Numerical and experimental study of pump as turbine for sediment affected micro hydropower project in Nepal

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Abstract. Designing and manufacturing site-specific turbines for small hydropower is not economical. Using abundantly available Pump, from the market, as Turbine (PAT) instead of designing a completely different turbine can be much more economical for small-scale hydropower. Lot of research have been going throughout the world on this and has already proven its effectiveness. In Nepalese hydropower, including the ones already developed and the ones that will be developed in the future, Francis turbines are supposedly the suitable turbine of choice. However, designing and manufacturing Francis turbine is a tedious task and the local manufacturers, who are expert in manufacturing Cross-flow turbines; do not have the technology and competence to manufacture the modern Francis turbines. Sediment in Himalayan rivers are the major hurdles of operation as they reduce the lifetime of the turbine by a very large factor, shooting up the maintenance cost of the hydropower. The operational region of Francis turbine and PAT overlaps quite a lot, thus indicating that PAT can be used in many of the hydropower in Nepal. The Chinese and Indian pump manufacturers are already renowned in developing a wide range of pumps and supplying them in Nepal. Despite having such great opportunity, pumps have never been used in turbine mode in Nepalese hydropower. In addition to that, no research has been done, in Nepal, regarding the effects of sediment on pumps being operated as pump or turbine. This paper describes performance of pump in erosive environment using Computational Fluid Dynamics (CFD). It also compares the results obtained from the CFD analysis of sediment erosion in pump operated in pump mode as well as turbine mode with other researchers work. Finally, it compares the results obtained from the CFD with the results obtained from the experiment.

Keywords: Pump, Pump as Turbine, Sediment Erosion, Operational Challenge, Performance

1. Introduction

Hydropower is the key source of renewable energy in today’s world. Nepal is a country rich in water resources with theoretical hydroelectric potential of 83,000MW and technically feasible 43,442MW[1]. Establishing its first hydropower in 1911, Nepal carries more than 100 years of history of hydropower development[2]. However, Nepal has not been able to exploit much of its hydroelectric potential, harnessing just 1128.705 MW in the year 2019 as depicted by annual report published by NEA[3]. Despite the slow development in the 20th Century and the first decade of the 21st Century, the future...
looks promising, as there are hydropower producing 2,613.895 MW, under construction and many more in the pipeline for development. Turbines are the heart of the hydropower converting the hydraulic energy of the hydropower to the mechanical energy and transmitting it to the generator, for electricity production, through shaft. There are different types hydraulic turbines available in the industries, among all the types Francis turbines are the most used types. Even in Nepal, a study performed in the prediction of turbine types for the hydropower that will be developed in the future have shown that 75% of the hydropower in Nepal will use Francis turbines [4]. Another study done at Turbine Testing Lab have found out that the micro hydro in Nepal are using Cross flow turbines even in the sites where Francis turbines are more suited. The same study also claims that the power and efficiency of the micro hydro would have been more had the micro hydro used the Francis turbines in those sites [5]. However, introducing Francis turbines in Nepalese sites come with numerous challenges, which can be classified as Technical, Financial and Operational challenges. Francis turbines are complex turbines to design as well as manufacture. The modern design technique of Francis turbines include CFD analysis and optimization based on its results. Nepalese turbine manufacturer do not have the expertise and skills to perform the CFD analysis at such high level. In addition to that, manufacturing Francis turbine components, especially runners, require a very high level of accuracy and tolerance, which is not available with the turbine manufacturers of Nepal at this time. Despite that, some methods like casting and forging have been used to manufacture the Francis runners but the results do not seem satisfactory [6]. Adding the equipment and machines for the manufacturing of precise blades could have been possible, however, the reluctance of Nepalese manufacturers to take the risks and invest on research for new product or technology is often mentioned as one of the reasons for not being able to manufacture Francis turbines till date. There are operational challenges associated with the application of Francis turbines in Nepalese, sediment laden, hydropower. Many hydropower developers complain about the reduction of efficiency after a short period of operation, depicting huge monetary losses. In Francis turbines operated in sediment-laden rivers, the frequency of repair and maintenance of underwater parts are comparatively high, resulting in an increase in the outage time of the machine. One of the main reasons, which can be attributed to machine outage, may be because of inappropriate assembly design of turbine [7].

Some of the challenges associated with Francis turbine could be minimized if there existed an alternative. One of the alternative of Francis Turbine could be using pump as turbine. A lot of research has been done worldwide to utilize pump as turbine. Also the head range and operational behavior of PAT overlaps with that of Francis turbines [9]. As mentioned earlier, the technical challenge associated with design and manufacturing of Francis turbine could be overseen, as pumps are readily available in wide range of heads in Nepalese Market. Instead of frequently designing site-specific turbines and

![Figure 1. Operating range of various turbine with PAT [8]](image-url)
manufacturing them, choosing the pump from market with some calculations of head and discharge value of any site can be much more convenient. This is even more intriguing financially, as their payback periods, 2 years, are much lesser than that of other turbines[9]. As there has been no research on the sediment erosion of pumps used as turbines, it is still not possible to compare the two in this regard. Although a lot research has been done worldwide in field of pump as turbine and installed successfully, this is still a challenge for a country like Nepal where the sediment is prominent. This paper focuses on the performance of pump in erosion environment using Computational Fluid Dynamics (CFD). Further the experimental testing is done at lab with sediment samples from a local river for both pump and turbine mode to investigate the erosion pattern. For experimental set up, pump impeller was painted with different colors in the order of ANSYS post processors’ color mapping. The paper also shows results of the laboratory tests and their analysis.

2. Methodology
2.1 Pump Selection

The actual performance of pump in turbine mode is difficult to predict. Generally, pump manufacturers do not provide performance curve in turbine mode. However, a study conducted in the past have concluded that that the BEP of the impeller in turbine mode is obtained at a higher flow and head than that of the same impeller in pump mode[10]. In the same research, an attempt has been made to relate the head and flow conversion factor for prediction of head and flow for the impeller to be operated in turbine mode with the rated head and flow of the pump. The research has concluded that the conversion factors were a function of the specific speed. The research has conducted experiments on eighty different pumps to obtain the performance of the pumps in turbine mode and to plot a graph for the conversion factors for head and flow against the specific speed. The research have sampled data from more experiments than any other research available, thus the graph plot in this research has been considered to determine the conversion factors for head and flow.

Two pumps have been used in this study: Pump 1 and Pump 2. The rated head and discharge of the Pump 1 is higher than that of Pump 2. Pump 1 operates in pump mode to pump the water and runs Pump 2 in turbine mode. The head and discharge conversion factors of Pump 2 are determined to be 1.12 and 1.6 respectively. The specifications of each pump are given in Table 1. The speed of the pump in turbine mode is kept as high as possible such that its runaway speed does not exceed the rated speed of pump. However, in actual practice permissible speed, for pumps driven by 50Hz and 60Hz grid frequency, are usually 3000 or 3600 rpm[8]. In addition, while considering the nominal speed of the turbine, the coupling of generator load to the pump is considered. For a turbine coupled directly to the synchronous generator, the nominal speed of the turbine is chosen to be one of the synchronous speeds. Generators with 1500 rpm are generally available in the market as they are relatively smaller than generators with lower synchronous speed. Therefore, 1500 rpm is chosen to be the nominal speed of the pump in turbine mode, for this case. The specifications of two pumps used in this experiment is given in Table 1.

**Table 1.** Data provided from pump manufacturers

| S.N | Specific Speed | Rated Output | Rated rpm | Rated Head (m) | Rated Discharge (lps) | Duty Selected |
|-----|----------------|--------------|-----------|----------------|----------------------|---------------|
| 1.  | 42             | 2.82 kW      | 2870      | 18             | 16                   | Pump mode     |
| 2.  | 36             | 1.57 kW      | 2870      | 16             | 10                   | PAT mode      |
2.2. Numerical analysis

After a thorough observation of the impellers taken from the pump, it has been modeled in a commercial design software. Similarly, the spiral casing has been modeled using the drawings provided by the manufacturer. The fluid domain of the spiral casing is then created using the same model. The hexahedral mesh elements for the impeller are generated in ANSYS Turbo grid 18.1. The tetrahedral mesh for the spiral casing are generated in ANSYS workbench.

![Figure 2. Domain of pump impeller for CFD analysis](image)

The erosion pattern of pumps are studied numerically in ANSYS CFX. ANSYS CFX allows users to use one of two erosion models, available within it, at a time. The two erosion models available in ANSYS CFX are Finnie and Tabakoff models. Based on the argument provided by Gautam et al. [11], Tabakoff model has been chosen for this case. Gautam et al. argue that Tabakoff model can capture the real scenario of sediment erosion in hydraulic turbines as, parameters considered by this model are more than that of Finnie model and it also combines all angle of attack of sediment particle for calculation of erosion [11].

Erosion rate $E$, in Tabakoff erosion model, are determined from the following relation:

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

(1)

Where,

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

(2)

$$R_T = 1 - \frac{V_p}{V_3}\sin\gamma$$

(3)

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

(4)

$$k_2 = \begin{cases} 1.0 & \text{if } \gamma \leq 2\gamma_0, \\ 0.0 & \text{if } \gamma > 2\gamma_0 \end{cases}$$

(5)

Here, $E$ is the dimensionless mass (mass of eroded wall material divided by the mass of particle). $V_p$ is the particle impact velocity, $\gamma$ is the impact angle in radians between the approaching particle track and the wall, $\gamma_0$ being the angle of maximum erosion. $k_2$ and $k_{12}$ are model constants; and depend on the
particle/wall material combination. The boundary conditions and values of constants used for combination of quartz and steel are shown in Table 2 and 3 respectively.

### Table 2. Boundary Conditions

| Parameters          | Conditions                        |
|---------------------|-----------------------------------|
| Analysis Type       | Steady State                      |
| Inlet               | Mass Flow: 16 l/s                 |
| Outlet              | Average Static Pressure: 0 Pa     |
| Walls               | No Slip                           |
| Turbulence Model    | SST                               |
| Working Fluid       | Water at 25°C and quartz          |
| Convergence Criteria| 1E-4                              |

### Table 3. Tabakoff and Grant’s erosion model constants for combination of quartz and steel

| Variables           | Coefficient | Value  |
|---------------------|-------------|--------|
| $k_{ij}$            | $k_{ij}$    | 0.585  |
| Velocity $V_1$      |             | 159.11 m/s |
| Velocity $V_2$      |             | 194.75 m/s |
| Velocity $V_3$      |             | 190.5  m/s |
| Angle of maximum erosion $\gamma$ | $\gamma_o$ | 25$^0$ |

2.3 Experimental set up

The experimental setup consisted of two pumps of unequal sizes. The larger pump, Pump 1, was used to pump the water through the pipeline, while the smaller pump, Pump 2, was being operated as a turbine as shown in Figure 3. The two pumps were connected in series, such that the discharge from Pump 1 was delivered to Pump 2 at its spiral casing. Both the pumps were controlled by using variable frequency drives. In absence of highly accurate electromagnetic flow meter, rate of discharge was measured by a pitot tube fitted on the pipeline and an ultrasonic flow meter. The head converted by the turbine has been measured by tapping the pressures from inlet section and outlet section of PAT as shown in Figure 3. The impellers of both the pumps are colored with five layers of colors in the order: blue, green, yellow, orange and red. Locally available acrylic based aerosol spray paint has been used. These colors provide faster drying, high gloss, color retention and excellent adhesion on both metal and wood surfaces. The order of color is adopted from the color mapping of ANSYS CFD Post Processor. Painting in this order makes it easier to validate the CFD results based on the experimental results. Two different experiments has been performed, during the first one; Pump 2 is run by Pump 1, in turbine mode, in clean water. In the second set of experiment, sediments were introduced into the sump to make the concentration of sand in sump 6000 ppm, which is the average concentration of sand in most of the Nepalese rivers[12]. The experiment was performed by operating the pump 1 at 2870 rpm at 50 Hz frequency, for which it’s motor was designed while, pump 2 was operated at 1500 rpm using an induction motor and a Variable Frequency Drive controller. Pump 1 maintained a discharge of 16 liters per second at 14.85 meters head thus driving pump 2. The experiment was performed for three hours with three one-hour intervals to maintain the temperature of the setup within limits.

![Figure 3. Schematic diagram of test set up](image-url)
The sump available is relatively small and does not have proper cooling system, thus the components tend to heat fast and tends to melt the paint on runner. Also after seeing the painted surface gets part off by heating, temperature sensor was introduced in the sump and the temperature was limited to 35 Degree Celsius. Due to this fact, the experiments were performed in the intervals of one hour, not allowing the water to exceed this temperature. The sediment samples used were sampled from cooling tank of Jhimruk power plant of Nepal, during monsoon season. For the purpose of experiment, sediment particles between 63 micron and 200 micron were used, which is the range of sediment size passing through the turbines in an actual hydropower[13]. Sediment of the above-mentioned size were separated from the rest of the sand by performing a sieve analysis. As per past research it suggested that, the sediment in Jhimruk power plant are generally in size between 100 micron to 200 micron to cause erosion in hydro mechanical components. The mineral analysis done from previous research suggested that about 59.4% of sediment type contains quartz material at downstream which is a very hard material than steel causing erosion in hydraulic components. [14].

4. Results and discussion

The results of numerical analysis performed on the pump shows that the sediment erosion rate density concentrated the most at the leading edge of the impeller for pump mode. The results obtained are in accord with the results of the study done by Dong et. al.[15]. This is because the rate of erosion is highly affected by the velocity of the quartz striking it, and the velocity of the fluid is generally maximum at the inlet of the pump. The pattern of erosion obtained from numerical simulations on the pump are shown in Figure 5 a while the erosion pattern obtained from the experiment are shown in Figures 6, 8 and 10. The CFD analysis showed that the erosion for Pump 1 as shown in Figure 5a, mainly occurred at leading edge on pressure side and near the trailing edge on suction side. Similarly, the experimental result also showed erosion at leading edge as shown in Figure 10 and erosion near the trailing edge on suction side as shown in Figure 6. In addition to that, some erosive phenomenon was observed near the outlet on the pressure side, as shown in Figure 8. Erosion at this location was not discovered in the results of CFD. This could be because this experiment just shows the weak areas in the hydraulic profile and not the actual erosion on metal caused by sediment. It is clearly visible in the figure that just one to two layers of paint has been eroded at that location, making it area with relatively less possibility of erosion, compared to other areas where erosion has been seen, which could not be quantifiable on metals. Similarly, the erosion pattern were studied on the impeller of the pump 2, which was operated as a turbine. The numerical analysis of the runner showed that the erosion was mostly concentrated in three locations i.e. near the hub region on suction side of the blade, along the pressure side and at the trailing edge on the pressure side as shown in Figure 5b. These erosion patterns were seen in the results of experiment as well. The erosion near to hub region on suction side can be seen in Figure 9 and the erosion on pressure side can be seen in Figure 11. However the erosion on pressure side is significantly less prominent in the results of experiment, compared to the results of numerical analysis. This may be the limitation of erosion model or the duration of experiment, in which case, more areas could be eroded.
Erosion leading edge can be seen in Figure 9, which shows resemblance with CFD results. Relatively more regions were eroded in the impeller operated in pump mode than the one operated in turbine mode and the reason behind it could be the rotational speed of the hydraulic machines and their blade profiles.

Figure 5. Erosion rate density on a) Pump 1 and b) Pump 2

Figure 6. Erosion at outlet suction side for pump 1

Figure 7. Erosion near hub at suction side for pump 2

Figure 8. Erosion at outlet pressure side for pump 1

Figure 9. Erosions at trailing edge for pump 2

Figure 10. Erosion at Inlet leading edge in Pump 1

Figure 11. Erosion near hub at pressure side for Pump 2
5. Conclusion
The erosion pattern predicted by CFD has been validated by the experiment to some extent. However, some differences has also been noted. The results obtained from both CFD and experiment cannot be fully trusted as of now, due to the limitations in both the methods. The experiment shows, regions on the impeller, which are relatively more prone to erosion. Even though the experiment was performed in relatively simple setup, areas that are more susceptible to erosion are discovered. The objective of this research to determine the erosion prone areas in the hydraulic profile of the impeller blades has been fulfilled using numerical and experimental methods. The method used in this study is one of the most economic and accurate method to predict the erosion pattern in any hydraulic machinery. However, it should not be mistaken as a method to quantify the sediment erosion on impellers or runners. It can clearly predict the sediment erosion pattern better than the Rotating Disc Apparatus (RDA), as the actual hydraulic conditions in the hydraulic machines can be replicated in this method rather than in RDA method.

6. Limitations and Recommendations
As this was the first experiment for pump and pump as turbine in case of Nepal, there are some major areas and findings, which could be corrected in future research and experiments. Due to the small volume of sump, temperature of water rose up, because of the heat produced on the shaft, which softened the paint surface making it weak and inconsistent. This problem was solved by used of temperature sensors and allowing water to cool. However, the limitations was experiment could not be done continuously. This limitation can be reduced and even be eliminated by increasing the size of the sump and adding a cooling system. The paint with higher quality and temperature ranges could be selected for further works. The painting procedure should be thoroughly looked as done by Dong et al. The erosion samples used has been reused for the whole experiment, which could have lost its shapes and erosive characteristics. In order to avoid it, the shape of the sediment should be monitored at regular interval and replaced continuously, without tampering with the concentration of the sand in water.

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