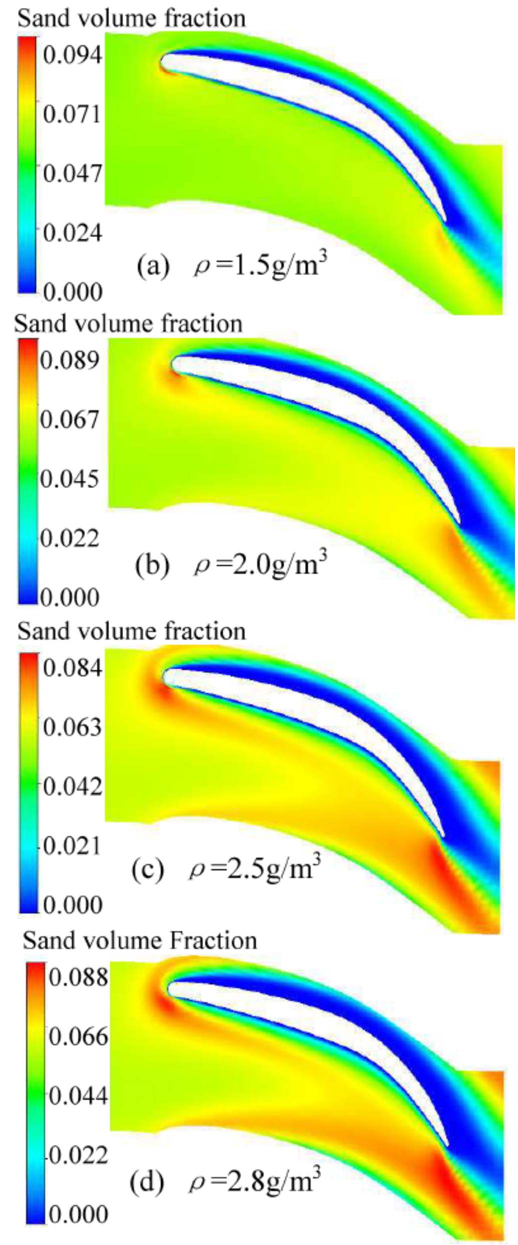

Figure 6: Volume fraction distribution of solid phase particles at the same blade span (span=0.5)

quickly from the hub to the shroud with the migration trend towards the downward ring of blade, especially close to the shroud. The effect of solid particles on the blade is largest, thus resulting in the most serious wear.

To further analyze the wear effect of different particle densities on the runner blades, Figure 6 shows the solid particle volume fraction distribution of different particle densities at the same section The analysis shows that with the increase of particle density the volume fraction of solid particles at the inlet and outlet of blade increases, especially at the outlet where the volume fraction increases to a maximum. This is because when the solid-liquid two-phase flow flows through the high-speed rotating runner, under the action of inertia and centrifugal force, the solid particles have a serious impact on the inlet and pressure surface of the blade, and as the high-speed water scours the blade near the shroud exit, the volume fraction of the solid particles is the largest. The results are consistent with the abrasion of the turbine blades in the actual hydropower station [20]. During the solid-liquid two-phase flow in the runner, the collision of solid-phase particles and over-flow components is more intense, which is very easy to cause cavitation, so the abrasion for the over current components is much more than the loss caused by them. Therefore, in the design of turbine runner, the abrasion resistance of the blade under the condition of solid-

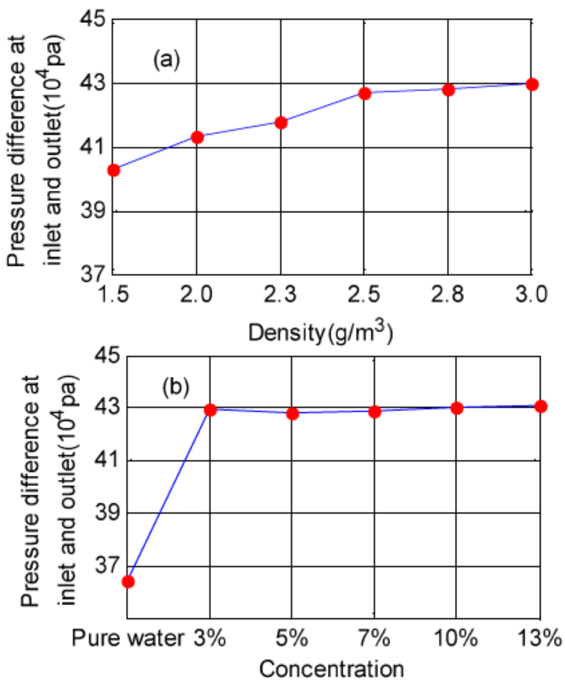

Figure 7: Variation of pressure difference of two phase flow at inlet and outlet in solid-liquid two-phase flow

liquid two-phase flow should be considered such as rational designing the blade form and making the flow distribution of solid-liquid two-phase flow in the runner more reasonable. Only then can the service life of the turbine be increased and its operating efficiency be improved.

4.2 Analysis of external characteristics

Figure 7 shows the variation curves of the pressure difference of the mixed-flow turbine at different densities and concentrations. As shown in Figure 7(a), with the increase of density, the pressure difference of the import and export increases and the degree of change is also larger. Figure 7(b) shows that the change of pressure difference is less obvious than the increase of concentration but the overall shows increased tendency. According to the two-phase flow conveying mechanism under the same conditions, the higher the gravity of the solid phase property is, the greater the energy requiring to maintain its suspension is and the greater the efficiency loss is. Under the action of inertia and centrifugal force, the flow of particles in the flow of water will inevitably lead to the loss of local head and the increase of head loss along the path, thus reducing the efficiency of the turbine.

5 Conclusions

In this paper, the fluid analysis software CFX coupled with the two-order upwind scheme discrete difference equation based on the SIMPLEC method, the particle model and heterogeneous model are used to analyse the HL240 turbine in solid-liquid two-phase flow. The wear and external characteristics of the flow parts of the Francis turbine are investigated, and some flow laws of the mixed-flow turbine are obtained. It provides some reference value for the design of turbine and the improvement of service life. The main conclusions are summarized as follows:

1. The particle model can be used to simulate the Francis turbine in solid-liquid two-phase flow, which can reveal its internal flow state and analyze the wear of overcurrent components, and the results are consistent with the experimental results. From the analysis of the external characteristic results, when the density and concentration of solid particles increase, the pressure difference at the inlet and outlet increases, which leads to the increase of the efficiency loss of the turbine.
2. Under solid-liquid two-phase flow, the volume fraction of solid particles at the turn of the volute and the nose end is large and the wear of the wall is significant. This seriously affects the symmetrical distribution of the flow in the volute, and brings a certain influence to the safe and stable operation of the runner.
3. In the high-speed rotating runner, due to the inertia and centrifugal force, solid particles mainly concentrate on the blade inlet and shroud exit and the wear here also increases. Meanwhile, due to the violent collision between the solid particles and the wall surface, it is easy to induce cavitation in the runner which increases the head loss in the runner, and the unsteady flow will then affect the flow in the draft tube.

In the future research, the optimization design of the guide vane based on metaheuristic methods [21, 22] and analysis of solid-liquid two-phase flow will be investigated. Moreover, the cavitation erosion of turbine in solid-liquid two-phase flow will be another study [23]. These studies will be of great importance to the normal and high-efficiency running of turbine.

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