A Review on Experimental Study of Sediment Erosion in Hydraulic Turbines at Laboratory Conditions

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Abstract. Experimental erosion testing of hydro turbine components in laboratory conditions over field testing and simulation testing is a necessity as effects of individual erosion influencing factors like particle size, speed, concentration, angle of attack and behaviour of the eroded material can be studied in close compromise as that with components in actual operating environments. Extensive experimental results have been reported from the past studies from different erosion tests performed. In this paper, recent research and development of a wide range of laboratory scale erosion testing is reviewed. Considering the complexities of developing a setup that replicate the actual erosion behaviour of turbine, a test rig is suggested for future works that closely meet the operating requirements.

Keyword: Erosion, Experiments, Laboratory, Hydro-turbines

1. Introduction

Sediment erosion is a serious problem that is prominent in hydropower plants originating directly or indirectly from Himalayan region, European Alps, Andes and Pacific Coast Ranges [1]. The factors influencing sediment erosion are: i) sediment type and its characteristics (shape, size, hardness, concentration etc.), ii) hydraulic design and operating conditions of turbine (flow rate, head, rotational speed, velocity, acceleration, turbulence, impingement angle etc.), and iii) material used for the turbine components [2]. This problem is most severe in run-of river type of hydropower plants due to no storage or limited amount of storage for settling of suspended sediments. This issue of sediment erosion has resulted in frequent plant maintenance and decrease in turbine’s life and its components, which cause a significant economical loss each year.

1.1. Erosion Study Approaches

The approaches for studying the erosion can be classified in three groups, based on the available literatures: CFD study, experimental study and case study. Study of erosion with the help of CFD technique is widely adopted for numerical prediction of erosion using available erosion models. In CFD study, Finnie model and Tabakoff erosion model are widely used to simulate the erosion phenomenon [3]. Using this approach, the prediction of erosive behaviour of different material under different operating conditions will eliminate the need of carrying out costly experiments. Besides, it also helps in identification of constants required for existing analytical models [4]. Despite its advantages, validation of the obtained results, especially in terms of the nature and quantity of erosion remains as a challenging issue. Noon et al. [5] conducted CFD analysis to study erosive wear on Francis turbine components and compared the simulated results with experimental data from field for validation. Study shows only qualitative comparison of simulated results from actual site data for various turbine components as in Figure 1. Thus, CFD study has demanded the need of experiment to quantify erosion rate in laboratory setting and to validate the numerical results in the same time.
In case study approach, the study of erosion behaviour is carried out at the targeted hydropower plant. Quantitative measurement of erosion in the actual prototype plant is difficult and time consuming process as it requires partial or complete de-assembly of the components which is normally not carried out until there is a considerable efficiency loss in the plants. Abgottspon et al. [6] carried out erosion measurement of pelton buckets during sediment season and found significant reduction of splitter height at HPP Fieschertal as shown in Figure 2.

Due to the limitations of case study and CFD approaches, experimental study has been reviewed as the most realistic way to observe and study erosion phenomena in controlled laboratory conditions on different types of materials. This paper aims to study different types of experimental test rigs developed so far to study erosion phenomena in lab environment.

2. Laboratory Erosion Testing
Past researches include development of wide varieties of sediment erosion test set up to carry out laboratory scale sediment erosion studies. Also, several standardized test methods have been developed. In experimental study, the specimen is subjected to be tested under actual prototype conditions as well as under some defined operating conditions in controlled environment. Experimental test rigs are designed in such a way that the parameter variations can be easily incorporated according to the test requirement. Laboratory testing requires less time to attain results, cheaper and relatively less risky than the prototype measurements due to smaller scale experiment in well-designed environment.
Erosion can be observed in laboratory condition either by the motion of the particle, the specimen or both, where relative velocity between these is maintained [7]. In most of the laboratory testing, the precondition for collision of fluid particle on surface of test specimen is provided by either the motion of the fluid particle or the specimen. Whereas the quantitative erosion measurement in terms of weight loss is a difficult process in prototype plants, it is measured as the ratio of weight loss of material to mass of erodent in case of laboratory testing. Further, if the densities of eroded material are considerably different, erosion rate should be measured as volume loss to mass of erodent. Hence, loss of volume or reduction of thickness is a practical way to represent the erosion rate. In laboratory conditions, for the ease of measurement, erosion rate is usually measured on weight loss basis, thickness loss change and roughness change.

2.1. Standardized Erosion tests
Comparison of the results from erosion test on different test equipment or different procedures from same equipment is unreliable because slight variation in key parameters can influence the erosive wear. Standardized erosion tests have been formulated to provide standard test procedures to study erosive wear of surface or coatings. Standard tests like ASTM G32-03, ASTM G76-04 and ASTM G73-98 [8] deals with laboratory erosive testing of coatings on stationary specimen. ASTM G32-03 defines a standard test method for cavitations erosion using vibratory apparatus. This procedure is used to rank the cavitation resistance of the material. It uses the vibration from high frequency ultrasonic actuator to the specimen dipped inside liquid to cause cavitation wear [9]. Likewise, ASTM G76-04 defines a standard test method for conducting erosion tests by solid particle impingement using gas jets. The test is performed as sand-blasting; using compressed air and abrasive particles, at right angle against a sample surface [10]. Similarly, IEC 62364:2013 provides standard guidelines for dealing with hydro abrasive erosion in Francis, Pelton and Kaplan turbines [11].

2.2 Non-Standardized Erosion tests
These rigs are designed based on the specific purpose of study like locating erosion on surface, pattern of erosion, rate of erosion, influence of key parameters, quantitative erosion measurement etc. This paper deals with test rigs classified based on the arrangement of the specimen i.e. stationary specimen and rotating specimen test rigs.

2.2.1 Stationary Erosion test rigs
Lin et al. [12] developed and conducted an experiment on impingement erosion testing equipment to determine the slurry erosion characteristics of three Ti-Ni shape memory alloys and SUS304 stainless steel by using the liquid/solid impingement as shown in Figure 3. Rig is specifically designed to conduct erosive test to rank the erosion resistance of the test materials; varying impingement angle and speed. Findings are independent of the size of quartz particles (263-363 µm) used as eroding agent. However, particles sizes less than 200 µm inherit both turbulence and inertial force leading to maximum erosion in case of real hydropower plants [2]. In this type of jet rig, it is difficult to ensure that impingement angle of all the solid particles remains same [13]. Moreover, due to wear of the nozzle, calibration and measurement of the velocity should be done periodically. Furthermore, the jet is locally concentrated onto the specimen, so the distribution of wear is only localized on that particular point.
B. Thapa [7] conducted test on high velocity jet erosion test rig at NTNU/SINTEF to predict the erosion in turbine coating and different turbine materials. Experimental test rig developed can provide a jet velocity up to 80 m/s, has low test cycle time and easy control of parameter variation. Tests were performed on test plates with soft and hard coatings at varying angles and velocities to investigate effect of erosion influencing factors. He concluded that coarse grain impacted close to splitter while smaller grains moved farther away, may be due to lower impact energy [14]. Result variation can come across from this type of high velocity tests due to difference in test specimen shape and size. It is found that the erosion rate is proportional to the curve radius of the surface. Also, small size specimen exposed to different velocity test conditions can influence the test result because of change in flow dynamics after the incident of particles on specimen. Gliding of the smaller particles along the curve surface can results in diminishing erosion rate. Despite these drawbacks, these types of test are useful for ranking of materials conforming to their resistivity in terms of velocity effects. Study concluded the ranking of erosion rate of ceramic coatings in term of volume loss per unit striking particle is 75Cr3C2-25NiCr>86WC-10Co-4Cri>86WC-6Co-8Cr.

Liu et al. [15] developed rotating jet experiment system with high velocity up to 120 m/s to study the anti-performance of erosion of material used in needle, nozzle and bucket of pelton turbine. Velocity and concentration of the sediment are taken into considerations for studying erosion of three different materials. Study showed that a measured value of erosion velocity of the jet is dependent on nozzle ejecting velocity. However, no effort has been made to minimize the erosion on nozzle which is responsible for maintaining constant velocity. Also, the effect of the particle size (<100 µm) taken for testing takes longer operation time to occur considerable amount of erosion as past literatures has identified [16].
Grewal et al. [17] conducted non-recirculating type of slurry erosion test on hydro turbine steel, 13Cr4Ni in both martensitic and austenitic phases to investigate the erosion effect of operating parameters like velocity, impingement angle and concentration. Study has taken into account, the sediment size below 300 µm that can easily pass through the runner and is responsible for major erosion in most of the hydropower plants [16]. Scanning Electron Microscopy (SEM) and X-ray diffraction technique is used to investigate the degree of eroded surfaces. As the slurry jet with velocity of 20-60 m/s is locally concentrated on the stationary specimen surface, it does not simulate slurry erosion phenomenon as encountered in prototype plants. The pattern of erosion on surface is ring shaped with protruded mass at the centre which is uncommon case found in actual erosion.

2.2.2 Rotating Erosion test rigs
Bajracharya et al. [18] developed probably the efficient sediment erosion test rig with improvised injecting system and sediment separation system as shown in Figure 7. This test rig was designed to study erosion in pelton buckets at constant head and flow with varying concentration of sediment. He argued that result is valid for prototype plants due to geometrically similar conditions although materials of test specimen are brass which is different from prototype runner. However, Duan and Karelin [19] stated that different material in similar conditions exhibit different erosion behaviour. But material properties of the substrate i.e. brass and steel are significantly different; the erosion result will also vary accordingly. Thus, quantitative justification of the erosion rate can only be achieved by testing brass and steel in same rig under same operating conditions.
Figure 7. Erosion test rig developed by Dr. Tri Ratna Bajracharya [18]

Padhy et al. [20] designed and fabricated rotating test set up to investigate the effect of size and concentration of eroding particles and jet velocity on curvature of pelton buckets made up of brass (3-4 Mohs hardness) to observe erosion in less time as shown in Figure 8. Results from brass specimen cannot be supportive to estimate the erosion of steel. Close prediction and comparison of erosion results can be achieved by using reference material that is tested at the same time or at identical conditions as the test samples. Likewise, measurement of the erosion is done by high precision balance with accuracy of 0.1 mg which is still low because of loss of material in micro level during short test runtime. Also, this study accounts erosion of nozzle for maintaining impact velocity of erodent by use of control valve to maintain constant head.

The erosion of the impeller is simply tackled by replacement of new ones. The solution to this problem can be use of peristaltic pump especially designed to deal with abrasive pumping.

Figure 8. Schematic of the test set up [20]

Ranjitkar et al. [21] developed rotating disc apparatus (RDA) for testing of Francis runner blades as shown in Figure 10. Major sediment influencing factors like sediment size and concentration was taken into consideration for testing of painted Francis runner blade specimen to investigate the location, rate and nature of erosion. It has been observed that the wear patter and location of surface in blade was quite similar to that predicted from CFD analysis [22]. In this rig, specimen blade is subjected to high concentration of sediment (85,900 ppm) to observe erosion in less time which does not actually happens in prototype plants. Most of the hydropower plants shutdown or reduces number of unit operations when the concentration of the particle reaches above 3000 ppm as in case of Jhimruk Hydropower plant in Nepal, shown in Figure 9 [23]. Also in this type of rig, continuous contact of specimen with sediment results erosion in very short period of time. Though the erosion rate seems to be increasing with test runtime, it will start diminishing at some point of time due to loss of
angularity of the sediment after continuous contact with specimen. Shrestha et al. [24] also used same set up to conduct erosion testing on cross flow runner blades. This type of set up is limited for locating the erosion area in the specimen and for observation of wear pattern. Experimental results showed that the wear pattern started for leading edge and gradually moves towards trailing edge whereas erosion pattern is due to obstacles in flow field or secondary flow vortex formed around the blade.

Figure 9. Plant operation strategy of Jhimruk Hydropower Plant [23]

Rai et al. [3] developed a test rig that can simulate the actual hydro abrasive erosion phenomenon in laboratory condition as shown in Figure 12. Velocity of erodent, sediment concentration and sediment size are the parameters considered to conduct laboratory scale erosion test. Quantification of the erosion is done by erosion volume method with the help of optical scanning camera Comet L3D and also by weight loss method. Verification of the test rig for hydro abrasive test in pelton turbine is achieved through calibration of discharge and esurient of homogenous suspended sediment concentration through the nozzle.

Figure 10. 3D CAD model of RDA [21]

Figure 11. (a) Eroded test specimen (b) CFD result [22]

In this recirculating type (RC) of test rig, the erosion rate decreases with time due to a reduction of the particle shape ‘angularity ’unless efficient sediment separation system is employed. And, also control of concentration of sediment particles is difficult in RC test rig. Author mentioned that sediment was replaced after it reaches expected limits under screening through laser diffractometer. However, the limit is not specified in the paper. Also, the study does not mention any methods for reliability and reproducibility of the test. However, it is important to run the test for standard reference material along with the test material so that the data normalization can be done taking into account of reference material for reproducibility.
3. Future Works
It was studied from the literatures that it is difficult to design the set up that replicates the actual erosion scenario as in prototype plants. Nevertheless, a set up can be designed at its optimal level to closely meet the operating requirements. Firstly, implementation of slurry pump [3][11] especially designed for handling abrasives can be a better option over normal pumps for generating necessary flow and head in the experimental rig. The use of pressure tank can mitigate the limited use of setup for impulse turbine by providing a wide range of head and undisturbed flow at the turbine’s inlet. For injection of the sediment into the mainline, a peristaltic pump with inbuilt VFD and pulse dampener can be employed for varying the concentration in a continuous flow precisely. Efficient screw feeding system via. hopper can be alternative solution to sediment injection system. Further, proper design and use of sediment separation system can eliminate the entry of aged sediment into the runner, thereby causing no effect on the erosion rate. Costly sediment removal compartment can be designed to capture sediment particles as smaller as possible [14]. Hydro-cyclone separator in series combination can ensure optimum removal of the sediment particles after passing through turbine despite of need of back pressure for maintaining required flow. Figure 13 shows a layout of the experimental set up that can be an option for conducting the erosion test in laboratory conditions and meet the actual operating conditions as in prototype plants to get the optimum result.
Figure 13. Typical Schematic of a flexible test Setup illustrating sediment injection and separation system

4. Conclusion
It was studied from the literature that laboratory testing is the only way out to visualize, quantify and validate the effect of sediment erosion replicating the actual erosion phenomenon. IEC (62364, 2013) also recommends carrying out abrasive test studies on rigs that can replicate the erosion phenomenon of the prototype plants. Wide range of apparatus has been designed and developed according to the area of interest of study, in which variation of major erosion influencing factors like sediment size, velocity of impact of erodent, angle of attack of particles and concentration of the particles can be incorporated to study erosion on different materials. Experimental test rigs developed so far are limited to the study of erosion phenomena in impulse turbines. In recent studies performed on rotating specimen, the effects of centrifugal forces and secondary erosion like cavitations were not realized. Some studies attempt to validate the results obtained from numerical analysis using CFD with experimental results. However, a proper characterization and control of the sediment in the flow is crucial for future research.

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