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Abrasion predictions for Francis turbines based on liquid–solid two-phase fluid simulations

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ABSTRACT

The runner blades and guide vanes of Francis turbines are worn by sediment in the flow. However, there are few studies about abrasion of the runner blade and guide vane for normal turbine operating conditions. This study investigated the relation between the wear rates on the surfaces of the runner blade and guide vane and the sediment concentration, and analyzed the distribution of the wear rates for normal turbine operating condition. An Eulerian–Lagrangian Computational Fluid Dynamics (CFD) procedure was used to simulate steady liquid–solid two-phase flow for various operating conditions. The Finnie model was then used to predict the abrasion. The conditions leading to abrasion in the inner flow passage components of a Francis turbine are clarified through analysis of the abrasion conditions for the runner blades and guide vanes. Field tests and simulations show that the relative wear rate on the runner blades and guide vanes increases with increasing sediment concentration, and the maximum wear on the runner blades occurs in a small opening region with the maximum increasing as the head increases. The maximum wear on the guide vanes occurs at the maximum output and the relative wear rate on the runner blades is much greater than that on the guide vanes. There is no good data, so the relative wear rates on the runner blades and the guide vanes can only be obtained numerically. Thus actual wear rates cannot be given and are beyond the scope of this paper. This paper shows the abrasion characteristics on the runner blades and guide vanes with sediment flow and provides reference data for predicting the abrasion conditions in the flow passage components of a Francis turbine.

1. Introduction

Water resources are very abundant in China, thus hydropower plays a strategic role in China's energy planning. However, there is much sediment in the rivers with 115 rivers discharging more than an average of 10 million tons sediment annually and a total of 1.94 billion tons of sediment flowing directly into the ocean each year. The erosion and abrasion of mechanical components caused by the sediment has plagued hydropower development in China [1]. Severe abrasion destroys the material in the hydropower equipment, affecting operating reliability and stability and leading to low efficiency and output. The abrasion also shortens runner lifetime and brings about high maintenance and replacement costs. Therefore, more research is needed on liquid–solid two-phase flows for various working conditions since the abrasion characteristics significantly affect the operation and maintenance of hydropower station.

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Francis turbine is one of the most widely used hydraulic turbines and many researchers have studied its internal flow characteristics, which is the basis of two-phase flow calculation. Liu et al. carried out 3D transient calculation for a prototype Francis turbine and got the unsteady flow characteristics of the turbine [2]. Susan Resiga studied how the flow from runner outlet influenced the flow in draft tube with both numerical simulation and field test [3]. Hu and Hu calculated the unsteady flow in a model Francis turbine runner and made out the flow field structure, the characteristics of swirling flow and its developing process [4]. Researches on liquid–solid two-phase flow also have been carried on for Francis turbine. Haiku et al. simulated the flow in a Francis turbine with sand-laden water and discussed the corresponding flow mechanism and hydraulic loss [5]. However, they didn't make prediction of wear rate.

Now there are many abrasion prediction models that describe abrasion caused by solid particles impacting flow passage components. The abrasion rate ER model proposed by Ahlert [9,8,11] defines the abrasion rate ER as the ratio of the abrasion mass per unit area to the sediment concentration per unit volume. The turbine abrasion intensity estimation formula and Finnie model [11] were presented by Tsuguo [12] according to the data of abrasion from 18 hydropower stations in Peru. The mass wear rate E defined by Grant and Tabakoff [10] could predict the abrasion mass caused by particles that impact the wall surface. This work uses the Finnie model. Cao et al. used Finnie model to predict abrasion distribution on turbine guide vanes, which agreed well with experimental data [6]. Liu et al. simulated the impact progress between solid particles and machine surface in a centrifugal pump for low solid particle concentration by Finnie model, which was verified by experimental results [7]. Therefore, Finnie model is appropriate for predicting wear in Francis turbine.

This paper describes numerical simulation of the liquid–solid two-phase flow in a Francis turbine to analyze the abrasion on the runner blades and guide vanes for various working conditions and various solids concentrations. The analysis characterizes the wear rate distributions on the runner blades and guide vanes.

2. Theory

Numerical simulations of the two-phase flow were based on the solution of single phase flow without sediment. The two methods used to analyze two-phase flows are Eulerian–Eulerian method and Eulerian–Lagrangian method. This study used the Eulerian–Lagrangian method.

2.1. Governing equations

1. Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (i = 1, 2, 3) \tag{1}$$

Variable i from 1 to 3 stands for the x, y, z axis, ϱ is the density and u_i are the u, v and w velocity components in the x, y and z directions.

1. Fluid phase governing equations

$$\frac{\partial(\rho u \Phi)}{\partial x} + \frac{\partial(\rho v \Phi)}{\partial y} + \frac{\partial(\rho w \Phi)}{\partial z} = \frac{\partial}{\partial x}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial z}\right) + S_\Phi + S_{p\Phi} \tag{2}$$

where Φ is a governing variable that represents u, v, or w for the momentum equation, h and w for the turbulence equations and S is the general dissipation source term.

Compared with the governing equations for single phase flow, the fluid governing equations for two-phase flow have an additional force source, $S_{p\Phi}$, from the action of fluid and particles. The definition of source term $S_{p\Phi}$ is given in the chart below:

Name of equation	Continuity equation	Momentum equation on x direction	Momentum equation on y direction
$S_{p\Phi}$	0	$\sum_k \rho_k F_{Dk}(u_{pk} - u)$	$\sum_k \rho_k F_{Dk}(u_{pk} - v)$
Name of equation	Momentum equation on z direction	Turbulent kinetic energy	Turbulent dissipation
$S_{p\Phi}$	$\sum_k \rho_k F_{Dk}(u_{pk} - w)$	0	0

where $\sum_k \rho_k F_{Dk}(u_{pk} - u)$ are the resistance source terms caused by particles interaction with the fluid per unit volume and F_{DK} is the drag force between the particles and the fluid.

2.2. Abrasion prediction model

The abrasion on the wall surface caused by the solid particles is usually modeled as a function of the particle motion, particle characteristics and wall surface characteristics. For most metallic surfaces, the abrasion is a function of the impact angle and the velocity of the particle. The Finnie model is: