Performance Comparison of Optimized Designs of Francis Turbines Exposed to Sediment Erosion in various Operating Conditions

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Abstract. Erosion on hydro turbine mostly depends on impingement velocity, angle of impact, concentration, shape, size and distribution of erodent particle and substrate material. In the case of Francis turbines, the sediment particles tend to erode more in the off-designed conditions than at the best efficiency point. Previous studies focused on the optimized runner blade design to reduce erosion at the designed flow. However, the effect of the change in the design on other operating conditions was not studied. This paper demonstrates the performance of optimized Francis turbine exposed to sediment erosion in various operating conditions. Comparative study has been carried out among the five different shapes of runner, different set of guide vane and stay vane angles. The effect of erosion is studied in terms of average erosion density rate on optimized design Francis runner with Lagrangian particle tracking method in CFD analysis. The numerical sensitivity of the results are investigated by comparing two turbulence models. Numerical results are validated from the velocity measurements carried out in the actual turbine. Results show that runner blades are susceptible to more erosion at part load conditions compared to BEP, whereas for the case of guide vanes, more erosion occurs at full load conditions. Out of the five shapes compared, Shape 5 provides an optimum combination of efficiency and erosion on the studied operating conditions.

Keyword: Francis Turbine, Variable Speed, Pressure Pulsation, Hill Chart, Hydro Power

1. Introduction
Sediment problem is prominent in hydropower operating on run-off-river type projects. Erosion rate is higher during the monsoon period due to high concentration of sediment. Comparatively it is in the monsoon when the turbine components of the power plants suffer severe damage. Damage to the turbine components leads to the drop in efficiency. Eventually after a certain period of operation, it becomes necessary to shut down the plant for repair or for replacement of the damaged components [1] [2] [3] [4] [5] [6].

Karlen et. al., 2002 [7], proposed different types of hydro-erosive pattern for the evaluation of hydro turbines, such as metallic luster, fine-scaly erosion, scaly erosion, large sized scaly erosion, in depth scaly erosion and depth erosion. Brekke et.al, 2002 [8], classified the erosion phenomena into three different group as Turbulence erosion, acceleration erosion and secondary flow erosion. These categories of erosion are differentiated based on the location of impact and operating conditions of the turbine.
Jhimruk Hydropower plant located in Putthan district of Nepal is a run-off type power plant. It is an example of plants that suffer from severe problems due to sediments [2] [6]. It has three Francis Units, each of 4.2 MW. Figure 1 shows Francis turbine runner damaged by sediment erosion. An efficiency drop of 4% at BEP (Best Efficiency Point), within the period of 1 September 2003 and 11 November 2003 was studied during thermodynamic efficiency measurements of the plant, as presented in the figure [2]. Effect of sediments on turbine mainly depends upon flow parameter, sand particle characteristics and properties of material [1] [3] [9] [4] [10] [8]. Kaligandaki and Marsyangdi are some other examples of power plants in Nepal that suffer from severe damage due to sediments.

Figure 1. Hill Chart for the whole operation range. Guide vane opening from 1 degree to 14 degrees. NED varies from 0.08 to run away speed.

Neopane [3] showed that the erosion rate increases when turbine is operated in full load condition due to increase in turbulence and relative velocity at outlet. Several attempts have also been made to tackle the sediment problem using various methods of coating. The effectiveness of the coating to tackle sediment problem depends upon the spray parameters and powder properties [1] [12]. Coating done at Marsyangdi hydropower project and HVOF (High Velocity Oxygen Fuel) coating done at Kaligandaki ‘A’ reduced the erosion rate [6] [12], but in Jhimruk hydropower project, the coating was not of much effective as the coating did not even last for one season [6].

The conventional design of Francis turbine performs well in BEP in a clean water condition. However, erosion is more susceptible when operated in part and full load conditions [1] [3]. In the traditional design, most of hydraulic energy is converted at the beginning half of the blade [4] [13]. By changing the hydraulic design procedure, it has been shown is several studies that erosion can be reduced significantly [3] [4] [8] [10] [14] [15] [16] [17]. All of these studies gave priority to BEP, but there is a huge variation in the operating load and flow conditions. To maintain the constant speed of the turbine at different operations, the guide vane angle is adjusted. This adjustment changes the flow behavior, which eventually changes the nature and quantity of erosion in turbines. This study presents a numerical technique to investigate the performances of 5 designs of Francis turbine runner at several operating conditions.

2. Design methodology and numerical model
The basic design data of Jhimruk Power Plant, which is presented in Table 1, was taken as a reference case for developing new designs of Francis turbine [4] [10] [16] [17] [18] [19]. These design data were chosen for the initial design stage, and optimized design process was adopted to develop and evaluate the erosion impact on turbine.
Table 1. Basic Design Data for Jhimruk Power Plant [2] [16] [19]

| S.N. | Parameters                  | Value | Unit |
|------|----------------------------|-------|------|
| 1    | Net design head (H)        | 201.5 | m    |
| 2    | Net discharge per unit (Q) | 2.35  | m³/s |
| 3    | Targeted Runner efficiency | 96    | %    |

CFD simulation was performed on the five different types of blades with different guide vane angles in wide range of operating conditions. These five set of runners were compared on the basis of pressure distribution, velocity gradient, velocities at leading and trailing edges. Lagrangian particle tracking method was applied to observe average erosion density rate on runner, guide vane and stay vane respectively.

CFD simulations were performed for 100 combinations of Guide Vane (GV) opening angles and the runner blade profiles. The estimation of erosion on stay vanes, guide vanes and runner blades were done on the basis on Lagrangian calculation of particle paths in a viscous flow. The original turbine contains 17 runner blades, 24 guide vanes and 24 stay vanes. However, considering the cyclic symmetricity of the region, a single blade passage, containing one stay vane, one guide vane and one runner blade was modeled for the numerical analysis in ANSYS CFX. This method reduced the computational time and the resources required. CFX is a commercial tool for computational studies that uses a finite-volume multi-block approach to solve the governing equations of fluid motion numerically on a computational grid [20]. In this study, k-epsilon and SST turbulence models based on RANS (Reynolds Averaged Navier-Stokes) equations were used in all the cases, as it offers a good combination of accuracy and robustness [4] [20]. The algebraic equations were solved iteratively with second order accurate approach. The simulations were steady state having viscous and incompressible flows.

The meshing was done in each of the fluid domains by using Turbo-grid. This is an in-built tool inside ANSYS, which creates high-quality hexahedral meshes to perform fluid dynamics analysis in rotating machinery. The factor ratio, or the rate of increase in the size of the mesh from boundary to the adjacent mesh for this analysis was chosen to be 1.15 so that the near wall refinements in the blades can be incorporated [4]. Increasing the value of the factor ratio makes it possible to meet the desired criteria of y+ value, but it will also have a convergence problem [4] [16] [17]. In this study, y+ value of ~30 was maintained around runner blade for all simulations. Although the recommended value of y+ for SST turbulence model is less than 1 according to ANSYS CFX guide, it was discussed in a previous study that the quality of the mesh degrades at such a low value of y+ in the case of Francis turbines [4].

![Mesh](image1.jpg)

**Figure 2.** Mesh used in the study for different domains a) Stay vane b) Guide Vane c) Runner blade d) a portion of draft tube
Table 2. Number of mesh nodes used in all domains (typical case)

| S.N. | Parameters       | Value | Unit |
|------|------------------|-------|------|
| 1    | Net design head(H) | 201.5 | m    |
| 2    | Net discharge per unit (Q) | 2.35 | m³/s |
| 3    | Targeted Runner efficiency | 96 | %    |

This study uses k-ε and SST turbulence models for all the analyses. k-ε model has been very successful in a large variety of flow regime in which has high Reynold Number without adverse pressure gradient [23]. SST model is useful for conditions where flow separation under adverse pressure gradient and gives more accuracy for the boundary layer simulations.

In k-ε model, Turbulent kinetic energy is defined as the variance of fluctuating velocity and turbulence eddy dissipation is calculated by rate at which velocity fluctuation dissipate. The value of k and ε brought from differential transport equations for turbulent kinetic energy and turbulent dissipation rate [20] [21] [22] [24]. Shear stress Transport (SST Model) blended the demand of k-w and k-ε models [20, 23, 25].

As the boundary conditions, the characteristics of Jhimruk Hydropower Plant was used, which has a designed output of 12.6 MW with 3 units, each running at 1000 rpm. The net head of the plant is 201.5 m and the total discharge is 7.05 m³/s. This gives a total flow of 2.35 m³/s for each unit, according to the design condition. In this study, since a single blade passage was modeled, the mass flow rate for each passage was 97.9 kg/s. However, at off-designed conditions, the guide vanes have to be oriented accordingly to maintain the synchronous speed. The blade, hub and shroud are modeled as no-slip walls such that the fluid velocity near the wall decreases due to wall friction.

The sediment particle was defined as a Quartz material with a density of 2.65 gm/cm³ and a diameter of 0.1 mm and spherical shape [3] [20]. The particle mass flow rate was based on the amount of ppm of sediment recorded in the site, [4] [16] for the favorable conditions for operation of the turbine, which corresponds to 0.07 kg/s at a concentration of 1000 particles was consider as reference for the simulation [4] [16]. In this study, the model of Tabakoff and Grant [20] was used for modeling the erosion on the blade with Quartz-Aluminum erosion parameters. The erosion rate E from this model is determined from the equation incorporated in ANSYS CFX [4] [20].

This study contains the CFD study in 10 different guide vane opening angles corresponding to different flow conditions. The difference between maximum GV opening and maximum GV closing in rotational degree was found to be 22.8°. This degree was calculated over the axis of the GV rotation. The maximum closing that was used in this study was at 18% opening whereas the maximum opening of 100% was used. The inlet flow used for each of the cases varies according to the GV opening angle. Below 18% opening, it was not possible to use the same mesh quality as the guide vanes remained very close to each other. Hence, 10 guide vane opening angles were used in between 18% and 100%.

Table 3. Guide vane opening in % corresponding to flow conditions

| Flow kg/s | 132.8 | 121.2 | 109.5 | 97.9 | 86.2 | 74.6 | 62.9 | 51.2 | 39.6 | 27.9 |
|-----------|-------|-------|-------|------|------|------|------|------|------|------|
| GV open % | 100 | 91 | 81 | 72 | 63 | 54 | 45 | 36 | 27 | 18 |
Apart from the 10 different operating conditions, this study also investigates 5 shapes of the runner blades, which were modified based on the blade angle distribution from inlet to outlet. These shapes were proposed in some of the previous literatures [4] [16] [26], which showed a significant improvement on the erosion for some of the designs. Figure 4 shows the shapes of the blades compared. The blade angle distribution affects the position where the conversion of the hydraulic energy to mechanical energy takes place. Out of these shapes, Shape 3 represents the conventional design. In this case, the blade angle increases linearly from inlet to outlet, i.e. hydraulic energy is converted to mechanical energy linearly. In contrary, Shape 1 converts most of the energy towards inlet of the runner whereas Shape 3 converts towards outlet. Shape 4 and Shape 5 are 'S' shaped blade angles, where the conversion takes place in a more sophisticated way.

Previous works have compared the erosion potential of these shape of blades at the design condition. However, this study not only focuses on one operating condition, but also develops a trend of how the values of erosion changes in guide vanes and runner blades at 10 operating conditions. As all the simulations were performed for two turbulence models, the study contains results of 100 different combinations.

3. Result and discussion

3.1. Validation of simulated results
The results obtained from both k-ε and SST simulations were first validated with the site measurement values. The absolute velocities obtained at SV Inlet, SV Outlet, GV Inlet, GV Outlet and relative velocities at runner inlet and outlet were compared. The compared results are shown in Figure 6-9.

On studying the absolute velocities versus power, the graphs shown in Figure 6 were obtained, which shows that velocities at corresponding power on k-ε and SST matches, but the experimental values of power output in SV Outlet and GV Inlet are higher than the CFD results of both k-ε and SST. This means that the velocity of water needs to be higher than simulated data for the generation of same power. This is because of position of the sensor placed during the measurement and wear and tear of the turbine runner, guide vane and stay vane. The conditions of the turbine and the sensors locations are presented in Figure 5 [11]. However, the experimental value of power output with respect to the absolute velocity at SV outlet is higher than simulated value of k-ε and SST.
Ideally, increasing velocity of water also increases the output power. However, the results of CFD and measurement shows that the trend is deviated from one another while increasing the velocity. In the absolute velocity at GV outlet, power output at 2.5 to 3.5MW are found to be similar, i.e. decreasing trend, whereas for other cases, experimental and simulated values trends are substantially different from one another. This indicates that GV the runner were worn out during the measurement.

When comparing the relative velocities at inlet and outlet, both experimental and simulated values were found to be in a similar trend, i.e. increasing relative velocity gives the increase power output, as shown in Figure 8. However, this trend is slightly deviated from the trend line of relative velocity at runner outlet trend. The relative velocity of outlet shows the similar trend from power output 2MW to 5MW. Normally, the turbines at Jhimruk do not operate at power output less than 2 MW.

Simulation of erosion on the turbine was performed at a specific condition, i.e. spherical shape of the sand with same diameter, concentration and flow rate. In the real turbines, particles have varying shape, size and concentration. To compare erosion between simulated and actual condition, the eroded turbine in the plant was observed and compared with simulated results for extreme cases. Figure 9 a), b) and c) shows the erosion on the runner at BEP, full flow and part flow conditions respectively. It
shows that erosion is mostly concentrated at the outlet of the blades for full flow and designed conditions. Turbines in run-off-river type projects such as Jhimruk are mostly vulnerable to full flow conditions. This is because i) the flow has high velocity, which directly influences the erosion and ii) the flow carries plenty of sand particles during monsoon season, when excess water is available. In dry season, the water is cleaner, and is less susceptible to erosion. Figure 9 d) shows erosion on the actual runner, combining all the operating conditions. These observations also show that the runner is heavily eroded on the outlet of the blades. Figure 9 c) also shows that during part flow conditions, erosion is mostly concentration at mid-stream position of blades. Figure 11 shows that the erosion rate would be high in part flow conditions, but in a real scenario, the effect is reduced due to the clean water.

3.2. Comparison of Efficiency

Figure 10 shows the graph of efficiency vs Guide Vane (GV) opening for five different shape of runner. In this case, the flow conditions are represented by GV opening angles with reference to BEP. Hence, according to Table 4, 0° GV opening angle represents 72% opening. Similarly, 6° opening angle represents 100% opening and -12° represents 18% opening. The best efficiency for all the shapes is obtained between 45-55% of guide vane opening. In this condition, the runner is getting optimum flow and this condition is the design condition for all shapes of runner. When the turbine is operated in part load condition, i.e when the GVs are closing positions, minimum efficiency is obtained due to turbine is getting less flow. Towards the designed condition, the deviation of efficiency for the blades is not very prominent. The best efficiency of 97.71% was obtained in Shape-1 and Shape-3 for 55% GV opening. The deviation is more noticeable at lower and higher GV openings. Towards full opening, Shape-1 and Shape-3 showed best results, whereas towards full closing, these blades had lowest efficiencies. The deviation is more noticeable at lower and higher GV openings. Shape-2 and Shape-4, on contrary, showed best results towards full closing, whereas the efficiencies decreased significantly at larger GV openings. On comparing Shape-5 with other shapes in part and full load conditions, it was seen that this shape has the flattest efficiency curve demonstrating acceptable performances for both part load and full load conditions. The difference is not very
prominent between the two turbulence models. However, in overall, the efficiency predicted by SST model is higher than $k$-$\varepsilon$ model.

**Figure 10. Efficiency corresponding to runner blade design and operating conditions using two turbulence models**

### 3.3. Comparison of Erosion

The effect of the change of the runner blade shapes on the erosion of guide vanes and runner was observed. Erosion observed in runner blade and GV for all the designs and turbulence models are shown in Figure 11-12. In general, the trend of the curves of GV opening angles and the erosion for all the shapes is irregular. However, the graph in Figure 11 shows that towards best efficiency points, the erosion in runner blades is minimum. In this condition, particles carried by flow regime is less turbulent and glided with water rather striking towards wall of runner blades. The erosion in the runner blade was maximum towards full GV closing positions. When the guide vane is towards the closing positions, flow is more turbulent and the glided particles with flow experience high centrifugal force causing the particles to strike towards the wall of the runner blade. Out of all the five different blade shapes, Shape-1 and Shape-3 had the maximum erosion at all the GV openings for both the turbulence models. Rest of the blades showed a similar trend towards best efficiencies and full load conditions. Towards full closing, the erosion was found to be maximum for Shape-2 and Shape-4 whereas minimum for Shape-5, as depicted in the figure.

**Figure 11. Erosion on runner blade corresponding to runner blade design and operating conditions using two turbulence models**
4. Conclusion

This study presented the performances of 5 designs of Francis turbine runner blades for 10 operating conditions. The comparison was made based on their potential effects on erosion of turbine components. The results showed that the performance of the turbine changes significantly, depending upon the available flow and eventual guide vane opening angles. The results were also compared with the measurement and observation, done on the same power plant. Following results were obtained from these analyses:

i. Absolute velocities at SV inlet, SV outlet and GV inlet and runner outlet increased in a linear trend with respect to power for both CFD and measurement data. However, absolute velocity at GV outlet follows a nonlinear decreasing trend with respect to the power.

ii. Erosion was mostly concentrated at the outlet of the runner blades for full flow and BEP conditions. At part flow conditions, the erosion from simulation was seen to be concentrated at mid-stream positions. However, comparing that to the real turbine conditions, the effect in part flows are not seen to be vulnerable, because concentration of particles in flow is less in dry season compared to monsoon season.

iii. Taking into account the erosion rate at different operating conditions, distribution of efficiencies and relative velocities for power generated, shape 5 showed the optimum result.

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