Numerical Analysis of Sand Erosion for a Pelton Turbine Injector at High Concentration

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Abstract. Hydro-abrasive erosion due to sediment flow often leads to the efficiency loss, seriously vibration, and sometimes even failure for Pelton turbines. This kind of erosion can be greatly intensified when the concentration of sand increases. It is of paramount importance to study the erosion mechanism for such machines, especially in Asia, where the sand concentration in many rivers is relatively higher due to some geologically young mountains like the Himalayas. In this study, the erosion patterns of the injector have been predicted at high sand concentration. The simulated scenario was based on continuous measurement of sediment flow during the flood season in a power plant. Firstly, the three-dimensional modeling for the whole flow domain of the injector with jet has been carried out by ANSYS Fluent. The free air-water flow from the injector has been simulated with the SST k-ω turbulence model, where the VOF (volume of fluid) model was implemented to capture the air-water interface. Then after tracking the particle movement in the air-water flow by the Lagrangian method, the Mansouri model was adopted to predict the erosion patterns. The erosion mechanism was explained by detailed analysis of particle impact properties like the average hits, the impact velocity, and the impact angle. The results show that the "velocity deficit region" will reduce erosion on the needle tip. In addition, abrupt geometry change can be designed at low-velocity regions to reduce erosion. This paper can provide a better understanding of the erosion mechanism, which can help to reduce wear in future designs.

1. Introduction

Pelton turbines are widely used in hydropower plants designed with high-head water resources. Main flow components for this kind of turbine include the stationary injector and rotating buckets. As the jet flow formulated by the injector is usually high in velocity, the injector often suffers from significant erosion when the transporting water-sand flow. The erosion is significantly serious in Asia as many rivers will carry a large amount of sand and the hardness is relatively high[1]. The erosion will reduce the operational economy and safety of the hydro plant.

In general, the erosion is affected by many factors like the type of impact particles, the particle impact
velocity, impact angle, and the materials of the particles and target walls. The first step to model erosion is to accurately predict the flow field. For the modeling of the jet characteristics, a lot of work has been done both numerically and experimentally [2-4]. For erosion modeling, a large amount of efforts has been given to establish new erosion models and apply the model in practical engineering work[5-8]. Specifically, for the study of injector erosion, a few research has been conducted to understand the erosion mechanism of the injectors. Combined with the VOF and DPM methods, Zeng[9] attempted to model the flow characteristics and erosion patterns for the injector and achieved agreement of erosion pattern with that observed in the field tests. Messa [10] numerically studied the injector erosion at different injector opening and needle vertex angle, the results indicated that a reduction of needle vertex angle is likely to enhance the erosive wear.

Although there have been a few types of research about the injector erosion, the mechanism for the injector erosion has not been fully understood. For current study, a high concentration operation condition for the injector has been determined based on continuous measurement from the field test during the flood season. Based on the particle concentration and diameter distribution obtained from the test, the injector erosion has been predicted. Detailed analysis of the sand impact properties such as the impact angle, impact velocity and the number of hits has been carried out to explain the erosion mechanism.

2. Research model and numerical simulation method

2.1 Research model and mesh
The injector investigated for the current study consists of a needle body and nozzle casing. The water inside the injector will accelerate when approaching the outlet, and when it flows out from injector, the water will formulate into a free jet. Therefore, the calculation region was divided into two separate domains, namely, the water domain and jet domain, as shown in Figure 1.

![Figure 1. Computation domains.](image-url)
A structured mesh was generated with special refinement near the air-water interface and wall boundaries. This refinement would improve abilities to capture the local flow details. A final grid consists of 305081 nodes with an average y+ value of about 32 for all wall surfaces defines the whole geometry. The mesh generated for the whole flow region was shown in Figure 2.

2.2 Numerical scheme and boundary conditions.

The ANSYS Fluent was adopted to solve the Navier-Stokes equations by assuming the flow is three dimensional and incompressible. The SIMPLE scheme was used to couple the pressure and velocity with high-order resolution method. The turbulence model was chosen as the SST k-ω model. As for the modeling of the air-water interface, the VOF method was adopted by assuming there is no velocity slip between two phases.

Erosion modeling requires the particle impinging information like the impact velocity, angle and number of hits on walls. This is usually calculated by particle tracking by the Lagrangian method. In the current study, the DPM (discrete phase method) was used to track the movement of particles. This method is based on the Newton second law, and the forces considered in this law were the drag force, virtual mass force, and pressure gradient force for current study.

After obtaining the particle trajectories, the erosion rates can be calculated by choosing appropriate erosion models. Poplar models include the Oka[11], McLaury[12], Finnie[13] and etc. The model adopted for the current study is proposed by Mansouri [14], which is based on a modified angle function from Oka model. The erosion ratio (ER) of Mansouri model is calculated by the following equations:

\[ ER = C(HB)^{-0.59}F_s V_p^{2.4}f(\theta) \] (1)

\[ f(\theta) = A(\sin(\theta)^{n_1}(1 + HV^{n_3}(1 - \sin(\theta)^{n_2})))^{n_2} \] (2)

\[ HB = \frac{Hv(GPa) + 0.1023}{0.0108} \] (3)

where the \( V_p \), \( \theta \) and \( f(\theta) \) are impact velocity, angle and the function of impact angle respectively. \( HB \) and \( Hv \) are the Brinell and Vickers hardness of wall materials respectively. \( F_s \) is the shape factor for the particles.

The prediction of erosion rates are affected by the particle hardness, sharpness, diameters and etc. To better represent the actual sediment flow, continuous measurement has been carried out for three months during the flood season in the southwest of China to monitor the variations of particle contents. The information about the compositions of the sediment flow, the particle diameters and particle concentrations have been obtained. The average particle concentration through the turbine is 1.157kg/m³, and the distribution of particle diameters for this concentration has been fitted by the Rosin-Rammler curve and implemented in the Fluent code.

3. Results and discussions
3.1 Flow characteristics of the jet

To understand the erosion mechanism, the flow regime needs to be understood first as the carrier fluid greatly affects the particle trajectories and consequently the erosion patterns. Therefore, the flow characteristics of the jet from the injectors are firstly analyzed. Figure 3 gives the volume fraction distribution of the water inside the whole flow domain. The volume fraction of water inside the injector is almost 1 when the water flows out from the injector, a jet flow is formulated. This jet flow is characterized by a thin layer of the air-water interface, and the diameter of the jet is smaller than that of the injector.

Figure 4 gives the velocity distribution of the jet flow. Clearly, the water velocity increase significantly from the inlet to the outlet, the velocity at the inlet is about 3m/s and that at the outlet is about 100m/s. This increase of velocity is easy to understand as when the contracting process proceeds, the flow area will be decreasing, which will convert the pressure energy of water to kinetic energy and therefore increases the water velocity. When the water flows out from the outlet, the jet velocity becomes more stable and remains high. But it should be noted that near the surface of the needle tip, the jet velocity is slightly lower than the surrounding flow. This area is the “velocity deficit” region [15], which results from the continuous existence of boundary on the needle surface. For a further distance downstream, a large velocity gradient will occur again near the air-water interface in the air domain. This gradient results from the acceleration of stationary air by the moving of water jet.

3.2 Erosion patterns of injectors at high particle concentrations

Figure 5 gives the predicted results for injector erosion, the highly eroded areas on the needle and nozzle casing are both close to the outlet of the injectors, and they are axisymmetric for both of these two components. Clearly, this is because the flow is axisymmetric and stops accelerating near the outlet, consequently, the max impact velocity will be reached near the outlet. From equation (3), the erosion rate is exponentially related to the impact velocity of particles. As the exponent number is 2.41, the high velocity near the outlet leads to a significantly higher erosion rate than other areas.
However, the erosion distribution near the outlet show some differences for the casing and the needle surface. The erosion rate for the casing surface is higher when it is closer to the outlet, however, for the needle surfaces, the erosion rate will firstly increase and then decrease along with the flow directions. Especially, an obvious drop in erosion rate has been found for the needle tip.

### 3.3 Particle impact properties

In this part, the impact properties of particles, such as the impact speed, number of hits, and the impact angle, have been presented to analyze the erosion mechanism of injectors. As the erosion is almost axisymmetric, only two profiles (labelled as A and B respectively in Figure 6), were extracted along the axial direction at 0° on the needle and nozzle surfaces respectively.

**Figure 6.** Schematic diagram for erosion analysis: A is the profile along the needle body surface, and B is the profile along the nozzle casing surface; PA is the max erosion point on the needle surface, and PB is the max erosion point on the nozzle casing surface.
Figure 7. Erosion rates and impact properties of particles along with the profiles A and B (a) erosion rates (b) the number of hits (c) particle velocity (d) impact angle.

Figure 7 shows that, for the nozzle casing, the maximum value was located at x=0.256m, which is the end of the contraction part. This is consistent with the observation of the erosion pattern in Figure 5 (a). In addition, it can also be found that the erosion gets higher as the particles approach the outlet. Part of this reason is that the impact velocity continuously increases as the particles have been accelerated (Figure 7 (c)). Another reason is that the rise for particle hits number during this process (Figure 7 (b)), which results from the decreasing of the flow areas during the contractions process. Another interesting phenomenon observed is that the impact angle also keeps dropping during the contraction process (Figure 7 (d)). This may be related to the increasing curvature of the nozzle contraction curve.

As for the needle surface, the erosion rates firstly keeps increasing until it reaches the maximum value at x=0.26m, which is almost the same axial location as the max erosion point (labelled as PA) on the nozzle casing surface. Then the erosion rate decreases downstream the PA. This means when the needle tip is exposed to the air, it will be less eroded. This should be attributed to the “velocity deficit” region shown in Figure 4. This reduces the impact velocity of the particles Figure 7 (c) and therefore leads to erosion reduction in this region. From Figure 7 (b), it can also be found that a high impact region on the needle surface, which results from abrupt geometry change of the needle surface (as shown in Figure 6). However, this region does not lead to severe erosion as the velocity is still low. This also gives some engineering implications for further designs. Abrupt geometry should be designed at locations where the velocity is locally small to reduce the erosion.

4. Conclusions

In this paper, based on the data of sediment flow collected from a field test, a high concentration operation condition during flood season for the injectors has been determined. The injector erosion under this condition has been predicted and the erosion mechanism was explained by analyzing the impact properties of particles. The results show as follows:

(1) Highly eroded areas are located near the outlet for both the needle body and nozzle casing. This is due to the locally high flow velocity accelerated by the contraction process.

(2) The erosion rates will continuously increase until it reaches a maximum value at the outlet, however, the erosion rate on the needle body will increase firstly and then decrease. This decrease for the needle tip is related to the drop of impact velocity, which results from the “velocity deficit” near the needle tip.

(3) A high impacted but the low eroded region has been found for the needle body, which can be accounted for the locally low flow velocity. This gives some engineering implications for further designs. Abrupt geometry should be designed at locations where the velocity is locally small to reduce the erosion.
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