Study on the wearing law of the runner and guide vanes for a Francis turbine

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Abstract. The steady Solid-Liquid two-phase flow of a Francis turbine was simulated under various work conditions with the Computational Fluid Dynamics (CFD) technology and the Euler-Lagrangian method (ELM). The wear of the turbine was also predicted using the Finnie Wear Prediction Model with the wearing law of the runner and guide vanes analyzed. The following conclusions can be drawn from the simulation results. The relative wear rates on the surfaces of runner and guide vanes increase as the sediment concentration increases. However, the relative wear rate on the runner blades firstly decreases then increases with the increase of flow rate, and the relative wear rate on the guide vanes is proportional with the cube of flow rate. By contrast, the relative wear rate of runner blades is obviously higher than that of the guide vanes. The Solid-liquid two-phase numerical method offers some reference value for the study on the wearing law of hydro turbine flow-parts in the heavy sediment-carrying rivers.

1. Introduction

Solid-liquid two-phase flow is quite common in the field of fluid machinery. More and more attention is paid to the solid-liquid two-phase theory in these years. China is rich in water resource, which plays an important role in energy strategy plan. However, the rivers are very sandy. There are 115 rivers with above 10 million tons sediment a year on average which carries 1.94 billion tons sediment into the sea. This also causes sediment wearing problem with severe wear on the turbine in 30%-40% hydro power station. Therefore, it is significant to study the wear characteristics of hydro turbine in the solid-liquid two-phase flow condition.

Since the test for solid-liquid two-phase flow in fluid machinery leads to high cost, the numerical simulation method is more popular with the development of the computational fluid dynamics (CFD). Patankar N A [1-2] simulated the particle flow with LNS method with the continuity and momentum equation of the fluid solved based on the Euler grid, and the particles was simulated with Lagrange approximation method.

e-Ap two-phase turbulence model, and the sediment wear of turbine blades was predicted in accordance with the calculated results of liquid-solid 3D velocity field. Li qifei[6] predicted the area with heavy wear in the turbine with numerical simulation method. The conveyed medium is solid-liquid two-phase or even multi-phase flow, the motion of the particles in the fluid machinery is so complex that different methods were developed by different researchers.

This paper studies the solid-liquid two-phase flow with numerical simulation method with the wearing characteristics and laws of the vanes and turbine investigated under different conditions and concentration.

2. Fundamental theory of solid-liquid two-phase flow

Numerical simulation of solid-liquid two-phase flow was based on the computation of clear water field. At present, the methods to deal with the two-phase flow are divided into two parts: Euler-Euler method and Euler-Lagrange method. Euler-Lagrange method and the Finnie Wear Prediction Model were used in the simulation.

The wear on wall surface is the function of the movement of particles, the characteristics of particles and wall surface. For most metallic wall surfaces, the wear rate is related to the angle and magnitude of impact velocity. The relationship is the Finnie Wear Prediction Model [7] with the formula as follows.

\[ E_r = kV_p^{n}f(\alpha) \]  

\[ f(\alpha) = \begin{cases} 1 & \frac{1}{3} \cos^2 \alpha \\ \sin 2\alpha - 3 \sin^2 \alpha & \end{cases} \]  

\[ E_r \] is wear rate, defined as the ratio of mass wearing of target to mass of impacting particles; \( k \) is experience coefficient; \( V_p \) is velocity of particles; \( \alpha \) is the angle between the track of a particle and the wall surface; \( n \) gets 2.

The wear of wall surface is calculated by formula (3).

\[ E_{wr} = E_r \times \dot{N} \times m_p \]  

During the numerical simulation, single typical particle takes place of many real ones with the Finnie model. \( m_p \) is the particle mass; \( \dot{N} \) is the number of particles per unit time; The unit of \( E_{wr} \) is kg/s; The wear rate density \( \rho_{E_{wr}} \) in the post processing means wear rate per unit area with the unit kg/(sm²). The constant \( k \) of materials is unknown in the Finnie model, so the wear rate is just a qualitative rather than quantitative forecasting for the wear on the wall surface from particles.

3. Numerical simulation for solid-fluid two-phase flow

3.1. Basic parameters of the hydro turbine

The diameter of the turbine is about 6 m, rated speed 107.14 r/min, rated head 110 m, rated flow 300 m³/s, blade number 13, guide vane number 20, stay vane number 20, rated output 300 MW.

3.2. 3D physical models

The Francis turbine consists of four parts: volute, gate operating mechanism, runner and draft tube, shown in Figures 1-3. The volute is meshed using unstructured grid with 581236 elements and 108683 nodes. The water operating mechanism is meshed using structured grid with 232274elements and 267225 nodes. The number of elements and nodes of guide vanes change with the degree of opening. The runner uses unstructured grid with 432591 elements and 89014 nodes, while the draft tube uses structured grid with 281253 elements and 293664 nodes.
3.3. Calculation and boundary conditions
Five guide vane openings: 10°, 16°, 20°, 24°, 28°, represented by A10, A16, A20, A24, A28, respectively; Four heads: 68 m, 87 m, 112 m, 141 m, represented by H068, H087, H112, H141. Four sand concentrations: 21.5 kg/m³, 35.3 kg/m³, 52.0 kg/m³, 68.6 kg/m³; 80 work conditions totally. Inlet conditions consist of inlet velocity of fluid phase, volume flow and inlet velocity of solid phase; Outlet condition sets reference pressure. Disserting item is the solid particle. The shape of the particle is assumed to be ball and its surface is perfect elastic collision. Particle attribute: minimum diameter 0.05 mm, maximum 0.5 mm, medium 0.25 mm, standard deviation 0.07 mm, particle density 2300 kg/m³.

![Figure 1. 3D model of the Francis turbine](image)

![Figure 2. Grid of runner](image)

![Figure 3. Grid of water operating mechanism](image)

4. Calculation results and analysis
The wear rate density on the flow surface can be obtained through the numerical simulation of sandy flow. The wear rate, \( E_{\text{rr}} \) (kg/s) can be calculated by integrals with respect to the rate density \( \rho_{E_{\text{rr}}} \) mentioned above, as shown in the formula (4).

\[
E_{\text{rr}} = \int \rho_{E_{\text{rr}}} dS
\]  

(4)

The wear rates of blades and guide vanes were obtained for 80 work conditions with 4 concentration, 4 heads and 5 opening degrees. The relative value of wear rate was the ratio of the wear rate with reference value.
4.1. Analysis of the wearing law of runner blades

Figure 4 shows the relationship between relative wear rate and the flow rate in the condition that sand concentration is 21.5 kg/m³. Under the same head, the relative wear rate decreases firstly and then increases, while the efficiency of the hydro turbine increases firstly and then decreases as the flow rate increases, which indicates that the relative wear rate on the turbine blades is low when the efficiency is high. In addition, the wear rate increases correspondingly as the head increase because the pressure on the flow parts increase.

Figures 5 and 6 shows the results of numerical simulation about the wear rate density in which the red indicates the position with severe wear while the blue means that with slight wear. Figure 7 shows the measured value that is cumulative results of three years. So the measured value can’t be simply used to compare with the numerical value under a certain opening degree or water head. However, the numerical results are consistent with the measured values in terms of the wear zone. For example, the inlet, outlet and zone close to the band of the blades show good agreement. In addition, in Figure 6, the wear of suction side is very serious with an opening of 10°, which attribute to the chaotic flow in the turbine under small opening. This phenomenon is not shown in the measured results because the turbine hardly runs under small opening.
Figure 5. Distribution map of wear rate density on pressure side of the blades in the sand concentration of 21.5 kg/m³.
4.2. Analysis of the wearing law of guide vanes

Figure 8 shows the relationship between relative wear rate of guide vanes and the flow rate in the sand concentration, 21.5 kg/m³. Under the same head, relative wear rate increases as the flow rate increases; it also increases as the head increases; consequently, the relative wear rate is mainly decided by the flow rate of the turbine.
Figure 8. Relative wear rate of guide vanes in the sand concentration of 21.5 kg/m$^3$

Fit the values in Figure 8 as power-series shown as in Figure 9. The relationship between them is as follows.

$$Y = 2.521 \times 10^{-10} Q^{3.157}$$  \hspace{1cm} (5)

Correlation coefficient $R^2=0.971$, $Y$ in the formula above is relative wear rate. The wear rate is proportional to the 3.157\textsuperscript{th} power of the flow rate. Figure 10 shows the distribution map of wear rate density from numerical simulation and most wear occur at the head of the guide vanes.

Figure 9. Fitting curve for relative wear rate of guide vanes in the sand concentration of 21.5 kg/m$^3$
Figure 10. Distribution map of wear rate density on surface of a guide vane in the sand concentration of 21.5kg/m³

5. Conclusions
The fluid-solid two-phase flow was simulated for a Francis turbine in this paper. The effect of sand particles on the flow part was estimated using Finnie Wear Prediction Model in the simulation. The wear characteristics of a Francis turbine were predicted under different work conditions. Some conclusions can be drawn from simulation results.

(1) The relative wear rate of the blades decreases firstly and then increases as the flow rate increases under the same head and sand concentration. This is consistent with the fact that the efficiency of the turbine increases firstly and then decreases, which indicates that the relative wear rate is low when the efficiency is high. When the water head increases, the relative wear rate increases correspondingly.

(2) The measured wear zones agree well with the relative wear rate distribution. The relative wear rates are larger with smaller guide vane openings. What’s more, the relative wear rate increases as the head increases.

(3) The relative wear rate of guide vanes is decided by the flow rate. The rate is almost proportional to the 3th power of the flow and most wear occur at the head of the guide vanes.

The distribution law of sediment wearing was obtained using the numerical simulation of solid-fluid two-phase flow through the whole flow passage of the Francis turbine under multiple working conditions. This study offers some reference value for the optimization design and operation of the hydro turbine in the heavy sediment-carrying rivers.

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