A review on erosion of a Pelton turbine bucket

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Abstract. Hydro-power energy is the most efficient renewable energy sources in the world. India stands in the top ten hydropower generation countries list. Pelton turbine is a well-known hydro-power extraction machine. The Pelton turbine buckets play an important role in the efficiency of the hydro turbine which is in continuous interaction with high velocity jet and there are possibilities of damages to the bucket in the form of erosion as water contains small debris as sediments. Eroded buckets greatly reduce the efficiency of the turbine. Attempt is made by researchers to developed co-relations to evaluate wear rate and efficiency reduction based on the practical data. The majority of erosion takes place at splitter areas. An erosion cannot be eliminated, but it can be reduced by some amount. The results of the mathematical model indicate that the effect of silt size to the wear rate is 0.0001 gram per gram of bucket weight for a particular silt concentration and the result of silt concentration to wear rate is 0.0007 gram per gram of bucket weight for a particular silt size. The normalised efficiency loss is increased to 0.13% for a specific silt size with the variation of silt contraction. The average wear rate is nearly 3.1 mm per year for laboratory-scale Pelton turbine bucket; which is manufactured from brass and bronze materials. The coating of various materials over the buckets are used by researchers to reduce erosion. Among all coating materials, WC-Co-Cr gives better results against erosion.

1. Introduction

Worldwide electric power production from hydropower changes every year with changes in climate patterns and additional native environments, was approximate as 4,210 TWh in 2018 [1]. Universal pumped deposited size increased by about one per cent in a year [1].

India is among the top 10 hydropower generating countries with a share of 4% of total hydropower generation worldwide as shown in Figure 1 [1]. India has surplus its power production volume by half a gigawatt in 2018 as shown in Figure 2 [1]. The Kishanganga hydropower plant is a unique substantial outline with 330-megawatt power production capacity, which is situated in the north portion of India [1].

A one hundred and ten megawatts capacity hydropower plant has started in the east side of India in Arunachal Pradesh [1]. India’s persisting power production from the water contained comparatively minor services, an aggregate of hundred megawatts [1]. India had under construction of 37 surplus power production plants consisting of twelve gigawatts of size, among them six gigawatts installed for many purposes, like a deficiency in capitals even for ecological aspect at the end of this year [1].
The vital issue related to the hydropower projects is the erosion of turbine blades. The issues are conspicuous in control base point and that is of the run of river class [2]. Such kind of issue ends up noticeably genuine if the silt contains a giant amount of quartz, to an extraordinary level of hardness. The collisions of solid and liquid fragments in opposite to the bucket inner and outer surface are known as erosion. It is also known as erosion wear [2]. Water contained the solid fragments with the flow which hold the power of velocity and that is adequate to harm the metal surfaces. The erosion happens due to sand is known as abrasive wear. Cavitation type of erosion can take place due to the collapse of the oxide film from the metal exterior. It makes surfaces uneven [2]. An enormous amount of wearing contamination is available in the flowing water of hydropower projects. Such kind of degradation like sand may be the reason for delivering and supplying to harm the bucket [2].

Silt erosion is one of the major complications that already take place at more than twenty hydropower projects in India [3]. Concerning the level of injury, the hydropower plants are categorised in three ways: the rigorous injury which demands maintenance yearly; a significantly high injury which demands maintenance at the end of three years; a considerable injury which demands extra care and supplies at the end of 15-20 years [3].
There are two dominant locations where sand erosion takes place in the nozzle are needle tip and seal rings. It also takes place in the turbine buckets [3]. Wear on the needle tip happens as stripes and craters onwards to tip. The sand impurities in the running water, wear the bucket space in reverse side. It undertakes late union with jet and creates mistaken splitter. The bucket boundary flatters broader because it is uncovered to wear and tear. The enlarged craters may happen in the back of the boundary.

2. Investigation on erosion

Padhy and Saini have highlighted that the sand erosion with grain dimensions smaller than sixty micrometres has steered to drastic harm of needle as well as the nozzle of the hydropower system [4]. It happens due to the powerful randomness in the excessive velocity jet piloting the molecules to swing and spin in ring form objecting impacts with the metal exterior [4]. Another reason is the supreme acceleration of a molecule travelling through the buckets of Pelton mechanism. Pelton has small buckets. The flow investigation indicates the acceleration range for the peak head impulse turbine alike Pelton is one lac metre per Second Square [4]. Bajracharya, et al. have discussed that the reasonable quartz included and additional silt charge in the course of monsoon with the minimum molecule size is the principal reason for the erosion of Pelton wheel components [5]. It has concluded an appraisal of erosion is 3.4 millimetre per year for the pointer & pail of Pelton which reduces efficiency at 1.21 per cent and as outcome waste in the power production [5]. Thapa B. has studied erosion damage of Pelton turbines in the power plant. The erosion of Pelton bucket is shown in Figure 3.

![Figure 3. Eroded Pelton buckets (a) Skagen power plant (b) Khimti power plant [6]](image)

The fine type of silt molecules will do erosion on the pointer vicinity, yet not ample effect in the buckets. The coarse particles will damage the buckets significantly as compared to needles. The intermediate size of the silt fragments will do erosion on the needle as well as buckets [6].

In the experimental investigation, four parameters show a major effect on erosion and efficiency loss [4]. These four parameters are silt concentration, silt measurement, speed of the jet and the working time. It has observed that the drop of hydraulic efficiency of a Pelton runner increased simultaneously with an increment in silt concentration, silt measurement and speed of the jet [7]. There are three standards to design the Pelton wheel to reduce the consequence of sand erosion are mentioned below [8]:

- The radius of the arc should be enormous at the area where the flow of the water changes.
- A hydraulic radius of pail and nozzle should be enormous to avoid the silt particles contact with the bucket exterior.
- Quantity of jet should be minimal.

To get the satisfied execution of Pelton runner in an erosion atmosphere at partial charge situation, the scale of sediment variables need to be optimized [9]. Computational fluid dynamics technique is
used to minimize the erosion effect and to modify the diagram of the bucket without oblation of ample hydraulic efficiency. The molecule tracking method is operated for a recommended realizing of erosion at the interior of bucket [9]. As per Leguizamón, et al. the multi-scale replica is a valiant move in connection with increase of the applied magnitude. To forecast an erosion of the components of hydraulic mechanism, a significant virtue for the drawing of best turbines in the environment of the silt-laden hydraulic situation of increasing value [10]. It has been concluded from the investigation that undertaking was only one stage towards enhancement. That was huge extent of work in this subject. Loop improvement should be possible by parametric investigation of circle that shift the thickness of band it has been accomplished. The exhaustion examination of Pelton wheel should be possible. By directing trial life cycle expectation of Pelton wheel is additionally conceivable [11].

3. Investigation on erosion effect

Ayli has identified the seven regions of the Pelton turbine bucket concerning cavitation as sown in Figure 4. Destruction occurs in the zones of first and second is because of the pail and jet connection. Zone third and fourth type of cavitation are begun due to the uneven boundary of the bucket, which affects the flow bifurcation and creation of vortices. Monsoon erosion is the source for the zone fifth type of cavitation. The inappropriate bucket release angle is the reason for the sixth and seventh type of zones for the cavitation [12].

![Figure 4. Erosion zones on Pelton turbine bucket [12]](image)

Robin, et al. have found that erosive wear charge grows with the growth in the velocity of jet, silt concentration, operational time, and silt measurement [13]. The erosion on the Pelton turbine bucket happens at the middle portion and the nick section of the Pelton pail. The answer has been matched with FE Analysis, which is demonstrated in Figure 5(c) and the highest deformation happens at the middle portion and nick section of Pelton pail [13]. From figure 5(a) and 5(b), it is seen that the maximum stress will be induced on the backside of the splitter edge. Anant, et al. have analyzed the erosion of the interior boundary pails has pointed the spill concerning the edgewise boundary of the exterior of the adjacent pail [14]. Two properties of the sediments are the most effective during the monsoon weather, they are silt concentration and silt measurement. The constant improvement tracking mechanism is required to measure the necessary effects of the properties on the bucket surface. Turbine manufacturing companies, engineers and plant officers can get information about the effect of erosion on Pelton from this study. It also emphasizes the requirement of coating for the eroded pails [14]. Zeng, et al. have concluded that the cavitation can happen at the leading side of the bucket and it may impact the overall outcome of the working plant [15]. The outcomes indicate that the cavitation begins closely by the cut side section on
the leading plane at the starting stage of the bucket trimming through the open jet and the arithmetic answers have shown that the cavitation would drop the performance of Pelton wheel [15].

![Figure 5](image)

**Figure 5.** Stress indication in Pelton turbine: a) equivalent elastic strain; b) equivalent stress; c) total deformation [13]

The impact of erosion on various components of Pelton pail was identified extremely based on the characteristics of the water flow bifurcation in the bucket [16]. The turbine components made from the metal have come across the plastic distortion. Crack formation for material removal is because of just coatings. A formation of erosion in the middle vicinity is principally directed to the strike of sit particles on the plane creating bowls. Material specialist and power plant officers can be benefited from this survey [16]. Manoj, et al. have concluded that the pure water flow simulation carried out using the k-epsilon turbulence model showed the efficiency of the turbine is found 92.41% and high pressure is observed at the center of half bucket and the splitter. Most affected location of Pelton turbine bucket is observed at splitter of bucket [17].

| Component               | Working situation and demand                              | Materials                  |
|-------------------------|----------------------------------------------------------|----------------------------|
| Needles, Nozzles        | high velocity, prone to cavitation, sand erosion          | 16Cr 5Ni 13Cr 4Ni          |
| Runner (bucket and disc)| high velocity, acceleration, prone to cavitation, corrosion, sand erosion | 13Cr 4Ni                  |
| Shaft of needle Servomotor | Low friction                                                | Stainless steel with hard chrome surface |
| Turbine housing         | Weld-ability at site                                       | low carbon mild steel of fine grain quality |
| Inlet pipe of Injectors | -                                                         | fine grain cast iron       |
4. **Investigation on erosion and coating materials**

Needle tips and nozzles are the two components of the Pelton turbine is uncovered to the higher kinetic energy of the water. Chromium and nickel contain should in a range of 13 to 16 per cent and 4 to 5 per cent respectively. Ceramic coating is applied on the needle tip and nozzle circle to keep away from the drastic silt erosion. It is a scope of research to commercially use the ceramic as a coating material for the Pelton components [18]. Table 1 suggests the coating materials used for different parts of Pelton turbine to reduce the erosion.

Experimental studies have been executed on a prototype Pelton turbine model with a scale of one to eight, to analyse the effect of erosion. Different six kinds of composite materials were examined in a related manner to identify the suitable one for further experimentation. The hard ceramic tungsten mono carbide and a softer CoCr metal binder are registered as the finest coatings material. WC-CoCr is covered by the high velocity oxygen fuel method. Cr$_2$O$_3$ coating is exerted by the plasma sprayed method to prevent silt erosion. WC-Co-Cr is the foremost coating material as an alternative to Cr$_2$O$_3$ [19].

5. **Correlations for efficiency and wear rate**

The number of correlations has been originated by many researchers to identify the behaviour of parameters similar to the speed of a jet, silt congregation, fragment dimension s and working hours on wear rate and hydraulic efficiency of Pelton runner [20]. Most cited correlation are listed in Table 2.

| Researcher         | Erosion Model | Parameters                                                                 |
|--------------------|---------------|-----------------------------------------------------------------------------|
| (Gupta) [21]       | $E_w = KV^\beta C^\phi d^\gamma f(\alpha)$ | $V = (3.92–8.06)$ m/s, size = (448.5, 223.5, 112.5 & 37.5 μm), $C = (15, 25, 35 & 45)$ |
| (Krause and Grien)  | $\delta = P Q C V^{3.4} f(D_{50})$ | Particle size = 40–70 μm, (sand containing 99% quartz) |
| [22]               |               |                                                                             |
| (Naidu) [23]       | $W = S_1 S_2 S_3 S_4 M^k V^x$ | The value for the exponent $X = (1.5$ for Pelton buckets, $2.5$ for Pelton nozzle) (3 for Francis runner, $2.5$ for guide vanes and Pivot ring liner) |
| (Tsuguo) [24]      | $W = \beta C^x a^y k_1 k_2 k_3 V^n$ | $W =$ material loss in mm/year, $\beta =$turbine coefficient at eroded part, $C =$ solid concentration, $V =$ relative flow velocity, |
a = an average grain size coefficient on the basis of unit value for grain size 0.05 mm, 
\( k_1 \) & \( k_2 \) = shape and hardness coefficient of sand particles, 
\( k_3 \) = abrasion resistant coefficient of material, 
\( x \) & \( y \) = exponents value of concentration and size

(Thapa B.) [6] 
\[ \eta_f = a \text{ (erosion)}^b \] 
\[ (\% / \text{year}) \]

(Bajracharya) [5] 
Erosion wear rate \( \propto \) a size\(^b\)

(Boss) [25] 
\[ W = 7.56 \times 10^{-8} u^3 C \quad (C \leq 45 \text{ mg/l}) \]
\[ W = 1.82 \times 10^{-8} u^3 C^{1.375} \quad (C > 45 \text{ mg/l}) \]

(Phady and Saini) [26, 7] 
\[ W = 4.02 \times 10^{-12} (S)^{0.0567} (C)^{1.2267} (V)^{3.79} (t) \]
\[ \eta_f = 2.43 \times 10^{-10} (t)^{0.75} (S)^{0.099} (C)^{0.93} (V)^{3.40} \]

(Thapa) [27] 
\[ E_r = C (K_{\text{hardness}}) (K_{\text{shape}}) (K_m) a (K_f) \text{ size}^b \]
\[ (\text{mm/year}) \]

(Khurana) [28] 
\[ W = 9.41 \times 10^4 S^{-3.137} D^{0.187} e^{0.326\left[\ln\left(s\right)\right]} c^{-3.961} e^{0.277\left[\ln\left(c\right)\right]} t^0 \]

(Khurana) [29, 30] 
\[ W = 1.976 \times 10^{-10} t^{1.117} S^{0.118} V^{1.368} C^{0.967} \eta^% = 2.93 \times 10^{-8} t^{0.737} C^{1.113} S^{0.212} V^{1.409} \]
\[ \text{C = 3000-12000 ppm} \]
\[ \text{S = 50-390 \mu m} \]
\[ \text{V = 26.81 - 28.81 m/s} \]
\( W = 3.733 \times 10^{-11} S^{0.1159} C^{0.9096} V^{2.285} t^{1.1317} \)  

Size = 90-450 μm,  
\( C = 2000-8000 \) ppm,  
\( V = 25.46-27.32 \) m/s,  
\( t = 8 \) h

5.1. Validation of wear rate equation given by M.K. Padhy & R.P. Saini [7 and 26]

Equations developed by M.K. Padhy has proven to be very accurate at primary stage of design. G.C. Chaudhari has done an extensive study based on wear and generated experimental data for a wide range of fragment dimensions, congregation, and working hours. The experimental data from G.C. Chaudhari has been evaluated with the help of co-relations developed by M.K. Padhy. Table 3 shows the parameters of the study.

| Variable             | Value         |
|----------------------|---------------|
| Silt dimension (S)   | 75 μm         |
| Silt congregation (C)| 2500 ppm      |
| Speed of jet (V)     | 18 m/s        |
| Cycle time (t)       | 4 hour        |

5.1.1. Sample calculation of wear

\[
W = 4.02 \times 10^{-12} (S)^{0.0567}(C)^{1.2267}(V)^{3.79} (t) \quad (1)
\]

\[
W = 4.02 \times 10^{-12} (75)^{0.0567}(2500)^{1.2267}(18)^{3.79} \quad (4)
\]

\[
W = 0.01731 \text{ gm/mm}
\]

The wear rate is predicted as 0.017 gm/mm by the use of M.K. Padhy's equations. Comparing the results with the experimental data of wear in Pelton turbine buckets in grams per mm as shown in Table 4, the prediction of wear shows very good agreement with experimental data.

| Bucket No. | Mass loss (gm/mm) | Bucket No. | Mass loss (gm/mm) |
|------------|-------------------|------------|-------------------|
| 1          | 0.000             | 10         | 0.010             |
| 2          | 0.030             | 11         | 0.040             |
| 3          | -0.110            | 12         | 0.010             |
| 4          | 0.050             | 13         | 0.030             |
| 5          | 0.020             | 14         | 0.040             |
| 6          | 0.060             | 15         | 0.030             |
| 7          | 0.050             | 16         | 0.010             |
| 8          | 0.030             | 17         | 0.030             |
| 9          | 0.050             | 18         | 0.050             |
5.2. Prediction of wear rate & efficiency equation for proposed bucket design with brass and bronze material

Relation: 
\[ W = 4.02 \times 10^{-12} (S)^{0.0567} (C)^{1.2267} (V)^{3.79} (t) \]  
\[ \eta\% = 2.43 \times 10^{-10} (t)^{0.75} (S)^{0.099} (C)^{0.93} (V)^{3.40} \]

Above equation are used to forecast the weight and performance drop of the original model during the working hours. Table 5 shows the operating parameters of the model.

**Table 5. Parameters of study**

| Parameters               | Value          |
|--------------------------|----------------|
| Silt size (S)            | 60, 90, 120 μm |
| Silt concentration (C)   | 5000, 7500, 10000 ppm |
| Velocity of jet (V)      | 18 m/s         |
| Cycle time (t)           | 4 hour         |
| Bucket weight            | 550 gm         |

**Figure 6. Normalised wear rate versus silt size**

The wear rate and efficiency loss based on this parameters are expressed in Figure 6 and Figure 7 separately. From Figure 6, it can be noticed that wear rate is not varying significantly with change in silt size. The variation is within 0.0001 gm/gm of bucket weight. The effect of silt concentration is notable for wear rate which is of 0.0007 gm/gm of bucket weight for a particular silt size. Figure 7 suggests the variation normalised efficiency loss of Pelton turbine is reduced to 0.04% for a given concentration of silt having a range of silt size. The normalised efficiency loss is increased to 0.13% for a specific silt size with the variation of silt contraction. This predictions are having better accuracy similar to the M.K. Padhy’s experimental data. Figure 8 shows the relation of normalised efficiency with normalised wear. The results shows the loss of efficiency is 9 to 11 times to that of the wear rate.
5.2.1. Evaluate wear rate in mm/year

\[
\text{Wear rate} = \frac{\text{Bucket Weight}}{\text{Wear rate}} \times \frac{(\text{in gm})}{(\text{in gm/mm})} = \frac{550}{0.24384965} = 2255.4881 \, (mm)
\]

\[
\text{Wear rate} = \frac{2255.4881}{2 \times 365} \times (\because \, 1 \, \text{cycle} = 4 \, \text{hr}) = 3.0897 \, \frac{mm}{year}
\]

The wear rate is calculated as 3.1 mm/year. Which is quite similar to the wear data of Bajracharya [5].

Figure 7. Normalised efficiency loss versus silt size

Figure 8. Normalised efficiency loss versus normalised wear rate
6. Results and discussion

Many investigators have used different tools to scrutinize the operations of erosion in the Pelton runner by the plant work, demonstration, and arithmetic research with the restricted victory. Many correlations have been originated to evaluate the erosion rate along with efficiency drop in Pelton wheel at the various design setups. Erosion in hydro plants can’t be ignored however, it can be decreased to a reasonable justifiable degree. Particular variables are proposed by researchers to examine the exact erosion rate at Pelton hydro plant. Some of the variables are flow characteristics, type of turbine, plant environment. The correlations develop for the erosive wear rate and hydraulic efficiency as a reception of silt dimensions, silt congregation, speed of the jet and working hour. This study of erosion on Pelton buckets might be helpful to plant officers, engineers and construction companies to check the drop of hydraulic efficiency at the time of production.

Equations given by M.K. Padhy have proven to be very accurate at the primary stage of design. The rate of erosion rate grows with the growth in the size of silt fragments irrespective of silt concentration as shown in Figure 6. Similarly, with increases in silt concentration, the erosion rate increases irrespective of the silt size. Based on investigations; it has found that highest erosion happens at the middle portion of the Pelton bucket, which includes splitter and notch. Satisfying results obtained from the comparison between FE analysis and demonstrative parametric information. For Brass and Bronze materials, the erosion of the Pelton turbine bucket is predicted as approximately 3.1 mm per year. To decrease the erosion of the Pelton turbine, the size of the turbine should increase simultaneously, it grows the hydraulic radius of an arc, and it drops further. The erosion affected Pelton turbine buckets of the prototype model can reuse after the coating. Tungsten carbide can apply by high-velocity resistance oxygen fuel as a coating material.

Conclusions

Based on case studies and theoretical investigation:

- The erosion rate grows with the increment in the size of sand particles; no matter what of silt concentration. Similarly, the erosion rate grows with the increment in silt congregation; whatever of the silt dimension.
- Highest erosion happens at the middle portion of the bucket, which includes splitter and notch.
- The correlation for an erosive wear rate and efficiency drop is the reception of silt dimensions, silt congregation, speed of the jet and working hour. This study of the Pelton turbine will help significantly to turbine production companies to understand the importance of erosion and to calculate the hydraulic efficiency drop at the production point for an identical plant location.
- For brass and bronze materials the erosion of Pelton turbine bucket is almost 3.1 mm/year.
- The size of the turbine should be increase to decrease the erosion of the Pelton turbine. It grows the hydraulic radius of arc and drops further. Coating of Pelton turbine bucket plays the principal character to reduce an erosion rate in buckets of Pelton turbine.

References

[1] Renewables 2019 global status report (ren21) Secretariat Paris France
[2] Kjolle A 2001 Mechanical Equipment a survey Trondheim
[3] Naidu BSK 2004 Silting problem in hydro power plant & their possible solutions Delhi India
[4] Padhy M K and Saini R P 2008 A review on silt erosion in hydro turbines A review Renewable and Sustainable Energy Reviews 12 1974-1987
[5] Bajracharya T R, Acharya B, Joshi C B, Saini R P and Dahlhaug O G 2008 Sand Erosion of Pelton Turbine nozzles and buckets: a case study of Chilime hydropower plant Wear 264 177-184
[6] Thapa B 2004 Sand erosion in hydraulic machinery Ph.D. thesis Norwegian University of Science and Technology (NTNU)
[7] Padhy M K and Saini R P 2011 Study of silt erosion on performance of a Pelton turbine Energy 36 141-147
[8] Brekke H 2002 Abrasive erosion and corrosion of hydraulic machinery London
[9] Saurabh S, Shighal M K and Saini R P 2018 Hydro-abrasive erosion in hydro turbines: a review International Journal of Green Energy 15 232-253
[10] Leguizamón S, Alimizrazadeh S, Jahanbaksh E and Avellan F 2020 Multiscale simulation of erosive wear in a prototype-scale Pelton runner Renewable Energy 151 204-215
[11] Praveen K R 2018 CFD Analysis of Pelton Bucket International Journal of Mechanical and Production Engineering Research and Development 8 775-780
[12] Ayli E 2019 Cavitation in Hydraulic Turbines International Journal of Heat and Technology 37 334-344
[13] Robin T Anil K Sourabh K and Muneesh S 2017 Correlation Development For Erosive Wear Rate On Pelton Turbine Buckets International Journal of Mechanical and Production Engineering Research and Development 7 259-274
[14] Anant K R, Arun K and Thomas S 2017 Hydro-abrasive erosion in Pelton buckets: Classification and field study Wear 392-393 8-20
[15] Zeng C J, Xiao Y X, Zhu W, Yao Y Y, and Wang Z W 2015 Numerical simulation of cavitation flow characteristic on Pelton turbine bucket surface IOP Conference Series: Materials Science and Engineering 7
[16] Anant K R, Arun K and Thomas S 2019 Analytical modelling and mechanism of hydro-abrasive erosion in Pelton buckets Wear 436-437
[17] Manoj K Amit K and Saini R P 2016 CFD Analysis of Silt Erosion In Pelton Turbine International Research Journal Of Commerce Arts And Science
[18] Brekke H 2001 Hydraulic Turbines Design, Erection and Operation Endringsdato: Juni
[19] Anant K R, Arun K and Thomas S 2020 Effect of concentration and size of sediments on hydro-abrasive erosion of Pelton turbine Renewable Energy 145 893-902
[20] Pankaj G P and Saini R P 2014 Coalesced effect of cavitation and silt erosion in hydro turbines- A review Renewable and Sustainable Energy Reviews 33 280-289
[21] Gupta, Singh and Seshadri 1995 Prediction of uneven wear in a slurry pipeline on the basis of measurements in a pot tester Wear 184 69-78
[22] Krause and Grien 1996 Abrasion research and prevention Hydropower Dams 3 72-77
[23] Naidu B 1997 Addressing the problems of silt Erosion at Hydro Plants International Journal of Hydropower and Dams 3 72-77
[24] Tsuguo N 1999 Estimation of repair cycle of turbine due to abrasion caused by suspended sand and determination of desilting basin capacity In Proceedings of International Seminar on Sediment Handling Technique NHA Kathmandu
[25] Boss R 2009 Real-time monitoring of SSC and PSD in the headwater way of a high-head hydroplant Water Engineering for Sustainable Environment 4037-4044
[26] Padhy M K and Saini R P 2009 Effect of size and concentration of silt particles on erosion of Pelton Turbine 34 1477-1483
[27] Thapa B S, Thapa and Dahlhaug O G 2012 Empirical Modelling of Sediment Erosion in Francis Turbines Energy 41 386-391
[28] Khurana S and Varun G 2014 Effect of jet diameter on erosion of turgo impulse turbine runner Journal of Mechanical Science and technology 28 4539-4546
[29] Khurana S and Varun A K 2013 The Effect of Nozzle Angle on Erosion and Performance of Turgo Impulse Turbine Hydropower and Dams 2 97-101
[30] Khurana S, Varun and Anoop K 2016 Silt Erosion study on the Performance of an impulse turbine in small hydropower International Journal of Ambient Energy 37 520-527
[31] Robin T, Anil K, Sourabh K and Muneesh S 2017 Correlation Development For Erosive Wear Rate On Pelton Turbine Buckets International Journal of Mechanical and Production Engineering Research and Development 7 259-274
[32] G C Chaudhari 2016 Numerical, Experimental and Flow Visualization Studies on Traditional and Hooped Pelton Turbine Runner Ph.D. thesis S V National Institute of Technology, Surat India