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Pelton Runner Erosion due to Cavitation : A Case Study of Storage Hydropower Plant, Kulekhani First Hydropower Station

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Abstract
This study is an attempt to find out that Pelton runner erosion due to cavitation phenomena along with efficiency deterioration, though it operates under atmospheric pressure, where sediment concentration is quite low. This was found from the case study of storage hydropower plant, Kulekhani First Hydropower Station. Sediment Analysis were carried out on laboratory as per the guidelines of International Electro-Technical Commission (IEC) 62364. The laboratory Test report informs that the sediment concentration of reservoir water feeding to turbine is quite low i.e 70 ppm. Also the major mineral contents are Quartz, Feldspar, Mica and Other (Tourmaline, Homblende, Calcite, Clay, Hard rock fragments, clay lumps etc). Sizes of mineral content ranges from 0.4 to 2000 microns. The result of the study clearly shows that cavitation do occur, though it operates under atmospheric condition. The Pelton runner erosion due to cavitation occurs mainly at the splitter tip back side zone and gradually increasing on operation basis. Also the study reveals that the plant efficiency has a degrading trend line along with fluctuations. The efficiency calculations are done on the basis of daily water consumption and fluctuating effective head where water volume is determined with polynomial based reservoir capacity equation.

Keywords
Cavitation, Runner, Bucket, Splitter, Efficiency, Sediment

1. Introduction

Hydropower simply is a natural source of renewable energy. It is a traditional way of harnessing power from the flowing water due to elevation difference. Naturally Nepal is rich in water resource and poses hydropower potential of 83,000 MW theoretically and out which only 45,000 MW is techno-economically feasible. Presently about 2.% of techno-economically feasible has been harnessed so far[1].Hydropower are generally classified as Run-Off-River (ROR), Poundage Run-Off-River (PROR) and Storage hydropower. Storage hydropower consists dam and a reservoir to impound water. Simple strategy behind the storage hydropower is storing water during monsoon season to generate electricity during a dry season. It provides flexibility to generate electricity upon demand and make us independent regarding variability of inflow. The primary advantage of storage hydropower is its ability to store huge amount of energy in the form of water at altitude and respond the variable load or demand with ease generation.Storage hydropower plant situated in Himalayan or Hilly regions are very likely to have high sediment concentrated water due to fragmentation of chemically composed rock and decomposition of mineral content rock under harsh weather phenomena. Sedimentation is a matter of great issue for the hydropower development in Nepal. Also, Nepalese river poses highest sediment loaded among the World [2]. Sediment is generally a mixture of particles with different sizes as presented in Table 1. Hydraulic turbines operating under sediment laden water flow are subjected to abrasive and erosive wear, which not only reduces efficiency and life of turbine but also causes problems in operation and maintenance and ultimately leads to economic losses [3]. Degradation of hydraulic machine especially turbine blades directly depends on sediment. Impulse turbines like Pelton and Turgo are more susceptible to abrasion than reaction types turbine [4].

Table 1: Classification of river sediment

Particle	Size(mm)
Clay	Less than 0.002
Silt	0.002-0.06
Gravel	2-60
Cobbles	60-250
Boulder	Greater than 250

2. Kulekhani First Hydropower Station

There are 19 hydropower plant under Nepal Electricity Authority of generating capacity categorized as below and above than 30 MW. Except Kulekhani Cascade Hydropower Stations all are Run-Of-River type and are effected heavily by sediment led erosion. Kulekhani First Hydropower Station is a storage hydropower plant feed with faint sediment concentrated water from the Kulekhani reservoir instead it is affected by erosion in gradual manner. KL1HPS has annual siltation rate of $0.65mm^3$ active volume. Due to high annual siltation the estimated life of reservoir is about 80 years i.e. upto 2100 AD [5]. Such erosion phenomena is a part of regular monitoring activities for hydropower maintenance. In the present study erosion of bucket due to cavitations has been carried out for Kulekhani First Hydropower Station.The KL1 is storage type 60 MW hydropower plant generally operated for 4 hour and 3 hour evening and morning peak load respectively due to its ability of handling variable load with great ease. It plays vital role in black start when the national grid system is totally blackout due natural calamities like landslides, heavy storm, flood, heavy rainfall and other technical faults. It takes water from various rivers and tributaries like Sim khola, Chakhel Khola, Palung Khola, Thado khola and Shera Khola along with seasonal tributaries. Inflow are collected during the monsoon season and generate electricity round the year for evening and morning peak load along with fluctuating load demands in national power grid. The water from various rivers and tributaries are collected in huge reservoir with $2.2km^2$ surface area and about $85.3 * 106\ m^3$ gross storage capacity where the sediments settles down easily to higher extent. Then water through intake gate flows into headrace tunnel and penstock which is about 1353.5 meter in length and 2 to 1.5 varying in diameter and enters into turbine nozzle through control of main inlet valve. The nozzle impinges a jet of water which strikes the bucket of runner coupled with generator to rotate and thus electricity is produced. The water after impacting the bucket falls down to pit and passes through the tunnel for the feed to the Kulekhani Second HPS cascade plant.

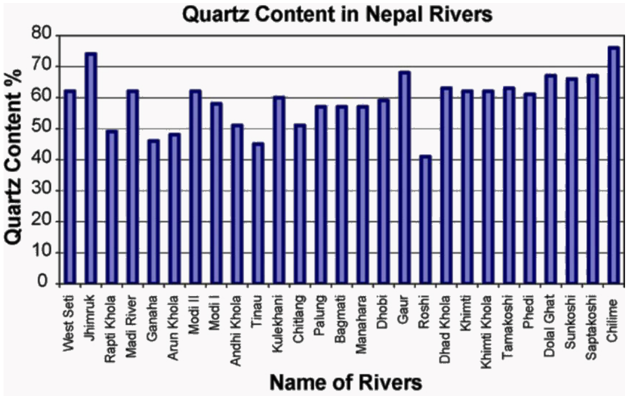

Figure 1: Figure 1Average quartz content in the rivers of Nepal

Two 30 MW units of quadruple jet Pelton turbines were installed in this plant. The inflow water for reservoir are mainly from hilly and rocky catchment area. The main sources of sediments are natural decomposition of hard rocks and minerals due to calamity and carried out by rainfall, flood, landslides etc. upto the reservoir. The heavy sediment particle easily settle down in reservoir bed, as per sedimentation survey (Bathymetric survey) sediment deposition layer is increasing day by day thus leading to storage loss, generation loss and reduced reservoir life. The minute sediment particle which are floating and insoluble flows along with the water and cause erosion of Pelton runner bucket and nozzles on intermittent operation

3. Research methodology

Research methodologies performed under this study are commonly followed steps in such type of research. The consecutive steps are problem identification, literature review, case study, data collection, modeling, analysis, evaluation, and findings, conclusion and recommendation. Under problem identification as first step was to sort out the problems regarding the erosion due to cavitations of Pelton turbine. As area of study was sorted out so various relevant research work and filed study were done like journal papers, conference papers, and power house visit. A case study of Kulekhani First Hydropower Station was considered for this study.

3.1 Data Collection

- The sample (5 No.) of reservoir water feeding to turbine was collected from site as per guideline of International Electro-Technical Commission (IEC 62364) and transferred to laboratory for sediment analysis test [6].

- Under laboratory various relevant test like sediment concentration analysis, mineral content analysis, were conducted. The result was collected from the laboratory.

- Kulekhani First Hydropower Station was visited to collect the various relevant data like log sheets of daily generation, daily reservoir water level, daily running hour, turbine old photograph from their collections and new photograph were also clicked during visit.

- Questionnaires with the Station Chief, Engineer and Operators regarding the regular operations, maintenance practices and nature of erosion of turbine.

- The eroded runner bucket of unit-1 (in operation) was selected for wear and surface texture measurement using dye-gauge and filler gauge as per instruction of Fuji Electric Co. mentioned in manual.

- Numerical values were fed in mathematical standard relation to determine reservoir level associated inflow volume of water, effective head, efficiency and wear etc.

- On the basis of thorough observation, rigorous measurement and analysis, fruitful conclusions were drawn.

4. Standard Erosion Models

Erosion on hydraulic machine expression quoted very often is as below [7].
Erosion α (Velocity)^{n}

There are various studies regarding of erosion behavior and its prediction. General erosion model put forward by researchers are as follows:The past research work has been done on "Sand Erosion of Pelton turbine nozzles and buckets: A case study of Chilime Hydropower "The researchers has collected the sample of sand and water from Chilime river and conducted an experiment. The researchers found out as following wear rate relation of Pelton turbine buckets and found that erosion rate is 3.4 mm/ year, turbine efficiency is reduced by 1.21 % and as a consequence loss in the power generation [8]The relationship between the erosion and the particle size at different quartz content levels are as follows: Erosive wear rate α a (size)^{b}

Where; erosive wear rate is in kg per year,
a = 351.35 and b = 1.4976, for quartz content of 38%
a = 1199.8 and b = 1.8025, for quartz content of 60%
a = 1482.1 and b = 1.8125, for quartz content of 80%.
Relationship between erosion rate and the reduction in efficiency was expressed as;Efficiency reduction
α a (erosion rate)^{b}

Where a = 0.1522 and b = 1.6946.
Similarly, various researchers have conducted experiments to study the effect of parameters such as: size, hardness and concentration of silt particles, velocity of flow, properties of the base material of the turbine components and operating hours of the turbine on erosive wear and found out that erosive wear rate increases with an increase in the silt concentration irrespective of the silt size. However, for a given value of silt concentration, the erosion rate has been found to be higher for larger size particles as larger particles have higher impact energy. Using experimental data a correlation for erosive wear rate was developed as a function of particle size, silt concentration, jet velocity and the time of operation which has been found to have a good agreement with experimental data of test rigs.[9]Correlation for normalized erosive wear rate is obtained as follows:

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

where,
S = Silt size
C = Silt concentration
V = Water Jet Velocity
t = Operating hours of the turbine

As per International Electro-technical Commission (IEC 62364 Hydraulic machines – Guide for dealing with hydro-abrasive erosion in Kaplan, Francis, and Pelton turbines) the particle abrasion rate in the turbine, the following formula is considered [6]:

$S = W3,4 \times PL \times Km \times Kf/RSpS$ is the numerical value of the abrasion depth in mm. The simplest of the various erosion criteria employs the factor H x C, where H is the net head of the turbine in meters and

C is the average annual particle concentration in g/l of all particles with a diameter of $> 50\ \mu$m [10]. The proposed ranges for hydro-abrasive erosion damage risk are:
H x C $\geq$ 7 : severe;
H x C $\geq$ .7 and $<$ 7: moderate;
H x C $\leq$ 0.7 : negligible

Proposed by Nozaki as an extension of the Zu Yan approach is the modified particle concentration factor, which is the product of the annual average particle concentration in g/l and modifying coefficients related to the variables of particle size, hardness, shape, and runner material.

$$PE = P \times a \times k1 \times k2 \times k3$$

where:
PE is the modified suspended concentration in g/l
P is the measured suspended concentration in g/l; and
Factors a, k1, k2, and k3 depend on the type and geometry of the particles and type of runner material

Also by Krause and Grein proposed the abrasion rate on conventional steel Pelton runner made of X5CrNi 13/4 which was expressed by the expression given below:

$$\delta = PQCV^{3.4} f(D_{50})$$

where,
δ is the erosive wear rate (mm/h);
P is a constant, Q is the quartz content,
C is the mean concentration,
V is the relative jet velocity and
$f(D_{50})$ is a function defining particle size.

5. Analysis

5.1 Sediment Concentration Analysis

The sample water collected from site of KL1 HPS were brought to laboratory. Sediment Concentration Analysis was carried out at laboratory. Weighing the original water sample, then carrying out the filtration; followed by drying and again weighing dry sample and hence calculating the ppm were the procedures which were followed by laboratory technicians. Standard filtration method was adopted for sediment concentration analysis. The filtration paper used for the analysis was of 11-micron capacity.

Table 2: Sediment concentration of Kulekhani First HPS feed water

Measure-ment No.	Data	Time	Conc.	Remarks
0	2078/3/31	11:00	48	Unit-I
1+4	2078/4/5	2:00	70	Both Unit
2	2078/4/6	11:00	292	Both Shutdown
3	2078/4/5	3:00	68	Unit II

(conc: Sediment Concentration ppm)

5.2 Mineral Content Analysis

The samples were transported to Kathmandu and mineral Content Analysis was conducted using zoom stereo type microscope by manual observation method. Each sample was divided into four sets and analyzed separately and then average of the individual readings was calculated to identify the mineral content of that sample. Hence, 88.5 percent of the mineral grains in the sediment contains minerals with hardness greater than 5 in Mohs' hardness scale which are Quartz, Feldspar, Tourmaline (1.8%), Hornblende (0.%) and other hard minerals/rock fragments (1.4%) as shown. Hence, they can abrade the turbine material. Remaining 11.5% of material comprises Mica (7.%), calcite (0.9%), clay lumps, highly weathered rock fragments, etc. which possess hardness lower than 5 in Mohs' scale.

Table 3: Mineral content in Kulekhani First HPS feed water.

Mineral	Obs-1	Obs-2	Obs-3	Obs-4
Quartz	64	60	71	57
Feldspar	20	29	16	21
Mica	8	5	4	14
Others(A+B)	6+2	3+3	5+4	2+6

Table 4: Average Sediment concentration and Mohs Hardness Kulekhani First HPS feed water

Mineral	Average	Mohs' Hardness
Quartz	63	7
Feldspar	21.5	6
Mica	7.75	2.5-3
Others(A+B)	4+3.75	$\geq 5 + < 5$

Note: Others A: Tourmaline, Hornblende, and other hard rock fragments Other
Others B: Calcite, clay lumps, highly weathered soft rock fragments, and few unidentified sediments

5.3 Particle Size Distribution Analysis

The samples collected from the site were transported to the laboratory and carried out PSD test by laser diffraction method using Beckman Coulter Particle Size Analyzer of capacity range of 0.4 micron to 2,000 microns. Laser diffraction method uses the scattering pattern of laser beam to determine the particle size of the sediment samples. The standard procedure provided by the equipment manufacturer was adopted for conducting the PSD analysis.

5.4 Erosion Observation

In order to have proper observation Kulekhani First Hydropower Station was visited. Actual dimensional drawing and photographs of Pelton turbine clicked during overhauling in 2009 was collected from KL1 data history. Turbine under operation was visually inspected and new photographs were clicked during plant shut-down with the help of technical team of KL1 HPS. Proper measurement of runner bucket using dimensional drawing and standard profile gauge of KL1 HPS were noted for erosion of bucket. Spare Pelton runner (after proper overhauling) at power house was also visually inspected and measurements were noted.

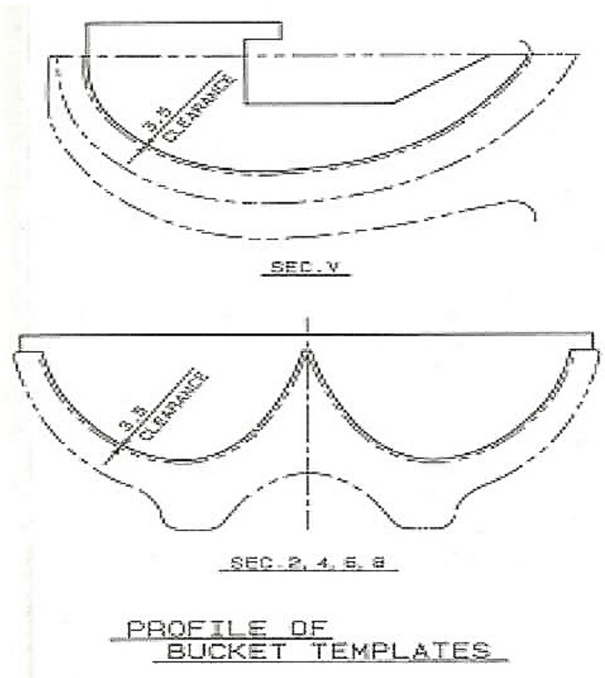

Figure 2: Runner bucket drawing KL1

Visual comparison of photographs shorted during 2009 and 2021 were done and noted the patterns of erosion due to cavitation. Erosion affected area as per KL1 Operation & Maintenance Manual were marked properly. Pattern of cavitation on runner bucket was mostly appearing at splitter nose back side zone. Similarly photograph of Puwa Khola HPS operating with Pelton turbine were also included and noted the pattern of erosion due to pitting mostly on bucket profile. As measurement work was rigorous so sample two buckets were only measured for this study assuming similar wear occurrence in almost nineteen buckets of runner.

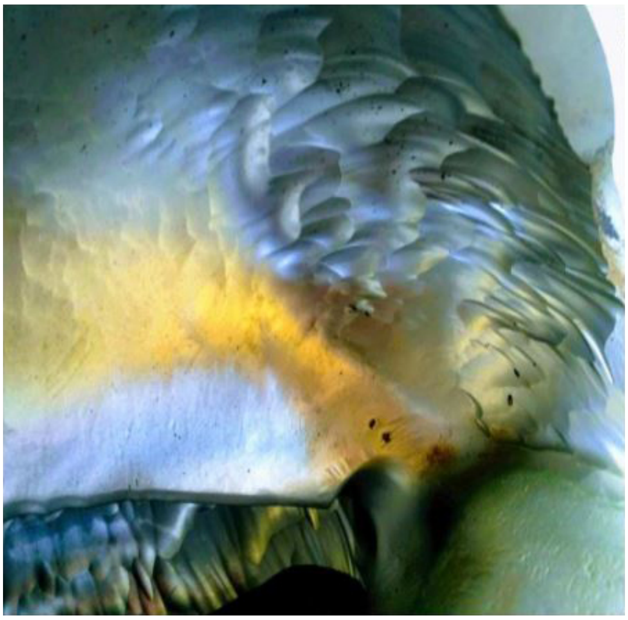

Figure 3: Pitting Puwa Khola HPS and Cavitation Pattern

Figure 4: Initiation of Cavitation-i

Figure 5: Initiation of Cavitation-ii

5.5 Water consumption quantity

The actual volume of water consumed during the generation was calculated using the Reservoir-Capacity standard polynomial based equation. General spreadsheet of Excel was used to determine the volume of water associated with the respective reservoir level. The require equation is as follows:

$$Y = a_0 + a_1 \times (EL) + a^2 \times (E)^2 + a^3 \times (EL)^3$$

Where,
Y = Reservoir storage capacity ($10^{-6} m^3$)
EL = Reservoir water elevation (m)
a_0 = -226,544.6
a_1 = 471.98683
a_2 = -0.3280187
a_3 = $0.76041656 \times 10^{-4}$

5.6 Plant Efficiency

Plant efficiency is the essential parameter of hydropower station to be considered while generating power. Turbine efficiency plays vital role in maintaining plant efficiency[11].The impact of erosion on runner bucket due to cavitation is easily noticeable through the fluctuations of efficiency. Higher the erosion on runner bucket lower will be the generating efficiency. The simple equation of efficiency was used to determine the respective efficiency while generating power associated with effective head and reservoir water level. The equation of efficiency is as below:

$$\eta = P/(\rho \times g \times Q \times H)$$

Where,
η is efficiency
P = Power (Watt)
ρ = Density of water (Kg/m^3)
Q = Discharge (m^3/s)
H = Effective Head (m)

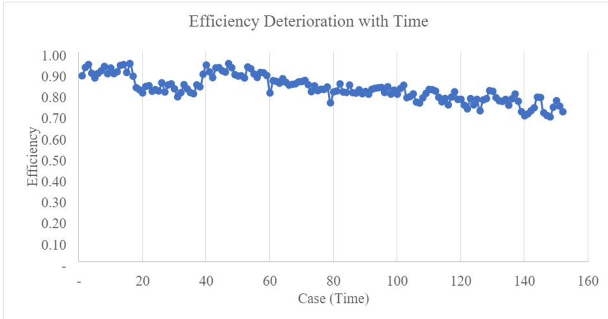

Figure 6: Plant efficiency trend line

6. Results and Discussion

- Visual and photographic analysis reveals the patches of cavitation phenomena are seen mostly on buckets splitter tips backside area along with bucket surface as well
- Complete erosion of splitter tip is initiated by cavitation, analyzing historical records.
- Efficiency trend lines are found.
- Sediment analysis results like sediment concentration and mineral content are known.

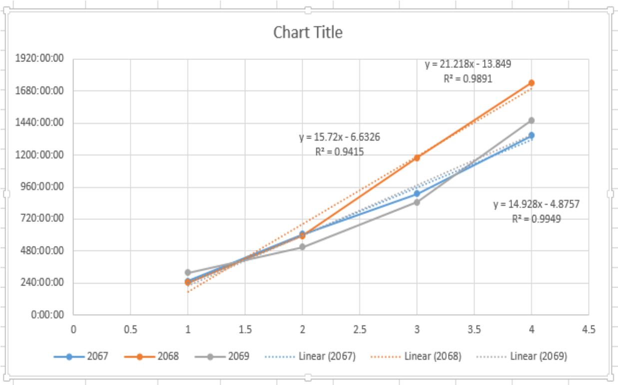

Figure 7: Running hour trend line.

Table 5: Unit-2 Runner Bucket (Measurement)

Position (Sample-1)	T1	T2	T3	T4	T5
Section 2	1.6	2.5	0.55	0.95	1.8
Section 4	2.3	3	3.2	2.9	0.4
Section 6	2.1	2.2	2.05	1.45	1.05
Section 8	2.25	2.4	2.15	0.95	0.95
Position (Sample-2)	T1	T2	T3	T4	T5
Section 2	0.95‘	1.85	2.05	2.2	3.65
Section 4	1.7	2.4	5.05	4.7	2.5
Section 6	0.5	0.8	1.5	1.65	1.15
Section 8	2	0.95	0.95	1.3	1.45

which has given the maximum wear of 3.2 for sample-1 and 5.05 for the sample-2, with the final wear 5.05.

Table 6: Theoretical Calculations.

Total generation (MWh) of KL1 till 2077/78	5,213,564.00MWh
Individual Unit generation (Each Unit generate equal quantity.)	2,606,782.00MWh
In a year number of hour	8760 Hr
Unit 30 MW can generate yearly (30 MW*8760 h)	262800 Mwh
Total running hour of machine (8760*2606782/262800)	86892.73333 Hr
Upon operation of 86892.733 hr wear is about	5.05 mm
Yearly (8760 hr) wear	.5091 mm
Wear (Per 1000 hr)	0.0581 mm

7. Conclusion & Recommendation

The following conclusions has been made from the study:

- Wear of bucket is about 0.0581 mm per 1000 hour operation.
- Being storage hydro power plant, energy produced by per unit volume of water is very important. With decreasing efficiency the energy produced by unit volume of water decreases and hence the plant output.
- It was seen that the plant efficiency is decreasing with years and thus overhaul is required to maintain desire plant efficiency.
- Last 12 years of operation the minimum recorded efficiency of plant was 0.69 and with the maintenance of nozzle & needle the higher efficiency recorded upto 0.94.
- It was seen that the high efficiency was observed at high reservoir water level of around 1527 meter.

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