

Sediment erosion in guide vanes of Francis turbine operating in Himalayan rivers

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Abstract. Guide vanes are stationary component in Francis turbine that performs periodic movement through a pivoted support, in response to the change in flow or load. To allow this movement, small gaps are provided at top and bottom of vanes, called clearance gap. They are internally lined with replaceable or metal clad linings called facing plates. Operational point of turbine is determined by this movement, which regulates amount and direction of flow to runner. In presence of sediment flowing with water, significant erosion occurs which affects life and performance of turbine. It has been observed that vane faces, leading edge, trailing edge and clearance gaps were severely eroded. Which in turn enhances flow friction and secondary flows. This affects performance of entire Francis turbine. Guide Vane erosion can be controlled by suitable selection of vane profile. This study focuses on erosion phenomena, its effect and solution measure focused in guide vanes.

1. Introduction

It has been a global initiative to utilize renewable technology for fulfilling current energy demand. Hydropower has been considered as one of the most flexible and consistent renewable energy source fulfilling both base and peak energy demand, utilizing the energy of naturally moving water. Its production cost consistency, low operation and maintenance cost, environmental acceptability, economic viability and constant cost makes it to be more reliable perpetual energy source. With global installed capacity of 1036 GW, it fulfills 16% of energy demand, which is 85% of total renewable energy generated. [1] Among two third of the undeveloped projects most of them lies in Asia and South America, where, to fulfill increasing energy demand, new projects are being conceived. From Figure 1, Asia and South America has larger global potential of hydropower development along with the problems, invited by sediment flowing with water. Hence, with larger opportunities lie greater challenges [2]. Problems from suspended sediment are one of the major technical challenges for hydropower as its mechanical impact reduces performance and life of the exposed components. Prior to development of new projects, identification of existing problems, its causes, severity and research approach on mitigation are important associated issues. This ascertains consistent or enhanced generation in more economical way.



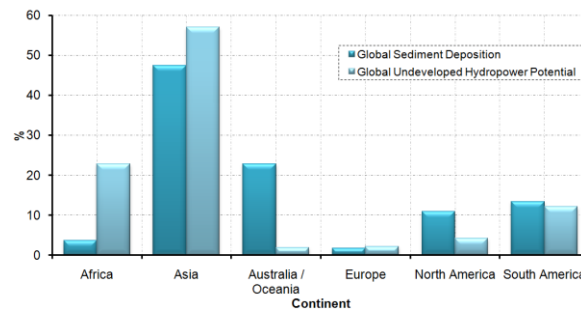


Figure 1. Global proportion of undeveloped hydropower and annual sediment load deposition [1] [2]

Francis turbines are reaction machinery with wide operational range, specific hydraulic characters, relatively higher speed and compact unit. The topographical land forms of most of the undeveloped regions are projected to have this turbine in future projects. Hence, have larger opportunities of future Research and Development. [3]

The erosion at the hub, shroud, tip and symmetric section limits the proper functioning of the guide vanes resulting the deterioration of performance at overall operation scenario. Leakage flow, secondary flows around the profile, wakes, vortex etc. are some of the major issues related with the guide vane erosion. Particularly they result into erosion due to Turbulence, secondary flow, Leakage flow and acceleration in the vicinity of the Guide Vanes. In a Francis turbine, internal pressure decreases with decreasing radius of the region. From figure 2, point 1 has higher pressure compared to point 2, which forces water to cross the vane from gaps, to reach point 2. This secondary flow is leakage and cross flow through the gaps. This flow energy remains un-utilized and disturbs the main flow stream. It has been considered a major part of internal losses. Brekke [4], 1988 in figure 2, illustrates losses at different regions from inlet to outlet of a High Head Francis Turbine. The possible total loss in a high head Francis turbine is around 5%–6%, during the operation in BEP. With minimum dry gap, losses of around 1.5% occur through leakage.

In presence of sediment flowing with water, due to erosion these gaps are further increased. In addition to it, wall roughness increases, affecting life and performance of Francis turbine. This study focused on trends of erosion, its effect and profile selection for erosion handling based on field observation, computational study and experimental study.

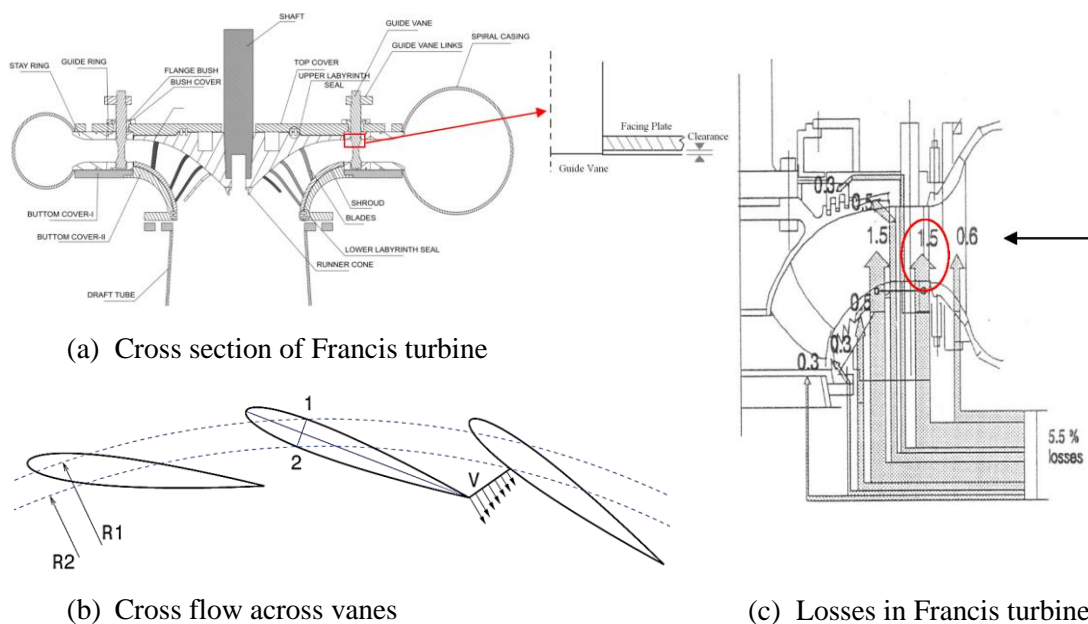


Figure 2. Flow phenomena in Francis turbine

2. Sediment Erosion in Guide Vanes of Francis turbine

At guide vane cascade highest acceleration occurs that results into higher amount of erosion resulted from sediment particles of different sizes. Theoretically four kinds of erosion are more prominent in guide vanes; Turbulence erosion, Leakage Flow erosion, Secondary flow erosion and acceleration erosion.

Turbulence erosion is caused at outlet of guide vanes due to high velocity of fine sediments. Secondary flow erosion occurs at the cornets between facing plates and guide vanes due to horse shoe vortex. Leakage flow erosion is often caused by fine sediment particle at the guide vane clearance gaps. Acceleration erosion are caused due to rotation of water in front of runner. Figure 3 shows erosion mechanism in guide vanes of Francis turbine.

So far earlier work lacks data and nature on guide vanes erosion of Francis turbine. This work fulfills the gap to some extent. During this course of this study, author visited power plants and took the relevant data, presenting the current operational scenario of guide vane in sediment laden water.

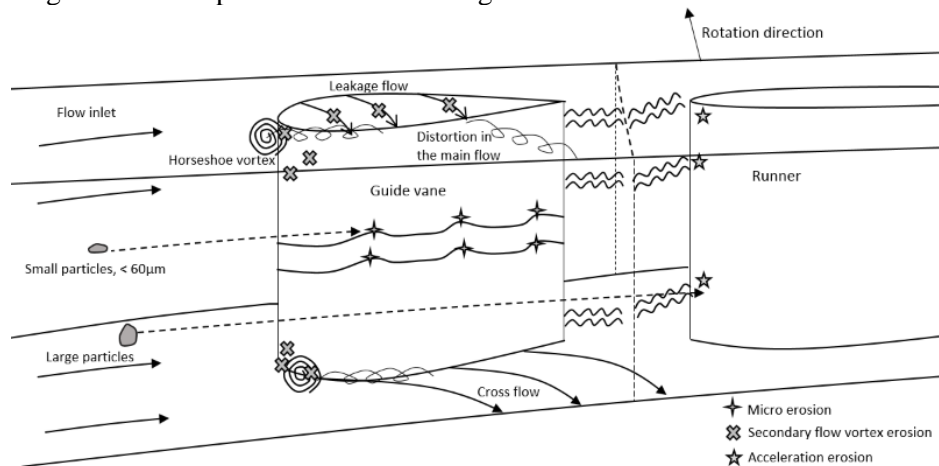
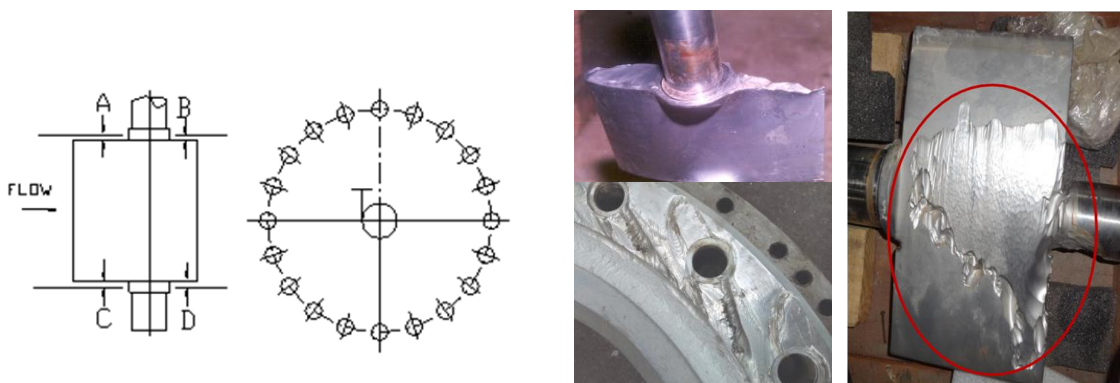
**Figure 3.** Sediment erosion in Guide Vanes of Francis turbine [5]

Figure 3 shows erosion in guide vanes. It has been reported that faces, leading edge, trailing edge and clearance gaps were severely eroded. During the study in five difference power plant almost similar and repetitive trends were observed.



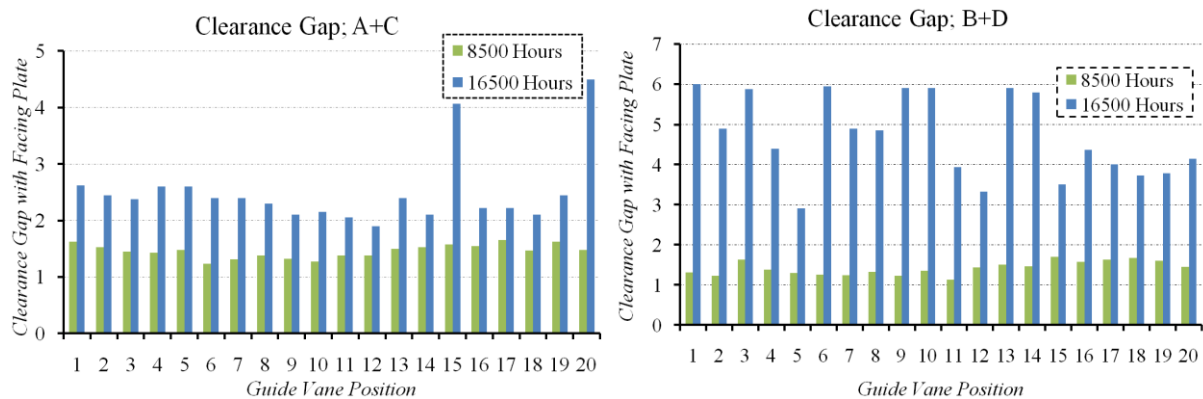


Figure 4. Sediment Erosion in Guide Vanes of Francis turbine

3. Effect of sediment erosion

Based on field study it has been identified that severe erosion occurs at faces of vanes and at clearance gaps. Two separate studies were performed; computationally and experimental in order to identify the effect of erosion.

3.1. Computational study on effect of erosion

This analysis used the geometry of model Francis turbine scaled based on IEC 60193, optimized for sediment handling by Turbine Testing Lab (TTL), Kathmandu University [6]. It was developed in reference to Jhimruk Hydropower Center (JHPC), Nepal. Separate domains for Spiral Casing, Stay

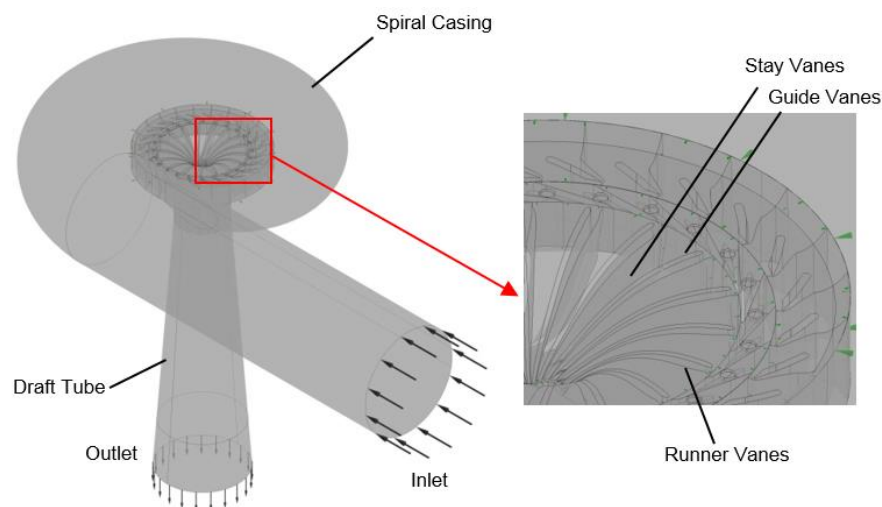


Figure 5. Computational Domain

The meshes were generated considering 5% convergence criteria in Grid Independent Analysis with an interval of 1.5 times mesh size. ICEM (a powerful meshing software) and Turbogrid meshing features of ANSYS (Analysis System software) 14 available at State Key Laboratory of Hydroscience and Engineering, Tsinghua University, China were used. Blades and Stay vanes were meshed using ATM optimized features of Turbogrid, whereas Spiral Casing, guide vanes and Draft tube were meshed using manual block refinement in ICEM to generate structural mesh. The flow cascade consists of 17 runner vanes, 24 guide vanes and 24 stay vanes. A single 3 Dimensional guide vane flow cascade was developed to generate high quality mesh. Stay vanes, guide vanes and runner vanes were transformed in CFX-pre. [7]

Seven different guide vane domains with clearance gaps of 0, 0.5, 1, 1.5, 2, 2.5 and 3 mm were prepared. The selection of gaps was based on the site observation, prototype to model relation and

computational result in Figure 5 shows hex dominant mesh in guide vanes and the runner. Boundary condition with Mass flow inlet of 227 kg/sec and absolute pressure at outlet. Rest of the boundaries were defined as wall. Frozen rotor interface was selection between rotor and stator. Turbulence was simulated using Shear Stress Transport Turbulence model, due to its robustness in predicting both near and away wall boundary flows. The RMS for solution convergence has been selected at 10^{-4} . All computations were performed in a cluster computer with eight CPUs of Intel 5645, 2.4GHz processor, 96 GB RAM and 2 TB storage.

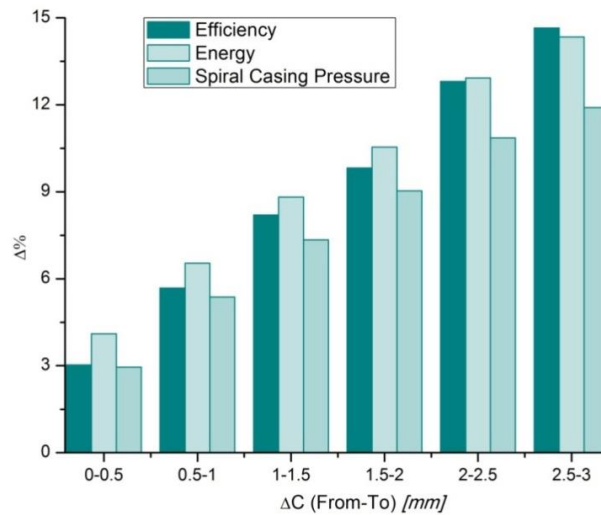


Figure 6. Effect of Clearance gap on performance of Francis turbine

3.2. Effect on flow around guide vanes

Here an additional attempt of effect of friction due to increased roughness after erosion will be studied. Erosion estimation is a destructive process, involving a test setup with agent and specimen. In a test rig either specimen or agent for both is moving, relative velocity between them is important. Laboratory estimation of erosion in hydraulic turbine is estimated with sand as agent, water as flow medium and turbine component as specimen. Sediment shape and mineral content is an absolute uncontrollable factor, whereas size can be segregated to a narrow range. This result into limitations associated with repeatability and redundancy of sediment erosion estimation. A simplified 3GV setup was developed to erode and observe the effect. Computational approach was used to study the flow similarity and structural rigidity.

Design methodology of Thapa et al. [8] was adopted to develop experimental setup. This setup has 3GV with flow equivalent to 4 passages. This kind of configuration is suitable to overcome wall effect on flow field of mid guide vane. 6 shows the design concept of the 3GV rig developed for this study. Walls on the test setup were determined based on free vortex theory, further refined with computational analysis to match the tangential and normal velocity component at outlet of vanes. The prime concept for this setup is matching velocity triangle to ensure flow similarity with model turbine, although the effect of rotating runner vanes on guide vanes has been neglected.

The Cartesian velocity components u , v and the angle θ are explained in Figure 7. The terms C_u and C_m are the tangential and meridional components of the velocity, which are analogous to the real turbine. C_u component is responsible for work done and power produced by the turbine, whereas C_m component is responsible for directing the flow downstream; defined by equation (1) and equation (2).

$$C_m = -(u \cdot \cos\theta + v \cdot \sin\theta) \quad (1)$$

$$C_u = (u \cdot \sin\theta - v \cdot \cos\theta) \quad (2)$$

Figure 7 is the plot for C_u and C_m obtained from analytical calculation, turbine simulation and cascade simulations. C_u -T and C_m -T were calculated from an earlier analysis in Koirala et. al.

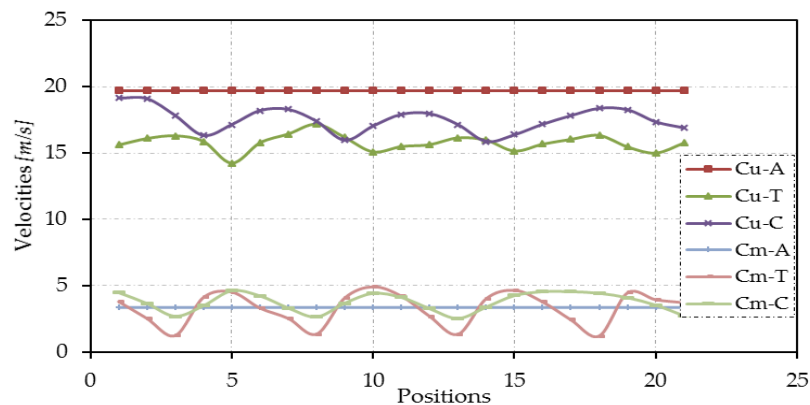


Figure 7. C_u and C_m plot of analytical, turbine simulation & Cascade calculation

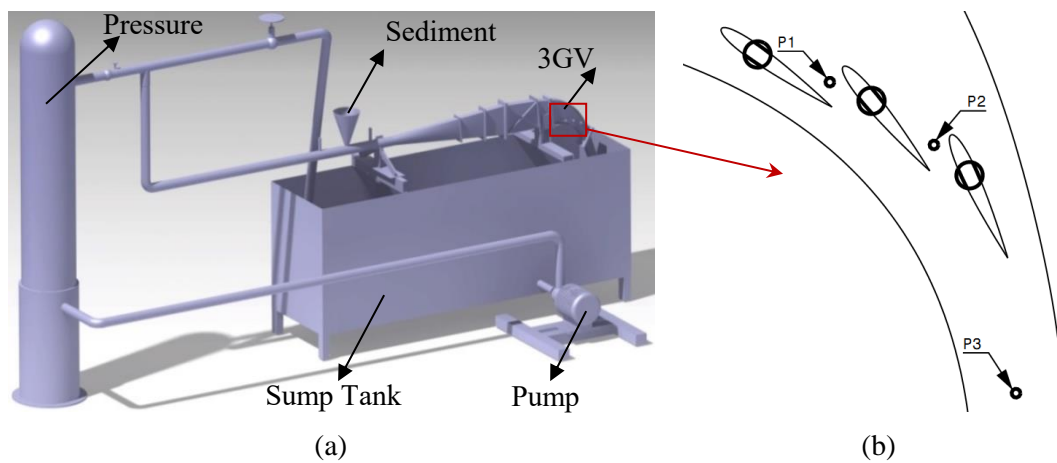


Figure 8. Test setup

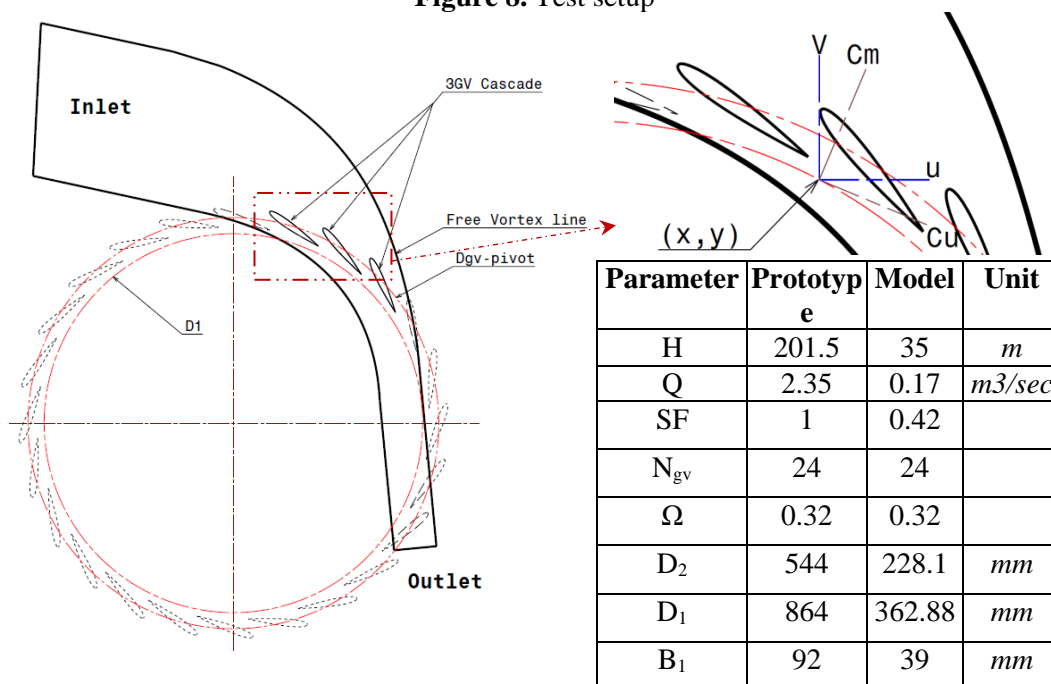


Figure 9. Design of 3GV test setup

Detachable mild steel shaft system GV was made up of Aluminum (Light weight sample for high accuracy weight measurement). Sediment was fed to the system through a hopper installed in the middle of the delivery pipe at an average rate of 7.8 gm/sec, which make the average concentration to be 1300 PPM. An Aluminum GV was installed in between two mild steel vanes in order to observe the effect of erosion due to mid vane. Figure 10 shows the erosion in mid guide vane after each interval of sediment passed through the system. Total of 21 kg sand were passed and found to have lost about 322.3 mg of weight.

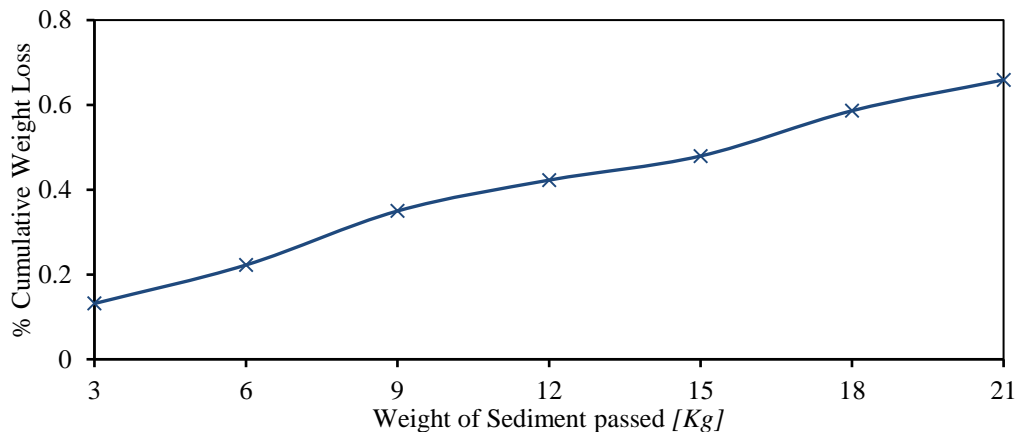


Figure 10. Experimental result of erosion in Guide Vanes

Pressure was monitored at three different points in the cascade as described in figure 9 using Omega PX 480A-100GV pressure transducers. Manufacturer's calibration sheet was used for this purpose. Data logging was performed in computer through an acquisition interface Graphtec GL500A. Figure 11 shows the increasing change in pressure with increasing mass of sediment passed through the cascade. It was found that, at pressure side of the vane maximum amount of changes occurs whereas minimum loss occurs at suction side. Considerable change of up to 2.5 % was found at outlet of vane. This change increases with increasing erosion. Increase in pressure of the flow passing vane is resulted from the flow friction induced from surface roughness caused by erosion. Random uncertainties of mean were calculated for each of the cases and were found to be in the range of 0.076% to 0.121 %, where maximum uncertainty was at P₃.

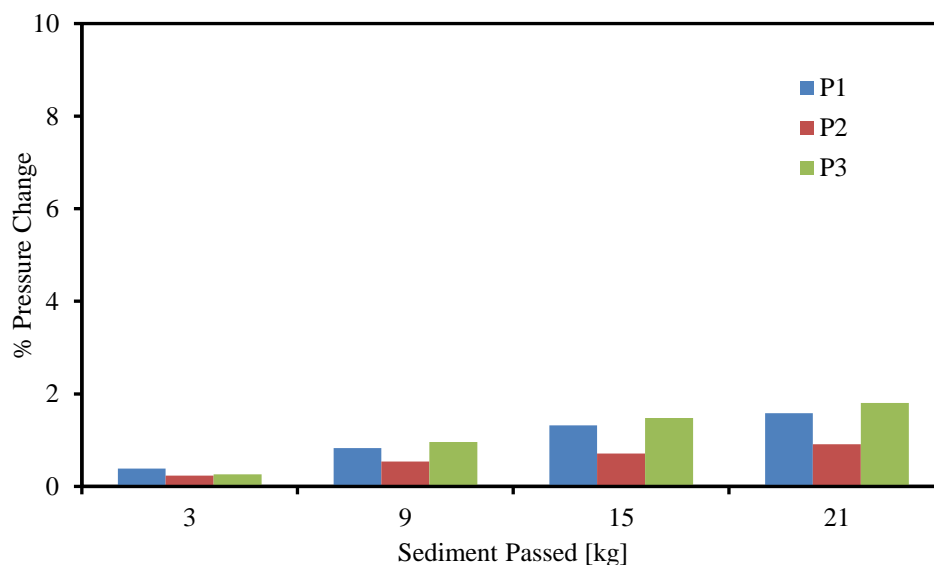


Figure 11. Effect of sediment erosion on Flow around guide vanes

4. Selection of Guide Vane Profile for Erosion handling

This study uses four digit NACA hydrofoils for guide vane. Here, hydrofoils with chamber percentage of 0% and 40% and maximum camber of 0%, 1%, 2% and 4% were used to select best profile for erosion handling. Computational studies were performed on the profiles shown in figure 11.

These profiles were generated with GUI based MATLAB interface developed for plotting guide vanes of different profiles at different angles for Francis turbine.

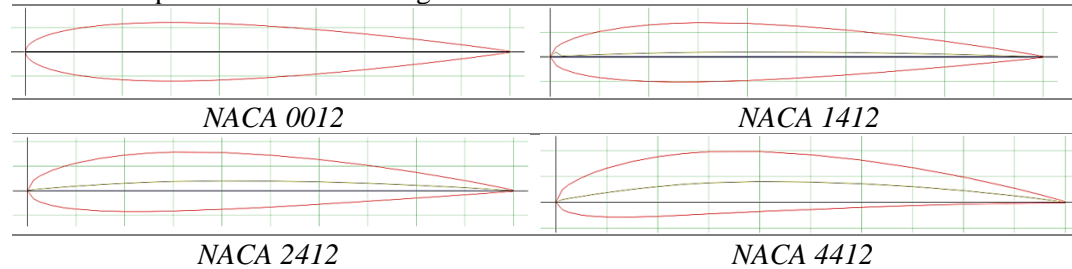


Figure 12. Guide Vane profile considered for study

Computational analysis shows that (Figure 13), Erosion Rate Density is lower at NACA 4412, hence lower erosion. Together with it, it has been observed that the pressure difference between Pressure Side and Suction Side is also lower with NACA 4412 and hence results in lower Cross Flow losses (Figure 14). In the cases with NACA 4412, it is likely that the problem on rapid increasing of clearance gap can be minimized.



Figure 13. Erosion Rate Density for various Guide Vane Profile

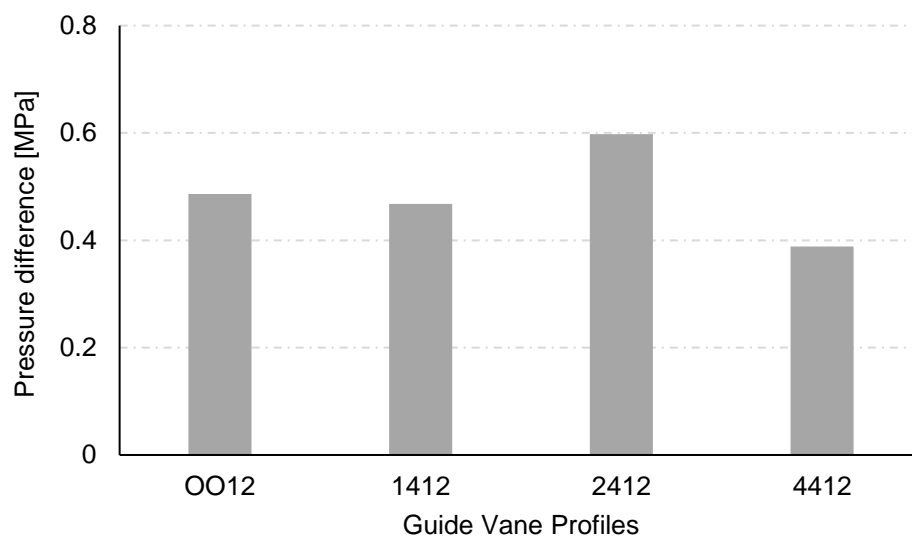


Figure 14 PS - SS pressure difference with Guide Vane Profile

Figure 15 shows the velocity triangle parameters at BEP in presence of various vane profile. It has been observed that, no significant change will upon selection of NACA 4412 over symmetrical hydrofoil except in the case of relative velocity.

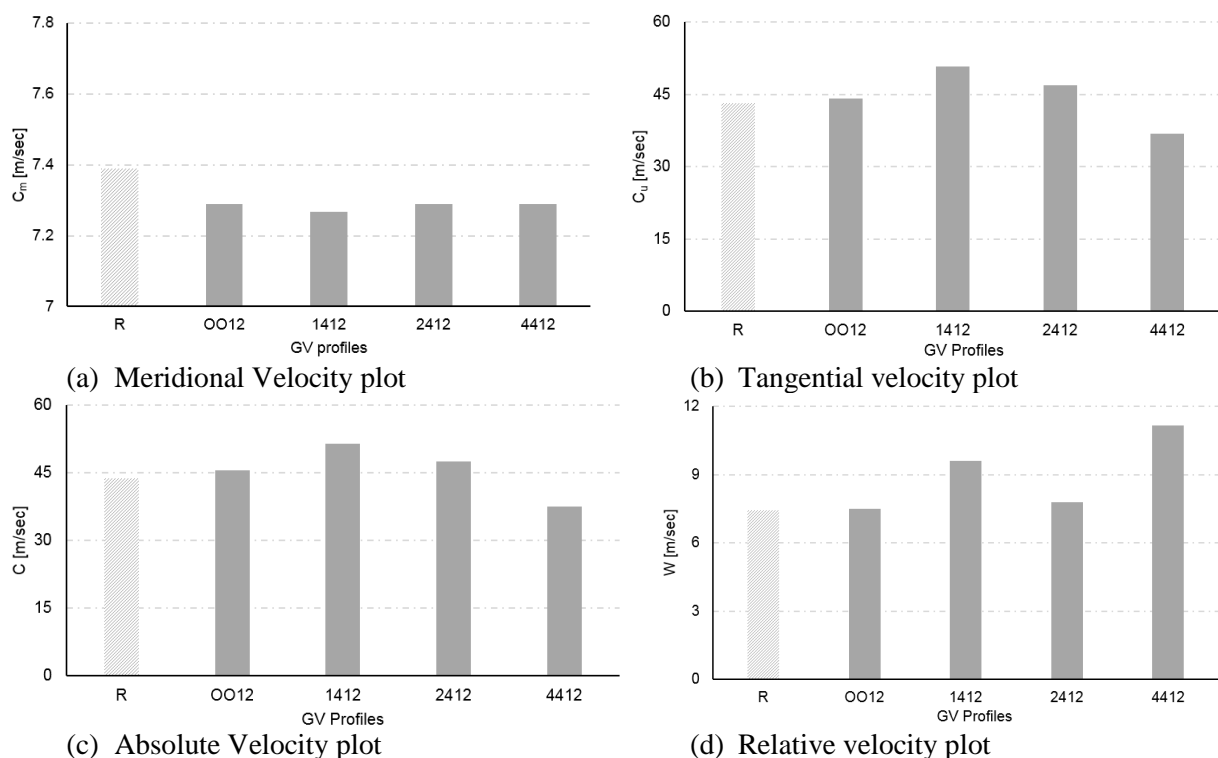


Figure 15 Velocity triangle with various Guide Vane Profiles

5. Conclusion

In course of this study, author focused on 5 majors associated with guide vanes of Francis turbine; Flow around guide vanes of Francis turbine, field observation of erosion in guide vanes of Francis turbine, Effect of clearance gap on performance of Francis turbine, Effect of overall erosion on flow around guide vanes and selection of vane profile for erosion handling.

Guide vane operates best at BEP, where wake in flow passing it, is dependent on guide vane profile and trailing edge geometry. Pressure stagnation occurs around guide vane shaft. The pressure difference between two sides induces leakage flow, whose rate is dependent on operational angle of guide vanes. Field study at KG-A showed that, at clearance gap larger losses (up to 10 mm) were found in trailing edge compared to leading one. Guide Vane angle is a strong function of localization and severity of erosion. Model turbine simulation was performed to estimate the effect of increasing clearance gap on performance of Francis turbine. About 3% of efficiency loss with increase in gap by 1% of passage height were observed. Similarly, spiral casing pressure was found to drop by 2% with every 1 mm increase in the gap. Using experimental setup of 3GV Cascade system, effect of erosion on flow around vane has been studied. It was found that with increasing erosion friction increases which ultimately increases pressure around vane and at GV outlet. After 21 kg sand passed to Aluminum guide vane 0.6 % of weight loss was observed. This consequently increases the outlet pressure of guide vane by about 2%. Finally, computational study was performed on different sets of GV profile to identify the best possible design. It was found that with unsymmetrical vanes better erosion handling and better performance can be achieved.

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