IX International Conference on Computational Heat and Mass Transfer, ICCHMT2016

Numerical study on sediment erosion of Francis turbine with different operating conditions and sediment inflow rates

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Abstract

Francis turbines are thought to be good solutions for both small and large-scale hydro power plant so, they have been used widely to produce power from the water sources. The turbines can be subject to erosion when the turbines operate in sediment-laden water. The erosion can reduce the performance, changes in flow pattern and even breakdown of turbine. To prevent this erosion in turbine components, predicting the region of erosion might be very useful for developing coating techniques and optimization of hydraulic design of the turbine components. In this study to predict the sediment erosion of Francis turbine runner with different operating conditions and sediment concentrations, Tabakoff and Grant model was used and erosion rate was calculated. In order to figure out the effect of different operating conditions, simulations were conducted at best efficiency and full load condition. Also, to investigate the effect of sediment inflow rates, inflow rates were varied with the value of 1, 5, 10, 20, 30, 40 and 50 kg/s. The predicted erosion patterns were similar for both operating conditions and mainly found on the pressure side of runner blades. Most of the erosion was thought to occur near the outlet side of runner due to high relative velocity for both best efficiency and full load condition. It was also found that erosion rate increased almost linearly on increasing sediment inflow rate regardless of the operating conditions.

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1. Introduction

Small hydropower of renewable energy is suitable for places where there are plenty of rivers and agricultural reservoirs; it has come into the spotlight for relatively low effects on the ecosystem. Of those of small hydro powers, Francis turbines have been used because they have broad head coverage and flow rates [1]. The sediment flowing along with water can erode the material surface of hydraulic turbine components in contact, especially for the sediments having higher hardness like quartz and feldspar. This could lead to the change in flow pattern, the loss in efficiency. Moreover it can cause the vibrations and even breakdown of Francis turbine and other components [2]. To prevent sediment related problems, settling basins could be constructed, but for small hydro power plant making it to remove sediments is uneconomical. And even with constructing and operating it, sediments cannot be got rid of completely. To avoid sediment erosion related failure in Francis turbine, it is important to predict where erosion can possibly occur.

Computational fluid dynamics (CFD) is a state-of-the-art technique that plays an important role in flow analysis of turbo machinery. CFD analysis is regarded as a strong alternative design tool which suggests insights into the flow characteristics of turbo machinery components. Many researchers have applied CFD as a numerical analysis tool for analyzing Francis turbine in areas such as prediction of rotor-stator interaction, part load performance, cavitation behavior etc. [3].

In this study, the steady state simulations were carried out to find out the area which was vulnerable to sediment erosion. Different operating conditions, best efficiency and full load conditions were considered to investigate the effect of operating condition in sediment erosion on Francis turbine runner. It also examined the effect of sediment inflow rates.

2. Basic wear theory and general erosion model

2.1. Basic wear theory

The general definition of wear is the loss of material due to the contact between a particle and solid material. There are many forms of the wear mechanism, but with regard to hydro turbines the principal mechanism is the mechanical wear which contains abrasive and erosive wear. The loss of material owing to damage on the surface by the passage of hard particles over a surface is defined as abrasive wear. A bed of particles slides over the surface with a velocity vector parallel with the surface, and the material is removed by cutting. Erosive wear is the effect of particles colliding with the surface. Particles hit the material with a velocity and angle. The continuous impact of hard particles sliding along or colliding with the material surface, results in material deformation, cutting, fatigue cracking or a combination of them. The surfaces damage first appears as small pitting, and gradually takes shape as fish-scale or wave-shaped grooves, and with time, small amounts of material tear away.

The wear [erosion] rate (mm/year) is often expressed as functions of the velocity of the impacting particles and proportional to V^n. The exponent n for pure erosion in between 3 to 4 has most often been reported. Since wear rate is a function of velocity, this means that the relative importance of erosion depends on the flow rate. Further, it depends on material hardness, grain size, solids concentration and temperature. The one most often quoted expression of wear is

$$Wear \propto (Velocity)^n \tag{1}$$

The value of the exponent n depends on the flow conditions and material properties, but the most values appear to be three. A bunch of more advanced equations estimating the erosion rate exist, but an accurate mathematical model is difficult to achieve and the results may only be used as a qualitative estimate [4-6].

2.2. General erosion model

The actual mechanism of the erosive wear is not yet clearly understood. Hence, simple, reliable and generalized model for erosion is not yet developed for engineering purpose. Most common expression for the erosive wear is based on experimental experience and they are generally expressed as a function of the factors that associated with erosive wear. The most often quoted expression is Eq. (1), as described already. The simplest way of writing equation for erosion is : Erosion = f(operating condition, properties of particles, properties of base material).

Generally, this expression is given as a function of velocity, material hardness, particle size, and concentration. The most general formula for pure erosion is described as,

$$W = K_{mat} \cdot K_{env} \cdot c \cdot V^n \cdot f(\alpha) \tag{2}$$

Where, W stands for erosion rate (material loss) in mm/year, K_{mat} is material constant and K_{env} is constant depending on environment, c is concentration of particles and $f(\alpha)$ is function of impingement angle α. V is the impact velocity of particle [7].

3. Numerical analysis

3.1. Francis turbine model and grid system

The 3D geometry of Francis turbine that was analyzed is shown in Fig. 1. The 3D domain of runner was acquired by 3D scanning and other components by 2D CAD files. The main characteristics of this hydro power plan are 16.8 m for effective head, 2.2 m^3/s for rated flow rate with 360 rpm. A grid system for computer simulation was constructed as shown in Fig. 2. ICEM-CFD, three dimensional grid generating software, was adopted to make the grid. Due to the complex internal geometry of the hydraulic turbine facilities, a hybrid grid system was made, which had a tetrahedron as a basic grid and was mixed with prism mesh to increase the accuracy of the numerical analysis. Finally, about 2.5 million elements were created.
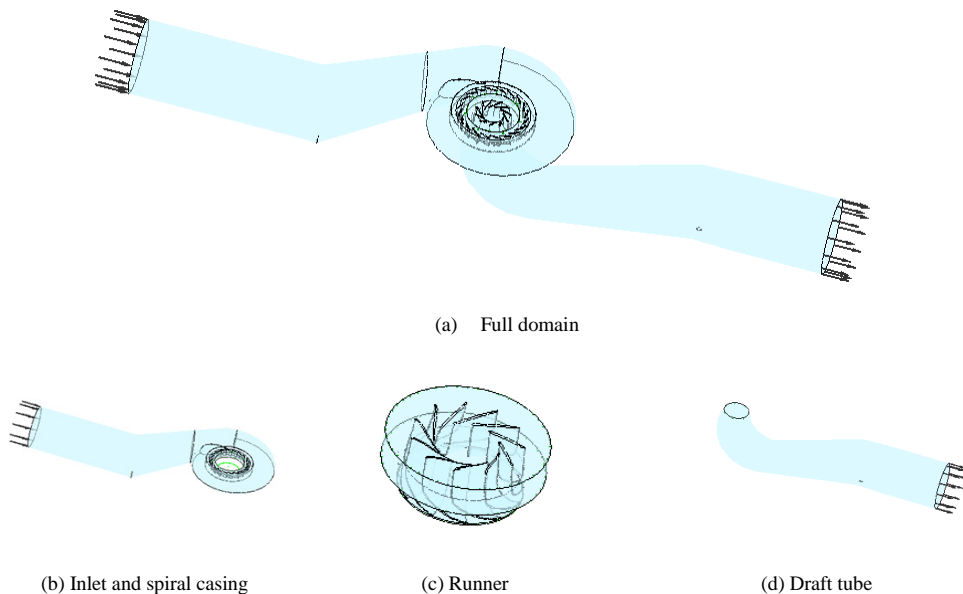

(a)   Full domain

(b) Inlet and spiral casing   (c) Runner   (d) Draft tube

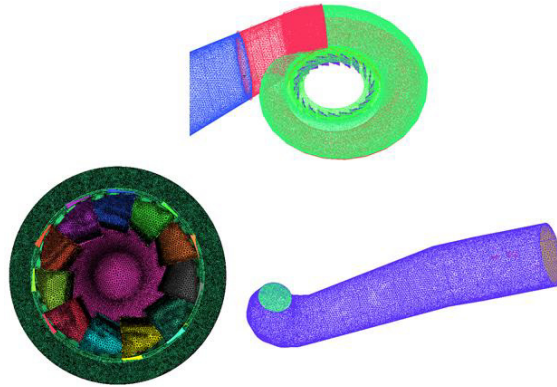Fig. 1. 3D geometry of Francis turbine for simulations.

Fig. 2. Grid system of Francis turbine.

3.2. Flow analysis

To investigate the flow field, commercial CFD code ANSYS-CFX was used. The governing equations for flow analysis are conservation of mass and momentum and as follows,

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0 \tag{3}$$

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{x_j}\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + S \tag{4}$$

From the above equations, ρ is density, u_i is velocity vector, p is pressure, τ_{ij} is stress tensor and S is source term. For turbulent flow, eddy viscosity is added and the governing equation is changed into RANS (Reynolds-averaged Navier-Stokes) equation. For the turbulence model, the Shear Stress Transport (SST) model was used, which takes advantage of k-ω and k-ε model. This model accounts for the transport of turbulent shear stress and gives highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients.

For the boundary conditions, no-slip condition was imposed on the wall of the hydraulic facilities. And for inlet and outlet boundary conditions, 2.11 bar and 0.461 bar was selected based on the past experimental data. To enhance the accuracy of the numerical analysis convective term of governing equation was discretized by high-resolution-scheme. A steady state analysis was considered and MFR (Moving Frame of Reference) was used to analyze the rotational part. The residual for velocity and pressure was 10^{-5} for convergence.

3.3. Erosion model for simulations

The sediment flowing along the water consists of various elements, such as sand, silt, clay etc. However, the main cause of the sediment erosion is affected by sand particle, especially quartz which has higher hardness than turbine components. Therefore particles were modeled based on the properties of quartz. The density of quartz is 2650 kg/m^3 and Molar mass of 1 kg/kmol is used. The diameter of particle has the minimum for 0.015 mm, maximum for 2 mm with the average value of 0.1 mm [8].

There are two erosion model supported in CFX. One is model of Finnie [9] whose erosion is a function of the velocity and impact angle. In this study, Tabakoff and Grant erosion model was adopted because it can consider more parameters, so it is relatively more reliable than model of Finnie. Tabakoff and Grant erosion model [10] is described as follows,

Table 1. Constants in Tabakoff and Grant erosion model.

Value	Dimensions	CFX-Pre Variable
k_{12}	(dimensionless)	K12 constant
k_2	(dimensionless)	
V_1	[Velocity]	Reference velocity 1
V_2	[Velocity]	Reference velocity 2
V_3	[Velocity]	Reference velocity 3
γ_0	[deg]	Angle of maximum erosion

$$E = f(\gamma)\left(\frac{V_P}{V_1}\right)\cos^2\gamma[1 - R_T^2] + f(V_{PN}) \tag{5}$$

Where, V_p is the particle velocity and

$$f(\gamma) = \left[1 + k_2 k_{12} \sin\left(\gamma \frac{\frac{\pi}{2}}{\gamma_0}\right)\right]^2 \tag{6}$$

$$R_T = 1 - \frac{V_P}{V_3}\sin\gamma \tag{7}$$

$$f(V_{PN}) = \left(\frac{V_P}{V_2}\sin\gamma\right)^4 \tag{8}$$

$$k_2 = \begin{cases} 1.0 \;\; if \; \gamma \leq 2\gamma_0 \\ 0.0 \;\; if \; \gamma > 2\gamma_0 \end{cases} \tag{9}$$

All model constants have a dimension of velocity or dimensionless value and listed in Table 1.Where,

$$V_1 = 1/\sqrt{k_1} \tag{10}$$

$$V_2 = 1/\sqrt[4]{k_3} \tag{11}$$

$$V_3 = 1/\sqrt{k_4} \tag{12}$$

In this study, constants in the erosion models were selected from quartz-steel correlation.
Overall erosion rate due to the solid particle is calculated from the following expression.

$$ErosionRate = E \cdot \dot{N} \cdot m_p \tag{13}$$

Where m_p is the mass of the particle and $\dot{N}$ is its number rate. The overall erosion of the turbine wall is the sum over all sediment particles [10]. This gives an erosion rate in [kg/s], and erosion rate density in [kg s^{-1} m^{-2}]. Erosion rate density is a good way to indicate the erosion area visually on the plane.

4. Results and discussion

4.1. Validation of simulations

To validate the computer simulations, simulations were conducted with different flow rates by changing the guide vane opening angles based on experimental data. Fig. 3 shows the performance characteristics of CFD and the experimental results. From these figures the maximum difference in efficiency was only 2%. It was observed that
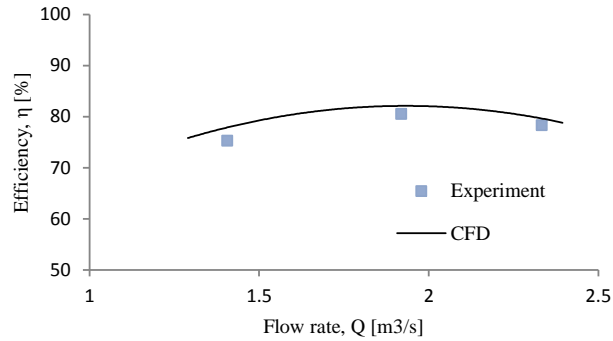
Fig. 3. Comparison of CFD and experiment.

CFD results tended to have a slightly higher value than those of the experimental value. This was ascribed to the roughness of the material which was not considered in the simulations. It was thus revealed that the simulation was reliable.

4.2. Erosion with different operating conditions

To investigate the effect of operating conditions mainly two operation conditions were considered namely the best efficiency (guide vane opening : 18 degree) and full load condition (guide vane opening : 25 degree) while other conditions remained same. Fig. 4 shows the erosion patterns on runner blade at pressure side by erosion rate density. These result means the predicted erosion rate density at full load condition is higher than at best efficiency condition because of the increased flow rate resulting in higher relative velocity at the outlet side of runner.

Fig. 5 shows the erosion pattern for one blade. It is observed that the area vulnerable to the sediment erosion was almost same even there is some difference in severity. Predicted erosion areas can divided into 3 regions, first (Fig. 5 (b), ①) is leading edge side, second (Fig. 5 (b), ②) is trailing edge side and the last (Fig. 5 (b), ③) is outlet side. In the case of leading edge side, erosion is relatively low and also severe region was small. This is because the maximum acceleration zone was found around at the inlet and leading edge side of runner. In the case of trailing edge side, the erosion area is larger than the leading edge side because of high relative velocity. The main erosion pattern is found in the outlet side of runner. This is contributed to the highest relative velocity at the outlet region of runner. And it also implies that the runner has steep curvature at outlet side, so it cannot avoid the direct impact from sediment particles.
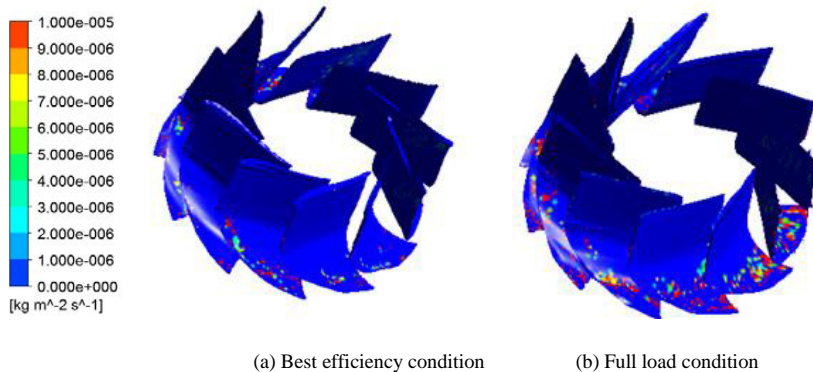

(a) Best efficiency condition   (b) Full load condition

Fig. 4. Erosion pattern on runner blades for different operating conditions.

(a) Best efficiency condition   (b) Full load condition
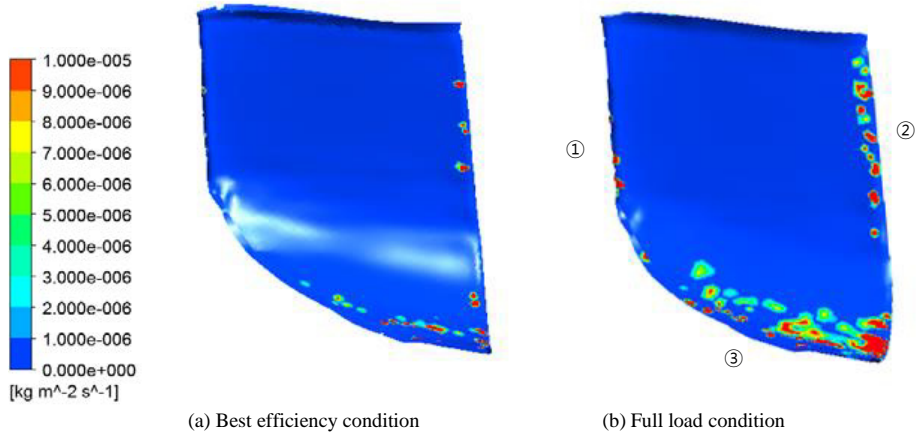
Fig. 5. Erosion pattern on a runner blade.

(a) 1 kg/s   (b) 20 kg/s   (c) 50 kg/s
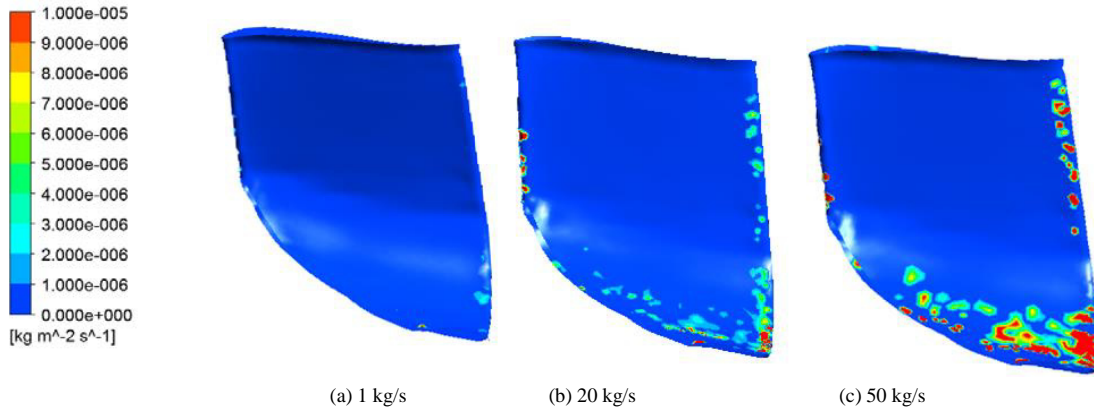
Fig. 6. Erosion pattern on a runner blade with various inflow rates
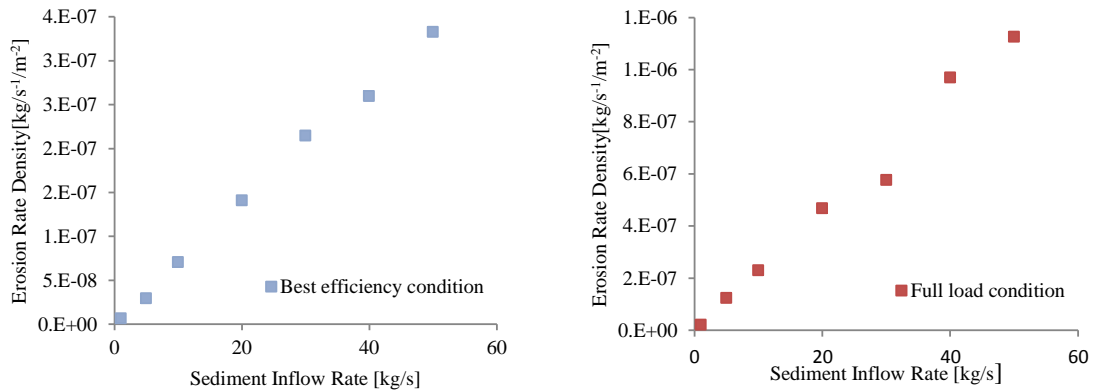

Fig. 7. Erosion rate density with respect to sediment inflow rate.

4.3. Erosion with different sediment inflow rates

To investigate the effect of sediment inflow rates, inflow rates were varied from 1 to 50 kg/s. The predicted erosion pattern on a runner blade with various inflow rates is shown in Fig. 6. As the inflow rates increased, the area where erosion rate density had high value increased. Also simulations were conducted with two operation conditions (best efficiency and full load condition) with changing the sediment inflow rate. Fig. 7 shows the averaged erosion rate density of runner blades with various sediment inflow rates at two different operation conditions. It is observed that the erosion rate density and sediment inflow rate had almost linear correlation at both of operation conditions. This means erosion rate is almost constant for given sediment inflow rate and operation condition.

5. Conclusion

The objective of this study was to predict the sediment erosion on Francis turbine blades and effects of operating conditions and sediment inflow rates on erosion. To conduct the study, 3D Francis turbine model was created and simulated with CFD code. For prediction sediment erosion, Tabakoff and Grant model was used and erosion was expressed in erosion rate density in the post-processor. As a result, it was found that three possible erosion regions were detected and mainly found at the pressure side of runner. The erosion region around leading edge was thought to be the high acceleration at the inlet side and the area around trailing edge and outlet side were attributed for the highest relative velocity around the outlet side of runner. And two operating conditions, best efficiency and full load conditions, were considered. Therefore it was observed that the predicted erosion region was similar but at full load condition, the higher erosion rate density appeared because of the increased flow rate. Additional simulations were carried out to find out the effect of sediment inflow rate. There was no specific distinction in erosion pattern but the vulnerable region to erosion was almost same for various inflow rates. As the sediment inflow rate increased the erosion rate density increased almost linearly. So when the sediment inflow rate could be estimated, the possible erosion damage might be predicted by this linear correlation. Also in this case of runner, the main possible region of erosion is around the outlet side of runner. This is because the highest relative velocity around the region, which was already known before the analysis. So if the curvature of outlet side was more considered at the design procedure, the damage by the sediment erosion would be minimized. Thus it is thought that the sediment related problem could be well prepared when the design of runner examined thoroughly.

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