Experimental investigation of sediment erosion of turbine steel used in Bhilangana-III power-plant

Shubham Sharma, Bhupendra K Gandhi

Department of Mechanical and Industrial Engineering, IIT Roorkee, Roorkee, India, 247667

E-mail: ssharma3@me.iitr.ac.in

Abstract. Turbines located in the geographical regions of Africa, Himalayan, South-East Europe and South America are subjected to erosion due to sediments flowing with water. The extent of damage due to erosion depends on the material property and the impinging condition of particles. In this work, experiments have been performed in a high speed pot tester on the steel used for Francis turbine of Bhilangana-III power-plant. The erosion rate is determined by mass loss of the specimens rotating inside the pot. The erosive wear behavior of turbine steel is evaluated at high velocities of 27 m/s and 32 m/s by varying the orientation angle from 15 to 90 degrees. The mean particle size and sediment concentration are selected as 300 µm and 3000 ppm, respectively. The erosion rate of turbine steel is increased with impact angle upto 30 degree and then decreased with a further increase in impact angle till 90 degree. The effect of variation of particle impingement velocity on erosion rate behavior of turbine steel is determined for the velocity range of 13-32 m/s. The erosion rate increased with increase in the velocity. Further, the mechanism of erosion with the variation in velocity is analyzed at different impact angles using SEM micrographs of worn out samples.

Keywords: Francis turbine, Turbine steel, Erosion rate, Pot tester, Sediments erosion.

1. Introduction

Sediment erosion of pumps and turbines is a key academic and engineering challenge for hydraulic machinery and material science engineering research. The hydropower plants, located in the region of young mountains; like Himalaya, are severely affected by sediment erosion [1, 2]. Sediment erosion is a complex phenomenon and it results in the material loss of wetted components of hydraulic machineries (see in Figure1). Erosion of hydraulic turbines due to sediment particles is the function of many parameters such as; particle velocity, impingement angle, type of mineral, size, shape, etc. In most of the cases, the sediment velocity and concentration have a dominant effect on the erosive wear of the turbines [2]. In-situ measurement and experiments in pilot plant test setups are time-consuming and expensive along with difficulties in monitoring and regulating different operating parameters, which results in limited understanding of the erosive wear phenomenon [3]. Alternate to these studies, experiments with controlled test parameters have been performed in a laboratory test rigs by many researchers [4-6] to study and evaluate the effect of influencing parameters. These studies have been performed upto the velocity of 16 m/s but the infield measurements of hydropower plants reported that the turbine generally runs in the range of 15-60 m/s [2, 7-10]. Truscott [11] reported that the intensity of erosion of stationary and rotating components are directly proportional to absolute and relative velocity, respectively. In the present experimental investigation, the erosive wear behavior of Bhilangana-III power-plant turbine steel at high impingement velocity is presented. The aim of the present study is to evaluate the erosion wear rate of turbine steel with the variation of impact angle and
velocities. The motivation behind the study is to understand the turbine steel failure mechanism at different impact angles in order to recognize the consequence of high velocities on material selection and hydraulic design of the turbine in the future. This may allow fulfilling the fundamental requirement of design and material selection for turbine parts to achieve better erosion resistance.

![Figure 1: Eroded component of Bhilangana-III power plant Francis Turbine](image)

2. **Bhilangana-III power plant**

2.1 **Turbine detail:**

The Bhilangana-III is 24 (3x8) MW hydropower, run of river plant, located in Tehri district of Uttrakhand state of India. The silent features of turbine are presented in Table 1.

**Table 1: Bhilangana-III powerplant turbine specifications**

| Items              | Details              |
|--------------------|----------------------|
| Turbine            | Francis turbine      |
| Rated net head, H (m) | 207                  |
| Rated flow rate, Q (m$^3$/s) | 4.33               |
| Rated power, P (MW)    | 8.33                 |
| Runner speed(RPM)     | 750                  |
| Turbine material      | CA6NM                |

2.2 **Sediment**

Sediment samples collected from the inlet of the trash rack (after desilting chamber) and analyzed by dry sieving sediment sampling method. Through sieve analysis, it is observed that more than 90% of sediment particles are measuring around 300 μm. Along with the size determination, the chemical composition of particles is also found by the EDAX analysis. The EDAX analysis report of the sand of Bhilangana-III power plant is presented in Figure 2.
The chemical composition of Bhilangana-III power plant is presented in Table 2. It is observed that the sediment contains 90% of silica having hardness 7 on Moh’s scale [2].

### Table 2: Chemical composition of Bhilangana river sand as per % by weight

| Element         | SiO₂ (Silica) (SiK & OK) | Albite (NaK) | MgO (MgK) | Feldspar (KK) | Wollastonite (CaK) | Iron (FeK) |
|-----------------|--------------------------|--------------|-----------|---------------|-------------------|------------|
| Weight%         | 90.18                    | 2.21         | 1.34      | 1.64          | 1.23              | 3.4        |

#### 2.3 Turbine material

The components of the turbine are generally manufactured with 13/4 martensitic stainless steel (MSS) and/ or 16/5 MSS material. For turbine of Bhilangana-III power plant 13/4 MSS, also known as CA6NM steel, is used for the turbine parts which has good resistance against corrosion and cavitation erosion, high impact strength and fracture toughness [12]. The chemical composition of turbine steel and its physical properties are presented in Table 3.

### Table 3: Properties of turbine steel used in Bhilangana-III power plant turbine

| Substrate material (Turbine steel) | Chemical composition (wt. %) | Hardness (Hv) | Density (g/cm³) |
|-----------------------------------|-----------------------------|---------------|-----------------|
| CA6NM                             | Cr-13.79, Ni-2.67, C-0.067, Si-0.55, Mn-0.77, P-0.0057, Cu-0.57, Mo-0.64, Fe-80.94 | 330           | 7.858           |

#### 3. Experiment

**3.1 Experimentation**

A high speed pot tester of 270 L capacity is used in the present experimental investigation. The description of the experimental setup and procedure is reported by Tarodiya and Gandhi [3]. The schematic layout of the experimental set up is presented in Figure 3. To determine the particle attrition effect and repeatability on experiments, some preliminary experiments are performed. Through these experiments, 40 min is obtained as a reasonable operating time for all experiments. During the whole experimentation, there is no sign of corrosion for mass loss of specimen.
3.2 Range of Parameters

Two series of experiments are performed to establish the effect of impact angle and velocity on the erosion of turbine steel. In the first set, experiments are performed at different orientation angles ranging from 15-90 degree for two different velocities. In the second set, experiments are performed at five different velocities in the range of 13-32 m/s for two impact angles 30 and 90 degrees. All the experiments are performed at a constant particle size and solid concentration of 300 micron and 3000 ppm, respectively.

3.3 Experimental procedure

Fresh machined specimens are used for each experiment. For every experiment, the specimens are cleaned with acetone and further dried with hot air blower before weighing. Experiments are performed using the sand water mixtures while rotating the specimen inside the pot. Indian standard sand (consist of 99.3% quartz) is used to prepare solid-liquid mixture of 3000 ppm concentration. The properties of Indian standard sand are presented in Table 4.

Table 4: Properties of Indian standard sand particles

| Property          | Value          |
|-------------------|----------------|
| Specific gravity  | 2.65           |
| Hardness (Hv)     | 1100           |
| Shape of grains   | Sub-angular    |
| Color             | Greyish white  |
| Silica            | 99.3%          |
| Fe₂O₃             | 0.1%           |

The experimental procedure is followed as discussed by Tarodiya and Gandhi [3]. Further, the weight loss of two specimens is measured to calculate the erosion rate (ER) at known operating conditions. The ER is defined as the ratio of mass loss of substrate (g) to the mass of the solid particle (g) and calculated as below [3]:


\[ \text{ER} = \frac{W}{\rho_s A_{\text{SP}} C_V V T} \]  

(1)

Where \( W \) is weight loss (kg) in time \( T \) (s), \( \rho_s \) is density of solid particle (kg/m\(^3\)), \( A_{\text{SP}} \) is the exposed surface area of specimen (m\(^2\)), \( C_V \) is the volumetric concentration of solids (fractions), \( V \) is the peripheral velocity of wear specimen (m/s). Further, the micrographic analysis of the eroded surface is performed using the scanning electron microscope (SEM) and X-ray diffraction (XRD) technique to identify the wear mechanism responsible for the material loss.

4. Results and discussion:

4.1 Effect of impact angle on erosion rate

The variation of erosion rate with the orientation angle at two different velocities is presented in Figure 4. It can be observed from Figure 4 that the erosion rate is increasing up to a certain angle and then decreases with further increase in the angle till 90 degree for both velocities. In addition, the maximum erosion has observed at around 32 degree for both the impact velocities. This shows that the erosion behavior of the steel is typical ductile type for the velocity range of 27-32 m/s [13].

![Figure 4: Variation of erosion rate of turbine steel at different orientation angle on d=300μm and solid concentration = 3000 ppm as an operating condition](image)

Along with the erosion rate evaluation the surface topography of eroded surface is also performed. The SEM micrographs of eroded specimens at different orientation angles are presented in Figure 5. (a)-(f). It is observed that at low impact angle, micro-cutting along with some plowing are dominantly responsible for the material loss of turbine steel. The intensity of cutting marks is changed with the impact angle (see in Figure 5a-c). This has also been observed in earlier studies [13, 14]. At high impact angles, the striking particles transfers large amount of kinetic energy and causes normal stresses on the target surface. The generated normal stresses accumulated the damage of surface by fatigue, microforging, extrusion and crack initiation (see Figure 5d-f) [14]. The material loss mechanisms at higher impact angles produce lesser erosion damages than that of at low impact angles, which results in the maximum erosion rate at around 32 degree. Moreover, the erosive wear process also influence the surface texture of the target material which may affect the erosion resistive property.
To investigate the effect of particle impact angle on surface texture of eroded specimen the XRD analysis of new and eroded specimens is performed and presented in Figure 6. The turbine steel (13/4 MSS) is composed of martensitic ($\alpha$) and austenitic ($\gamma$) phases. The XRD analysis of new and eroded
surfaces is indicated the dissolution of the softer austenitic ($\gamma$) phase due to erosion at different impact angles. Significant variation in relative intensities of the martensitic phase ($\alpha$) for each new and eroded surfaces is also observed. The results are in-line with Grewal et al.[4] and Kishore et al.[15]. It can be observed from the topographic analysis that the softer phase is removed from the target material due to erosion and surface texture gets affected.

4.2 Effect of impact velocity on erosion rate

The erosion rate variation of turbine steel with impact velocities at two different orientation angles is presented in Figure 7. It is observed that the erosion rate increases with velocity for both the impact angles but at different rates. This may be attributed due to increase in kinetic energy of impacting particles with velocity. It can also be seen from the Figure 7 that the rate of increase of erosion rate is different for both the shallow and large impact angles which may be due to the typical ductile behavior of the material. Many investigators [16-18] reported the erosion rate variation of target material with the impact velocity and relate it by power-law relationship. For this purpose, the curve fitting of experimental data is performed and the power-law index values obtained are 2.77 and 3.19 for the velocity at 30 degree and 90 degree impact angles, respectively.

![Figure 7: Variation of erosion rate of the target material with impact velocity on 3000 ppm solid concentration and 300 $\mu$m particle size at 30° and 90° orientation angle](image)

The micrographic analysis of eroded surface is also performed to investigate the effect of velocity on erosive wear behavior of turbine steel. The SEM micrographs of eroded surface at different velocities are presented in Figure 8(i) (a)-(d) and Figure 8(ii) (a)-(d) for the case of shallow and large impact angles, respectively. It is observed from the micrographs that at shallow impact angle condition micro-cutting and plowing are the dominating micro-mechanism for material loss of target material at every impact velocity. However on increase in velocity, the intensity of cutting marks on the target surface are increased [4, 5]. The impact particle generates the stress on the surface due to which the contact surface material deforms and moves in forward direction. On the subsequent impacts of particles, the material from the surface is removed in the form of microchips by the shearing action of particle [13]. The higher erosion rate at shallow impact angle is also supported by this micro-cutting and plowing mechanism of erosive wear. At a high impact angle, the subsurface deformation and crack initiation cause the material loss due to erosive wear of target material. The particle strikes with the surface at a
large impact angle and transfers a large amount of kinetic energy. The target material surface doesn’t endure this large amount of energy and fail out as brittle failure due to the intersection of cracks inside the subsurface of the target material. This brittle failure is responsible for the material loss of turbine steel for particle impinging at high angle. Although, it is also observed from the micrographs that on increasing the velocity the cutting marks, at low impact angle condition, and cracks strength (no. of cracks generation) at high impact angle condition seems to be increased. This micrographic analysis also depicts the increase in erosion rate with the velocity.

![Micrographs of eroded specimen](image.png)

**Figure 8:** SEM micrographs of eroded specimen of turbine steel at different impact velocities for the two shallow and large impact angles

5. Conclusion

The erosive wear behavior of Bhilangana-III Francis turbine material is investigated using a pot tester for high impact velocities. The variation of erosion rate with orientation angle and its material loss phenomenon at various ranges of impact velocities is discussed. Based on the experimental and microstructural investigations the following conclusions are drawn:

- The trend of variation of erosion rate with orientation angle is similar for the two high velocities namely 27 and 32 m/s.

- The maximum erosion rate of turbine steel is observed around 32 degree for the velocity range of 27-32 m/s for IS sand-water mixture.

- The power law exponent for the velocity is observed as 2.77 and 3.19 for 30 degree and 90 degree impact angles, respectively.

- XRD analysis confirmed that the softer Austenitic phases are more prone to erosion in comparison with martensite phase.
On the selective high impact velocities at 90 degree impact angle, subsurface deformation is observed as primary mechanism, whereas at 30 degree angle, micro-cutting along with some plowing is observed to be responsible for the material loss of turbine steel due to erosive wear.

6. Acknowledgments

Authors wish to acknowledge the Bhilangana-III powerplant, India personals for their cooperation. Also, the work shown in this research paper is the part of international collaborative project FranSed which is jointly carrying out by IIT Roorkee India, NTNU Norway and KU Nepal.

7. References

1. Liu J, Lu L and Zhu L 2012 *IOP Conf. Series: Earth and Environmental Science* **15**: 032055.
2. Padhy M and Sainee R P 2008 *Renewable and Sustainable Energy Reviews* **12**: 1974-1987.
3. Tarodiya R and Gandhi B K 2019 *ASME Journal of Tribology* **141**(9): 091602-1.
4. Grewal H S, Agrawal A and Singh H 2013 *Tribology Letters* **52**:287-303.
5. Shivamurthy R C, Kamaraj M, Nagarajan R, Shariff S M and Padmanabham G 2009 *Wear* **267**(1-4): 204-212.
6. Desale G R, Gandhi B K and Jain S C 2011 *ASME Journal of Tribology* **133**(3): 031603.
7. Kang M W, Park N and Suh S H 2016 *Procedia Engineering* **157**:457- 464.
8. Koirala R, Thapa B, Neopane H P, Zhu B and Chhetry B 2016 *Wear* **362-363**: 53-60.
9. Koirala R, Thapa B, P Neopane H P and Zhu B 2017 *Renewable and Sustainable Energy Reviews*, **75**: 1054-1065.
10. Neopane H P, Dahlhaug O G and Cervantes M 2011 *Global Journal of Research in Engineering* **6**:17-26.
11. Truscott G F 1972 *Wear* **20**(1): 29-50.
12. Iwabuchi Y and Sawada S 1982, *ASTM*: 332-354.
13. Abd-Elrhman Y M, Abouel-Kasem A, Emara K M and Ahmed S M 2019 *ASME Journal of Tribology* **136**: 011106-1.
14. Al-Bukhaiti M A, Ahmed S M, Badran F M F and Emara K M 2007 *Wear* **262**:1187-1198.
15. Kishor B, Chaudhari G P and Nath S K 2014 *Wear* **319**:150-159.
16. Islam M A and Farhat Z N 2014 *Wear* **311**:180-190.
17. Desale G R, Gandhi B K and Jain S C 2008 *Wear* **264**: 322-330.
18. Desale G R, Gandhi B K, and Jain S C 2011, *ASME Journal of Tribology* **133**(3):031603.