Pelton turbine Needle erosion prediction based on 3D three-phase flow simulation

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Abstract. Pelton turbine, which applied to the high water head and small flow rate, is widely used in the mountainous area. During the operation period the sediment contained in the water does not only induce the abrasion of the buckets, but also leads to the erosion at the nozzle which may damage the needle structure. The nozzle and needle structure are mainly used to form high quality cylindrical jet and increase the efficiency of energy exchange in the runner to the most. Thus the needle erosion will lead to the deformation of jet, and then may cause the efficiency loss and cavitation. The favourable prediction of abrasion characteristic of needle can effectively guide the optimization design and maintenance of needle structure. This paper simulated the unsteady three-dimensional multi-phase flow in the nozzle and injected jet flow. As the jet containing water and sediment is injected into the free atmosphere air with high velocity, the VOF model was adopted to predict the water and air flow. The sediment is simplified into round solid particle and the discrete particle model (DPM) was employed to predict the needle abrasion characteristic. The sand particle tracks were analyzed to interpret the mechanism of sand erosion on the needle surface. And the numerical result of needle abrasion was obtained and compared with the abrasion field observation. The similarity of abrasion pattern between the numerical results and field observation illustrated the validity of the 3D multi-phase flow simulation method.

1. Introduction

Pelton turbine is widely used in the mountainous area. The sediment contained in the water could lead the abrasion of the unit’s flow passage surface during the operation period. The nozzle, needle and the front face of buckets are the most dangerous components exposed to the erosion. The silt erosion of ejection mechanism will change the surface characteristic of needle. Therefore, this will lower the quality of high velocity jet, influence the energy exchange between the jet and runner, and lead unsteady flow which may reduce operation reliability of the whole unit.

Brekke divided the sand erosion in hydraulic turbomachines into three categories: micro erosion on surface exposed to very high velocities of very fine sand grains of magnitude 60 μm and smaller, secondary flow vortex erosion, collision with the wall of sand grains with sizes from 5mm and up[1]. Bhola Thapa investigated the sand erosion mechanism in Pelton turbine and Francis turbine with high water head. He studied the flow in the turbine and identified the region of highest velocity and acceleration where most serious sand erosion occurred and qualitatively summarized three factors...
affecting erosion rate which are operating conditions, eroding particles’ properties and substrate’ properties\(^2\). Bajracharya made a study of Chilime hydro unit about the sand erosion of Pelton turbine nozzles and buckets. He calculated the flow of different needle openings and considered that the initial of cavitation was the main cause of heavily eroded needle surface based on the pressure variations\(^3\).

With the development of computational fluid dynamics, 3-D multiphase flow simulation can be applied to predict the flow and abrasion characteristic of the ejection mechanism in Pelton turbine. This paper will adopt the Eulerian-Lagrangian multiphase flow model to investigate the erosion characteristic of nozzle and needle in Pelton turbine operating in sand laden water.

2. Simulation model

2.1. Governing equations

This simulation adopted the Eulerian-Lagrangian multiphase flow model. Water and air simulated with VOF model considered as continuous phases, while, sand particles simulated with discrete particle model.

The VOF model can be used to predict the interface shape of two or more immiscible fluids. This model introduces volume fraction of each phase and the interface shape can be obtained from solving the volume fraction of the phases in each control volume. A single group of governing equations is solved throughout the domain, which is dependent on the volume fractions of all phases through the properties \( \rho \) and \( \mu \) as shown below\(^4\).

\[
\rho = \sum \alpha_i \rho_i \quad (1)
\]
\[
\mu = \sum \alpha_i \mu_i \quad (2)
\]
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (3)
\]
\[
\frac{\partial}{\partial t} \left( \rho \mathbf{u} \right) + \nabla \cdot \left( \rho \mathbf{u} \mathbf{u} \right) = -\nabla p + \nabla \cdot \left( \mu \nabla \mathbf{u} \right) - \frac{2}{3} \nabla \cdot \left( \rho \mathbf{u} \right) \nabla \mathbf{u} \quad (4)
\]

The effects of turbulence is represented by the additional terms of Reynolds stresses, \(-\rho \mathbf{u} \mathbf{u} \), which must be modeled to closed the equation. And the \( k - \varepsilon \) turbulence model is chosen for closure. To analyze swirling flow in boundary layer, the renormalization group (RNG) \( k - \varepsilon \) model with a non-equilibrium wall function is adopted\(^5\). The equation for the turbulence kinetic energy, \( k \), and its rate of dissipation, \( \varepsilon \), are obtained from the following transport equations:

\[
\frac{\partial}{\partial t} \left( \rho k \right) + \nabla \cdot \left( \rho k \mathbf{u} \right) = \nabla \cdot \left( \mu \nabla k \right) + G_k - \rho \varepsilon - Y_m \quad (5)
\]
\[
\frac{\partial}{\partial t} \left( \rho \varepsilon \right) + \nabla \cdot \left( \rho \varepsilon \mathbf{u} \right) = \nabla \cdot \left( \alpha \mu \nabla \varepsilon \right) + \frac{C_{\mu} \varepsilon}{k} G_k - C_{\varepsilon \rho} \rho \frac{\varepsilon^2}{k} - R_k \quad (6)
\]

The discrete particle model is used to track the sand. This model can describe the interaction between discrete particle and continuous phase and the collision of sand particles. The governing equation of discrete particle is as follows:

\[
\frac{d \mathbf{u}_p}{dt} = F_d (\mathbf{u} - \mathbf{u}_p) + \frac{\mathbf{g} (\rho_p - \rho)}{\rho_p} + \mathbf{F} \quad (7)
\]

where \( \mathbf{F} \) is an additional acceleration (force/unit particle mass) term, \( F_d (\mathbf{u} - \mathbf{u}_p) \) is the drag force per unit particle mass and

\[
F_d = \frac{18 \mu C_d}{\rho_p d_p^2} \frac{d}{24} \quad (8)
\]

Here, \( \mathbf{u} \) is the fluid phase velocity, \( \mathbf{u}_p \) is the particle velocity, \( \mu \) is the molecular viscosity of the
fluid, $\rho$ is the fluid density, $\rho_p$ is the density of the particle, and $d_p$ is the particle diameter. Re is the relative Reynolds number, which is defined as

$$Re = \frac{\rho d_p |u_p - u|}{\mu}$$

Equation (7) incorporates additional forces ($F$) in the particle force balance that can be important under special circumstances. The first of these is the “virtual mass” force, which is required to accelerate the fluid surrounding the particle. This force can be written as

$$F = \frac{1}{2} \rho_p \frac{d}{dt} (u - u_p)$$

An additional force arises due to the pressure gradient in the field:

$$F = \left( \frac{\rho}{\rho_p} \right) u \nabla u$$

Erosion rate on the wall is predicted based on the equation as follow:

$$R_{\text{erosion}} = \sum_{p=1}^{N_{\text{particles}}} m_p C(d_p) f(\alpha) v^b(v)$$

here, $C(d_p)$ is a function of particle diameter, $\alpha$ is the impact angle of the particle path with the wall face, $f(\alpha)$ is a function of impact angle, $v$ is the relative particle velocity, $b(v)$ is a function of relative particle velocity, and $A_{\text{face}}$ is the area of the cell face at the wall[6][7].

2.2. Physical model

This article investigated a single nozzle of Pelton turbine. Figure 1 shows the computational domain of nozzle and its downstream space.

The computational domain is divided into two parts, the water domain and air domain. The 3D axisymmetric mesh grids are obtained from 2D mesh by rotation[9]. The grids near the needle wall, nozzle wall and the interface between air and water are refined, as shown in Figure 2. The total number of mesh nodes is about 3,005,000 and elements about 2,949,000.

The inlet of nozzle set as pressure inlet with the total pressure of water head, and the volume fraction of water as 1 which means the inlet is full of water. The outer surrendering and outlet set as pressure outlet with the gauge pressure of 0, and the backflow volume fraction set to $1[11]$. The discrete
particles are injected in the inlet and the volumetric flow rate set as 1% of the continuous phases. The diameter of particles is 0.05 mm [8][12][13].

3. Results and discussion

3.1. Erosion distribution of nozzle and needle
The Pelton turbine operating in sand laden water will heavily erode the needle and nozzle, as shown in figure 3. Figure 3(a) shows Pelton needle after the severe erosion damage followed by cavitation due to the fine particles strike. Figure 3(b) shows the nozzles’ erosion damage of two jet horizontal Pelton turbine. The lower nozzle is more damaged due to large quantity of particles passing through [2].

![Figure 3. Needle and nozzle erosion field observation](image)

![Figure 3(a) Needle erosion](image) ![Figure 3(b) Nozzle erosion](image)

The pressure of needle tip is relative lower and the cavitation induced by the erosion may easily flow the initial abrasion and make worse. The erosion of nozzle tip will increase the flow area and the discharge. In other words, this will make the turbine run at partial load even if needle is at closed position at the worst. This will reduce operation reliability of the whole unit.

3.2. Numerical results of flow
The three-phase simulation is based on the accurate two-phase simulation on the continuous phases. The water-air unsteady simulation stabilized as the jet flow steadily out from the outlet. The Figure 4 illustrates water distribution of nozzle jet. Figure 4(a) demonstrates the volume fraction of water distribution on the axisymmetric plane. The jet ejects from the nozzle tip and the interface between two continuous phases is start from this position. At the beginning of this research, the gravity is not taken into consideration, thus, the volume fraction distributes symmetry on the plane. Figure 4(b) shows the isosurface of $\alpha_w=0.9$, which denotes the mass fraction of water is 99.98%.

![Figure 4. Water distribution for nozzle jet](image)

![Figure 4(a) Volume fraction of water](image) ![Figure 4(b) Isosurface of $\alpha_w=0.9$](image)

Because the water flow influences the sand particles much more and the erosion image shows the eroded position mainly appears at the nozzle and needle tips. The pressure and velocity distribution are analysed near the nozzle and needle tips. The velocity vector of nozzle jet is shown in Figure 5. The flow area decreases along the flow path which results in the higher and higher velocity magnitude. The velocity changes dramatically near the nozzle tips due to the flow changes into semi free surface flow as the outer surface begins to contact with the air instead of nozzle wall from this position. While the
flow along the needle surface is still constrained by the no-slip wall, the velocity increases slower. Thus the core area of jet has relative small velocity magnitude at the needle tip and downstream. This matches the high pressure area in pressure distribution contour. The velocity out of the high velocity core indicates that the air gains energy from the jet. In the prototype unit the velocity of air should not be neglected, but this investigation ignored it to simplify the simulation.

Accordingly the pressure distribution is shown in Figure 6(a). The pressure decreases along the flow path and the pressure at the interface suddenly turns into 0 as the jet ejects into the air domain. The pressure near the needle surface decreases along the flow path before the nozzle tips. But, after the nozzle tips, the pressure near the needle surface decreases at first and then increases which results in a relative high pressure area near the needle tips.

As the water-air simulation becomes steady, the discrete particles are added into simulation. The particles tracks are determined by the initial condition and the interaction with the continuous fluid. Figure 6(b) shows the particle tracks and the streamlines from the inlet. The black lines are particle tracks and the blue lines are streamlines. They are roughly the same, distribute uniformly and continuously. This may mainly result from a uniform inlet and small particle diameter which leads to smaller inertial force than interaction force.

3.3. Prediction of erosion

With the completion of the three-phase simulation, the erosion prediction results can be obtained. Figure 7(a) and (b) shows the erosion distribution results of needle. The upstream of needle neck appears a heavily eroded area which may result from the direct impact of sand particles. And the needle neck and needle tip distribute less severe erosion. The velocity near the needle neck changes very fast and the needle tip has a quite high velocity, so these two positions appear eroded area.

Compared with the abrasion field observation characteristic in Figure 3 (a), the predicted needle tip area is less severe eroded and the needle neck is over predicted. This is probably caused by the initial cavitation followed the erosion which can accelerate the wear process dramatically.
The erosion results of nozzle are shown in Figure 7(c) and (d). The most erode area appears at the contraction section where the velocity changes direction rapidly. And the nozzle tip, where the velocity changes fastest and has a high velocity, distributes heavy erosion rate region. Compared with Figure 3(b), the erosion distribution of nozzle is quite consistent with the field observation.

4. Conclusion
This article investigates the numerical method of erosion prediction in Pelton turbine ejection mechanism based on the water-air-sand three-phase simulation. By using the Eulerian-Lagrangian multiphase flow model, the three-phase simulation is performed, the sand particles track is analysed and the numerical erosion results of nozzle and needle are obtained and compared with the abrasion field observation. The results show as follows:

1) Small particles are greatly influenced by the fluid and the particle tracks are quite like the streamlines. Thus the small particles can be analysed by fluid flow characteristics.

2) The erosion prediction method of nozzle and needle is feasible. The erosion distribution results of nozzle and the nozzle tip which is eroded heavily are consistent with the field observation. And the results also indicate the erosion appears on the needle surface. But the abrasion intensity is underestimated compared with the field observation. This may due to the acceleration effect of initial cavitation on erosion is not taken into consideration in the numerical method.

3) The recent research only simulates single operating condition and sand diameter. It will take the operating conditions, eroding particles’ properties and substrate’ properties into consideration in the following investigation.

Acknowledgments
Special thanks are due to the National Natural Science Foundation of China under Contract (No. 51009077), State Key Laboratory of Hydrosience and Engineering (Grant No. 2014-KY-05) for supporting the present work.

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