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A Comprehensive Review on Investigation of Sediment Erosion of Pelton Wheel Turbine

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Abstract- **Hydro turbines installed at different hydropower plants face the issue of sediment erosion. Sediment erosion is an ambiguous phenomenon influenced by several parameters, including silt concentration, size, jet velocity, diameter, and fluid viscosity. Silt erosion imposes severe issues for hydropower plants, like shutdown and maintenance costs. The hydro turbine efficiency decreases with the increase in sediment erosion and eventually the breakdown of turbine components. Various researchers conducted small-scale experimental bench studies and numerical simulations to analyze the influence of the above-mentioned parameters on silt erosion, but the actual flow conditions are too complex to simulate. Therefore, no such erosion model has been developed to predict exact erosive wear. This paper presents an extensive review of the literature survey on sediment erosive wear of hydro turbines, both the adopted methodology by previous studies and parameters affecting sediment erosion in Pelton turbine are summarized. Based on literature studies, various aspects of erosive wear, parameters influencing it, and its severe effects on efficiency are thoroughly discussed. Appropriate remedial measurements for erosive wear made by multiple researchers, erosion models developed so far, and their measuring accuracy and the future scope of this research study are articulated in detail.**

Key Words-- **CFD Analysis, Erosion model, Hydro turbine, Pelton buckets, Renewable Energy, Sediment Erosion, Turbine efficiency.**

I. INTRODUCTION

A Pelton turbine is an impulse turbine that operates at high heads. The Pelton turbine consists of a wheel, the runner, the nozzle, buckets, and the casing. Energy transfer takes place in two stages; in the first stage, the potential energy of incoming water is transferred into kinetic energy. In the second stage, the kinetic energy of fast-moving water leaving the nozzle is converted into mechanical energy through a Pelton wheel turbine rotating runner. All these parts are in direct contact with the flow of water.

In the young mountains, the water flow comprises several sediments, directly hitting the hydro turbine’s major components. As the Pelton turbine operates at significantly high speeds, this sediment-laden water flow causes severe erosion of the major parts of the Pelton turbine. The rate of this sediment erosion severely rises in monsoon seasons due to the increased sediment ratio in the flow. Sediment erosion occurs throughout the year but is maximal in rainy and minimal in dry seasons [1].

The Pelton turbine's erosion phenomenon depends on several factors, like (I) Sediment particles, their size, shape, concentration, and hardness. (II) Surface morphology, surface hardness, mechanical properties, elastic properties. (III) The Pelton turbine's operating conditions, like sediment concentration, flow velocity, and impingement angle [2]. Research studies reveal that fine and coarse sediment particles play a crucial role in the erosive wear of the Pelton wheel turbine. It is found that grain with a size less than 60 µm causes severe erosive wear at the needles and nozzles of the Pelton turbine. If sediment particles are coarse, buckets of the Pelton turbine get severely damaged due to erosive wear [3]. Due to the eroded surface, friction increases, thus generating turbulence conditions and thus enhancing erosion more and more quickly [1]. Fine particles cause erosion more on the needle and less in the buckets. Coarse particles like sand cause erosion more in the buckets and less on the needle. Sediment particles with intermediate size cause erosion, both in buckets and needles. Efficiency loss increases with silt size, concentration, and velocity of the jet [4].

Two types of schemes can be utilized under small hydropower plant schemes; (I) Pump storage and (II) Run-of-river (ROR). Both schemes are severely affected by sediment erosion of different natures [5]. In pump storage schemes, sediments get deposited in the reservoirs, resulting in capacity depletion [6]. This capacity depletion leads to a loss of power production characterized by head loss [7]. Previous research studies reveal that head loss (hf) due to silt disposition in the reservoir can be computed using the following formula [8]:

$$h_f = \frac{10.3 \times n^2 \times Q^2}{D^{5.33}} \tag{1}$$

Where; n is known as the roughness coefficient, Q is the flow rate, and L and D are the length and diameter of the penstock, respectively.

While run-of-river (ROR) schemes face devastating sediment erosion of different turbine components [9], the sediment erosion causes damage and eventually failure of different components of the Pelton turbine, thus enhancing the maintenance cost [9]. Developing a hydropower project in such sediment-laden rivers is a challenging goal to achieve. In such cases, a proper sediment management system should be established to avoid sediment entrance to reservoirs and channels, thus minimizing the sediment erosion of different components in hydro turbines [10]. This erosive wear causes a significant decline in the performance of hydro turbines. Therefore, hydro abrasive wear is considered a major technological issue in hydropower projects. Increasing demand for energy has necessitated providing solutions for mitigating erosive wear of different components of hydro turbines.

Previous research studies categorize sediment erosion as:

- “Plastic deformation as well as by plowing."
- “Plastic deformation and indentation, overlapping craters at the tip of the splitter.”

The major components of the Pelton wheel turbine that are vulnerable to hydro abrasive wear include the injector, splitter, and the front and back surface of the buckets. The sediment particles attain the speed of the host fluid (water) and hit the solid surfaces of the Pelton turbine, which causes the removal of microparticles from the base materials of the Pelton wheel turbine. The direct impact of erosive wear is efficiency loss, which is a substantial financial loss. The annual sediment load was predicted using the Multiple Linear Regression (MLR) model in the Nausehri reservoir, Pakistan [8]. This research study includes parameters like flow rate, density at different temperatures, and kinematic viscosity at a known flow rate. This research investigation reported a 12 % decrease in power generation capacity over the reservoir's life. An equation for the prediction of sediment at given flow rates was developed [6].

Sediment erosion also damages the in-contact parts, which causes mechanical vibration and a huge maintenance cost. Sediment erosion weakens the runner and buckets of the Pelton turbine. Sediment erosion also causes buckets' mass/weight loss, which mitigates the turbine's mechanical power output [4]. Previous research studies reveal that 3.4 mm/year of sediment erosion for buckets and needle causes a 1.21 % reduction in efficiency. This reduction in efficiency leads to a decrease in the power generation of the power plant. Erosion may also cause premature failure of major turbine parts, thus imposing a huge capital and maintenance cost on power plants [11].

The severity of sediment erosion depends upon several factors, which are discussed below:

A. CHARACTERISTICS AND TYPES OF SEDIMENTS

The severity of sediment erosion varies directly with the hardness of eroding particles, irrespective of their size. Similarly, erosion intensity also varies with the size of sediment particles. Generally, particles larger than 0.2-0.25 mm produce severe erosive wear in hydro turbines. Sediment particles of smaller size (fine particles) cause relatively less erosion at the lower operating head and severe erosion at the higher operation head of the Pelton turbine. Erosion rates also vary with the shape of sediment particles. Research studies reveal that sediment particles with sharp and angular shapes cause relatively more erosion than those of round shapes [12].

B. FLUID VELOCITY

The erosion rate varies directly with the velocity of water-carrying sediment particles [12].

C. IMPINGEMENT ANGLE

The angle between the surface of base materials (eroded material) and the traveling path of the silt particles is termed as impingement angle. The erosion rate also depends upon the impingement angle [12].

D. TEMPERATURE

Temperature plays a prominent role in the erosive wear of the Pelton wheel turbine. The primary role is softening the eroded surfaces, increasing eroding surfaces' erosive wear [12].

Hydro turbines that operate at high and medium heads prevail at higher velocities. Turbines installed at relatively higher heads are more prone to abrasive erosion [13]. Following are the factors of severe erosion:

- The high velocity of the sediment-laden water flow
- High concentration of angular shaped, coarse, and hard sediment particles in the water flow [13].

Sediment erosion in Pelton turbine leads to (I) Roughness on all those parts that are exposed to the sediment-laden water, (II) deterioration of profile/shapes of the parts that are in contact with the sediment-laden water, and (III) mass loss (especially buckets) of the eroded surface [14]. The erosive wear damages the splitter profile and thus causes fluid entry with shock and small axial forces to the Pelton turbine [15].

The above issues directly lead to (I) efficiency loss of Pelton turbine, (II) mechanical vibrations, (III) mitigation of mechanical power output, and (IV) loss of mechanical stability [14].

II. NUMERICAL AND EXPERIMENTAL INVESTIGATIONS

The actual mechanism of sediment erosion is not yet profoundly understood; therefore, no reliable and general quantitative model for computing erosion rate has been developed. Most cases are based on experimental studies. The following famous formula is designed for erosive wear based on experimental knowledge.

$$W = f(\text{properties of erodent, base materials, operating conditions}) \quad (2)$$

The above formula emphasizes that erosive wear rate (w) is a function of properties of eroding particles or sediment particles, base materials, and operating conditions, like flow velocity and sediment concentration [4].

In 2020, Bajracharya *et al.* investigated sediment erosion of the micro Pelton turbine numerically, using ANSYS CFX and experimentally. The most prone regions to erosion were identified as (I) the Splitter, (II) the inside and backside area of the bucket (III) the tip of the bucket. Mass losses of 69 and 82.5 mg were observed in every bucket in experimental and numerical studies. The deviation between experimental and numerical investigations was found to be less than 20 % [16].

Rai *et al.*, 2020, studied the role of silt size and concentration in the erosion of hydro turbines experimentally. Six different materials were used, including; (I) Bronze (II)16Cr-5Ni (III)16Cr-4Ni (IV) 13Cr-4Ni (V) 13Cr-4Ni with plasma sprayed Cr2O3 coating (200 µm thick) (VI) 13Cr-4Ni with WC-Co-Cr HVOF Coating (200 µm thick). The research that (I) erosive wear increases linearly with silt concentration for all materials. However, the erosion rate was different for different materials. (II) The erosion rate increased linearly with sediment size and operating time for all materials. (III) Erosion rate increases with the flow velocity. (IV) The erosion rate had no significant effect on roughness [17].

Phady and Saini, in 2012, performed an experimental investigation on the erosion mechanism in buckets of the Pelton turbine. The operating conditions were set to; (I) silt concentration was 5000 ppm, (II) silt size up to 355mm (III) jet velocity was 28.56 m/s^2. (IV) The operating time was 15 min for each set. He concluded that the coarser erodent particles moving at a relatively higher velocity than jet velocity generate pits and carters along the bucket's depth at a more considerable impact angle. However, the erodent particles caused erosion in the splitter [18].

The flow of smaller erodent particles along the jet caused abrasive-type erosion. The splitter tip was mainly eroded due to plastic deformation. The indentation and overlapping craters were found on the splitter tip. However, due to plastic deformation and plowing, erosive wear occurred along the bucket's depth [19].

Suwei (2015) performed a numerical investigation on erosive wear of the bucket of the hydro turbine using ANSYS Fluent. DPM, Grand, and Tabakoff models were used for erosion prediction. It was found that erosion increased with velocity, silt concentration, and particle size. It was concluded that the silt size, concentration, and jet velocity influence erosive wear of the inner bucket of the turbine [20].

Alomar *et al.* (2022) found that efficiency depends inversely on nozzle diameter. For a constant Brake Power (P_b.), the increase in volumetric flow rate (Q) led to a decrease in efficiency. The best operational conditions for the Pelton turbine are smaller nozzle diameter (d) and higher volumetric flow rate (Q) [21].

Bajracharya *et al.* (2008) performed a case study analysis of Chilime HPP. It was found that increased sediment load and higher quartz content cause severe erosion, especially in nozzles and buckets. The erosion rate at the needle and bucket surface was 3.4 mm/year, reducing the efficiency by 1.21 % for the first year and 4 % for the 2nd year. More erosion was observed at partial (half) nozzle opening due to cavitation plus sediment particles. It was suggested that diversion tunnels, provision of trench weirs, and a series of low head weirs can mitigate sediment concentration and thus improve turbine life [1].

X. Ge *et al.* performed numerical and experimental analysis to investigate the influence of jet opening and velocity on Pelton wheel turbine erosive wear with a deviation below 3% between numerical and experimental results. An increase of 7.14%, and 14.28 % in velocity of sediment-laden flow based on 28 m/sec, led to an increase of 26.89% and 57.14 % in the value of maximum torque, respectively. Velocity fluctuations did not significantly influence erosion-prone regions. It was found that; at t= 0.126 s and velocities v= 28, 30, and 32 m/s, the maximum erosion rates were 2.3e-6, 2.8e-6, 3.4e-6 kg.m2 respectively. Experimental results showed no significant relationship between the jet opening and the maximum erosion rate. The grid used in this research was not significantly fine due to a lack of computational resources. Future work can be refining the grid, computing, and eliminating errors [13].

M. Kumar (2016) conducted a CFD analysis of sediment erosion in the Pelton wheel turbine. His research study considered silt concentration, jet velocity, and shape factors. The simulation was performed in ANSYS Fluent, using DPM to predict erosion. For pure water, initially, hydraulic efficiency increased with discharge, and after a certain point, it started to decline. It was found to be a maximum of 92.41 % at the discharge of 100 %. For silt-laden flow conditions, the most eroded regions were splitter and some portions of the notch. It was noted that the erosion rate for shape factor 0.5 was the maximum, which is also a critical point. Normalized wear/unit discharge increased with silt concentration and jet velocity [15].

Guo *et al.* (2020) created both numerical and mathematical models to estimate erosion in the Pelton turbine injector. DPM, VOF, and continuous phase Models were used for erosion estimation, immiscible fluids, and validation. A maximum velocity of 95 m/sec happened after the injector's exit, and the average velocity at the inlet was nearly 5 m/sec. Weight/mass loss for the nozzle casing and needle decreased with the increase in the jet opening. For the nozzle casing, the critically eroded regions were primarily located in the contraction region near the outlet and preeminently decreased in the expansion regions of the injector [22].

Han *et al.* (2021) performed a numerical analysis of silt particle-induced energy loss behavior and phenomenon in hydro turbines using ANSYS Fluent. Measuring uncertainty was maintained below 2.5 %. It was noted that an increase in silt concentration mitigated efficiency significantly, but for constant silt concentration, particle diameter had a low influence on efficiency. The sediment particles perturbed the water distribution, and therefore efficiency was low in the case of sediment-laden flow as compared to pure water [23].

Liu *et al.* (2012) performed an Experimental analysis on erosive wear of Pelton wheel turbine component material. Silt concentration, jet velocity, and operation time were considered in this research study. It was noted that Sediment erosion damage was much more severe in the nozzle tip and needle shaft as compared to that of the runner bucket. For high velocity (106.47 m/sec), the cutting scribes on the eroded surface were present with more than a dozen micrometers in length. For the high impact velocity of erodent, selective mass/weight loss was the primary mode of erosive wear for metals [24].

Rai *et al.* (2015) developed a test rig to investigate erosive wear in the Pelton wheel turbine by 3D digitization of its buckets. Finnie and Tabakoff models were used for erosion estimation. Mass loss measured by weighing balance and 3D digitizations were 0.39 and 0.34 grams, respectively [2].

M.K. Phady (2009) studied the influence of silt parameters on erosive wear in Pelton buckets. Silt size, concentration, jet velocity, and operation time were considered for analysis. Maximum erosion was found at the splitter and a few points at the bucket’s notch. The erosive wear was found to increase with silt size and concentration, whereas it followed power law w.r.t jet velocity [4].

M. K. Phady and R. Saini studied the influence of sediment erosive wear on the performance of the Pelton turbine. The effect of silt size, concentration, jet velocity, and operation hours was analyzed. Initially, the efficiency and power decreasing rate was high, but in later stages, these decreased and finally became asymptotic. Efficiency losses for a silt concentration range of 5000-10000 ppm and velocities varying between 26-30 m/s were 2 and 0.25-0.40 %, respectively. About 8 % efficiency loss was observed against 3.5 % mass loss of the bucket [25].

Thakur *et al.* (2020) developed a correlation to predict erosive wear in the Pelton turbine. Erosive wear increased with silt concentration, size, jet velocity, and operation hours, which was extraordinary at sharp edges and scores. Erosive wear followed a power law $(W \propto V^n)$ w.r.t stream velocity. Maximum erosion was observed at the splitter and notch of the bucket [26].

Kumar and Varshney (2015) analyzed the estimation of silt erosion in the hydro turbine. It was observed that the rate of erosion increased as the silt concentration passing through the turbine increased. According to analytical results, the approximate value of eroded mass varied from 746 kg to 1111 kg for the silt load in the range of 114321 to 323041 tons. According to experimental results, eroded mass varied from 750 kg to 1125 kg for silt load in the range of 114321 to 323041 tons [12].

Goel and Khurana (2014) investigated the influence of jet diameter on erosive wear in the runner of the Turgo turbine. It was concluded that normalized silt erosion increased with silt concentration and size. It was noticed that the silt erosion and percentage efficiency are directly related to the jet diameter. Using multiple jets with smaller diameters is recommended instead of a single jet with larger diameters [27].

V. Goel and S. Khurana (2013) investigated the influence of silt particle size on the erosive wear of Turgo turbine blades. Maximum erosion was found along the depth of the blades and some portion of blade’s notch. The erosion rate enhanced with silt concentration and size and followed power law w.r.t jet velocity [28].

III. MAJOR PARAMETERS INFLUENCING SEDIMENT EROSION

Previous research studies reveal that several parameters characterize the mechanism of silt erosion in the Pelton wheel turbine. The main parameters influencing erosion include silt parameters (silt concentration, size, shape, and hardness) and operating conditions (jet velocity, diameter, and operation hours) [4].

A. INFLUENCE OF SILT PARTICLE SIZE ON EROSION

The sediment erosion increases linearly with operating hours. However, the increase in the erosive wear rate for operating time varies from material to material [17]. At the inlet of the bucket, it is evident that for the silt size ranging from 255 to 350 µm and concentration range of 5000 ppm, the mass/weight loss removal happened as a result of shearing of silt particles. For the sit size ranging from 180 to 250 µm, it is evident that material removal is due to the plowing behavior of sharp edges of silt particles. Scratches on the targeted surfaces are densely found for the silt size ranging from 90 to 180 µm. However, the length of the erosive cut in this study is smaller than in earlier cases, i.e., having large silt sizes. For the silt size below 90 µm, micro indentations are found on the substrate for the silt particles having a mean size of 45 µm [18].

At the bucket’s outlet, it is observed that for silt ranging from 255 to 350 µm, fewer Scratches due to erosion are found on the surface of the specimen glued to the inlet compared to the one glued to the outlet of the bucket. A plowing mechanism of material removal is observed. For silt sizes ranging from 180 to 250 µm, scar marks due to the sharp edges of the silt particles and shearing of the specimen are identified. The principal mode of erosive wear is the generation of new surfaces and plowing. The scar marks are denser, as in the case of silt particle size of 302 µm. For silt sizes ranging from 90 to 180 µm, the outlet surface is highly damaged by erosive wear. The principal mode of erosive wear is indentation and plowing by silt particles. For silt size below 90 µm, surface shear of the substrate is identified [18]. Maximum erosion at the silt size of 150 µm, the concentration of 500 ppm, and jet velocity of 57.38 m/s are observed for a shape factor of 0.5 [15].

It is observed that for the same silt concentration, silt particle diameter has no significant effect on hydraulic efficiency. It is because the silt particles perturb the water distribution [23]. The higher the silt particle size, the higher the perturbation, and vice versa. Therefore, larger silt particles, carrying higher impact energy, influence the hydraulic efficiency significantly compared to smaller silt particles. The increase in erosion rate is significant at relatively higher silt concentrations (10000 ppm) [4]. The influence of silt particle size on erosion is shown in Fig. 1.

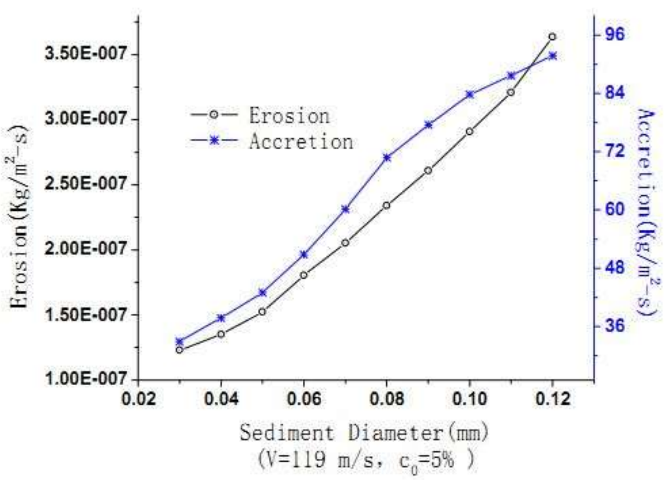

FIGURE 1. Erosion under different silt sizes [20].

B. INFLUENCE OF SILT PARTICLES CONCENTRATION ON EROSION

The erosive wear enhances linearly with sediment concentration for all materials and sizes. However, the increase in erosive wear rate varies from material to material [17]. The influence of silt particle concentration on erosion is more significant than silt particle size [23]. The silt concentration mainly influences the erosive wear of inner buckets [20]. The addition of sediment particles to the flow leads to a reduction in hydraulic efficiency [23]. During the monsoon season, the Sediment load increased severely. This increased sediment load and higher quartz content in the water flow causes severe erosion during the monsoon, especially in nozzles and buckets [1]. For the silt particle size up to 355 µm, a 2 % percentage efficiency loss is observed for the silt concentration in the range of 5000-10000 ppm [25], which is quite significant.

The following practices are suggested to avoid the alarming load of sediment content: Propose a diversion tunnel [1]:

- "Reservoir flushing through bottom outlets."
- Provision of trench weirs
- "Provision of series of low head weirs in the river course upstream of the hydropower plant."
- Proper desilting reservoirs.

Sediment Load can be calculated using the equation [1]:

$$SSL_t = Q_t \;\; T_2 - T_1 \;\; \left[\frac{C_1 + C_2}{2}\right] \times 60 \times 60 \times 10^{-6} \qquad (3)$$

Where: $SSLt = \textit{suspended sediment load in tons}$, $Qt = \textit{flow rate} \;\; m3/sec$. C1 and C2 are flow concentrations (ppm) at a time, T1 and T2, respectively. T1 and T2 are time durations (hours). The influence of silt particle concentration on erosion is shown in Fig. 2.

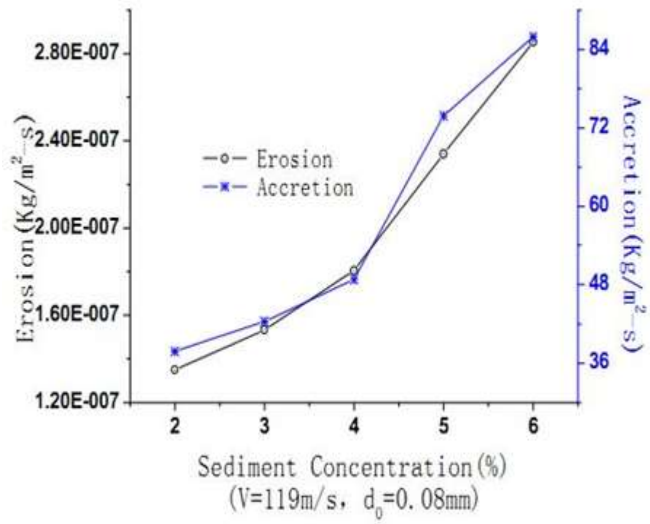

FIGURE 2. Erosion under different silt concentration [20].

C. INFLUENCE OF JET VELOCITY ON EROSION

Literature review reveals that the rate of erosive wear enhances preeminently with jet velocity. The enhancement rate in erosive wear for jet velocity fluctuates for different materials [17]. The silt erosion of the inner bucket increases with increasing jet velocity [20]. Jet velocity variations affect the torque significantly. An increase of 7.14%, and 14.28 % in jet velocity of sediment-laden flow based on 28 m/sec, led to an increase of 26.89% and 57.14 % in the value of maximum torque, respectively. The fluctuation of jet velocity does not affect the erosion-prone regions significantly. Thus, increasing velocity enhances the erosion rate, but the erosion-prone areas remain almost the same [13].

For high impact velocity (106.47 m/s), the cutting scars on the eroded specimen are present in the range of a dozen micron lengths. For metals, selective material cutting is the preeminent erosive wear mechanism at high impact velocity [24]. It is also found that the erosion rate obeys power laws w.r.t jet velocity (i.e., $\propto Vn$) [1], where "n" lies in the range of 1.3-3.80 [28] [4]. The influence of jet velocity on erosion is shown in Fig. 3.

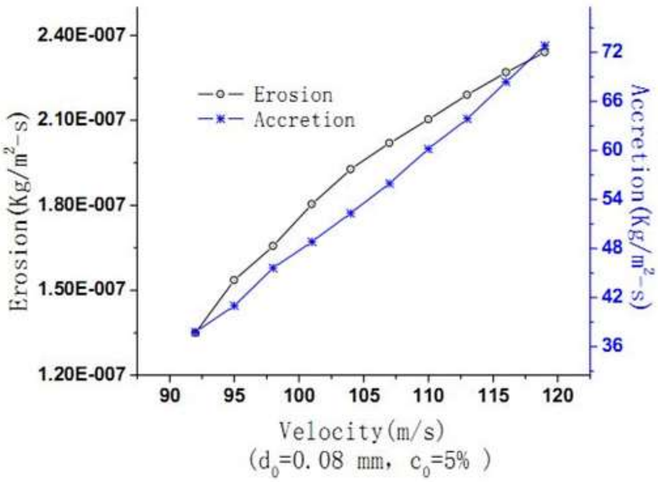

FIGURE 3. Influence of the Jet velocity on erosion [20].

D. INFLUENCE OF JET DIAMETER ON EROSION

It is observed that the diameter of the jet directly influences the rate of erosive wear. Using multiple jets of smaller diameters is recommended to meet the discharge flow requirements instead of a single jet with a larger diameter [27]. The pressure head (H) varies directly with the jet diameter, while efficiency varies inversely. Pressure head (H) depends directly, and efficiency depends inversely on the jet diameter [21].

IV. TECHNIQUES USED IN MEASURING EROSION

Various techniques are used to measure the erosion rate. They include;

A. MASS/WEIGHT LOSS MEASUREMENT

This approach measures the eroded mass/weight loss via physical balance having a specific least count. The higher the least count, the higher will be accuracy and vice versa. In the case of a small experimental setup, it is tedious to measure thickness reduction due to limitations in the least count; therefore, the weight/mass loss technique is recommended to estimate hydro-abrasive erosion [2].

In this technique, the mass of the specimen is measured before and after erosion. The difference between the two values is mass loss due to sediment erosion [27]. The limitation of this technique is that it can measure erosion in the entire specimen only, not at specific regions most prone to erosion in the specimen.

B. THICKNESS REDUCTION MEASUREMENT

In this technique, sediment erosion is measured through the thickness reduction of the specimen profile. For this purpose, 2D metallic templates are used at large hydropower plants (HPPs). The designed templates of the hydraulic turbines determine the difference gap between the actual and eroded profile of the specimen. The difference between actual and eroded specimen profiles is thickness reduction due to erosion [29]. The positive aspect of using this technique is that it can measure erosion in specific regions most prone to erosion.

C. 3D DIGITIZATION

It is the most recent technique that can be used to measure erosive wear in hydraulic turbines. This approach, a 3D scanner is used to scan surfaces using the triangulation principle. The original and eroded profiles are superimposed, which gives us erosive wear, erosion mechanism and pattern, volume loss, and regions prone to erosion. The accuracy of the 3D digitization system depends on the degree of superimposition [29][30].

The system's overall accuracy lies within the range of a 20 µm measurement and time limit of 2.5 seconds [31]. This method of measuring erosion is found to be more convenient than other traditional methods [32]. 3D digitization of Pelton buckets is shown in Fig. 4.

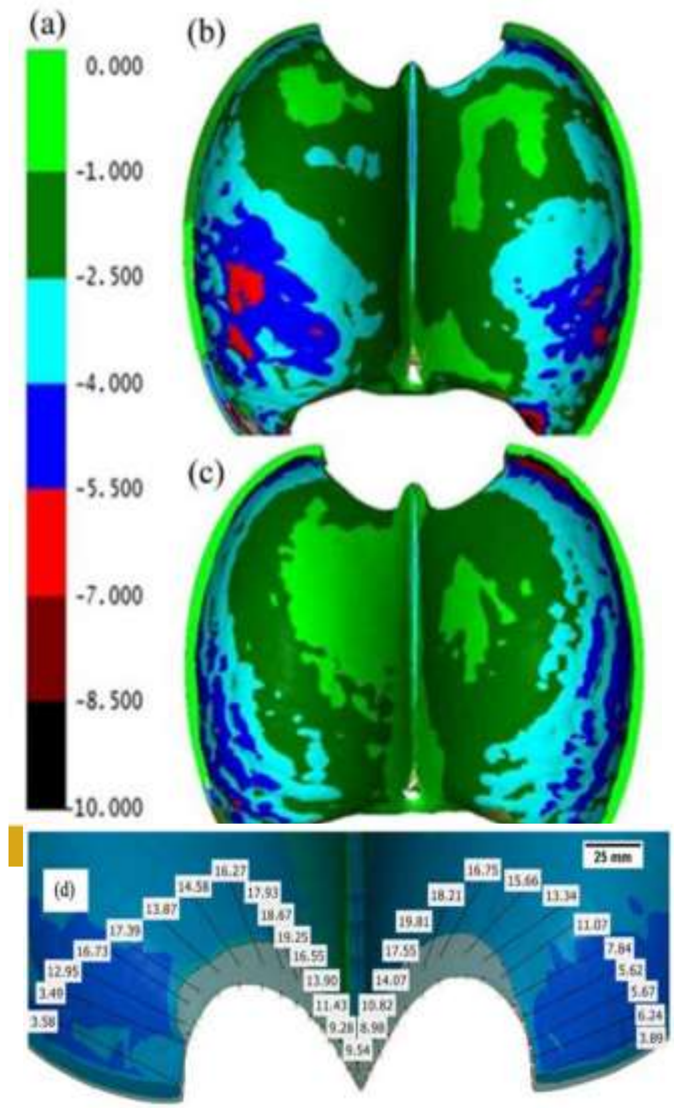

FIGURE 4. (a) Shows erosion depth in mm (b & c) Sediment erosion depth variation inside and outside the bucket (d) Erosion depth in cut-out region in mm [32]

V. MODELS USED IN EROSION PREDICTION

A literature review reveals that several models have been developed for silt erosion prediction in hydro turbines. Several parameters influencing erosive wear are considered while developing a correlation model for predicting erosion.

M.K. Phady (2009) developed a correlation for predicting erosion rate.

$$W = 4.02 \times 10^{(-12)} (S)^{(0.0567))(} C^{(1.2267))(} V^{(} 3.79))(t) \tag{4}$$

Where; $w = \mathit{erosion\ rate}$ [4].

R. Thakur and S. Khurana (2020) developed a correlation model using experimental values to predict erosion in Pelton turbine buckets.

$$\boldsymbol{W} = 3.733 \times 10^{-11} \boldsymbol{S}^{0.1159} \boldsymbol{C}^{0.9096} \boldsymbol{V}^{2.285} \boldsymbol{t}^{1.1317} \tag{5}$$

The correlation equation developed between erosive wear rate and silt concentration, size, stream velocity, and operation hours helps approximate erosion rate with the uncertainty of ± 12.8 % [26].

Sandeep Kumar & Dr. Brajesh Varshney developed a correlation model to predict silt erosion in the Francis turbine.

$$\boldsymbol{W} = 8.52\ \boldsymbol{C}^{0.384} \tag{6}$$

Where; $W = \mathit{erosion\ rate}$ and $C = \mathit{silt\ concentration}$. This research study's absolute percentage error varies from 0.52 to 1.52 [33].

S. Khurana and V. Goel (2014) developed a correlation model to predict the Turgo impulse turbine.

$$\boldsymbol{W} = 9.41 \times 10^{4} \boldsymbol{D}^{0.187} \boldsymbol{S}^{-3.137} \boldsymbol{e}^{0.326\ \ln \boldsymbol{S}^{2}} \boldsymbol{C}^{-3.961} \times \boldsymbol{e}^{0.277\ \ln \boldsymbol{C}^{2}} \times \boldsymbol{t}^{0.540} \tag{7}$$

Where;
$W = \mathit{normalized\ wear\ rate}$ $D = \mathit{mean\ silt\ size}$, $C = \mathit{silt\ concentration}$, and $t = \mathit{operating\ time}$. The deviation between experimental and analytical results (based on the above correlation equation) was observed to be within ± 8 % [27].

S. Khurana developed a correlation model to predict silt erosion in Turgo impulse turbine blades.

$$W = 1.976 \times 10^{-10} S^{0.118} C^{0.967} V^{1.368} t^{1.117} \tag{8}$$

The above-developed correlation equation is helpful for manufacturing industries to take care of parameters that play a crucial role in erosive wear. The deviation between the experimental and analytical results obtained from the developed correlation was ± 11 % [28].

VI. CONCLUSIONS

This research investigation presents a comprehensive review of the numerical and experimental investigations of sediment erosion in the Pelton turbine. The literature review clearly shows that though sediment erosion can be minimized, it is inevitable and cannot be avoided entirely. Many researchers found that major parameters influencing sediment erosion in Pelton turbines include silt concentration, size, jet velocity, operating time, and jet diameter. It is found that hydro abrasive erosion increases with jet velocity silt concentration, size, and jet diameter. It is highly recommended to use multiple jets with small diameters instead of single with large diameters to minimize the risk of silt erosion. A literature review reveals that changing the design of turbine components and coating with different materials may not reduce sediment erosion significantly. It would be interesting to decouple the relationship between erosive wear of Pelton turbine and carrier fluid temperature, as such studies have not yet been investigated. In addition, many studies have been performed to develop a methodology for erosive wear prediction predicting under liquid-solid flow. Taking account of multiphase erosion under three-phase conditions could offer a more comprehensive and accurate erosion model.

For future research scope, investigating the influence of different parameters, such as water viscosity, silt concentration, size, jet velocity, operating time, and jet diameter, on sediment erosion for different flow conditions is recommended. It is also suggested that the damaged bucket profile of the Pelton turbine due to erosion causes a lack of stability and thus leads to vibrations. Therefore, the effect of vibration on the erosion phenomenon should be investigated.

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CONFLICTS OF INTEREST

The authors declare they have no conflicts of interest to report regarding the present study.

SUMMARY OF LITERATURE REVIEW

S. no.	Reference	Parameters considered and their ranges	Methodology	Results
01	B. Guo et al. [22]	▪ Particle concentration = 1.157 kg/m^3 (over a three-month monitoring period). ▪ Particle size = 200 µm ▪ No. of injector = 4 ▪ No. of buckets = 19 ▪ Design operating head = 456 m. ▪ Materials = stainless steel. ▪ Turbine type = Pelton	• Three phase flow • DPM was used for erosion prediction. • VOF was used for immiscible fluids. • Mansouri's model. • The SST K-w model was used for turbulence modeling.	❖ **Flow Pattern and Particle Tracking** ▪ Maximum velocity (95 m/sec) was obtained after the injector exit, and the average velocity at the inlet was about 5 m/sec. ❖ **Erosion Prediction** ▪ Weight loss for both the needle and nozzle casing decreased with the increase of the injector opening. ▪ The overall weight loss rate for the needle was 12.65 Kg/year, which seems to be over-predicted compared to actual weight loss, which could be as high as 3 kg/year. ▪ Erosion on the needle surface first increased and then decreased.
02	A. Rai, A. Kumar [2]	▪ Min. required parameters as per IEC 60193 (1999) ▪ Min. bucket width =0.08 m ▪ Min. Reynolds No. = 2×10^6 ▪ Specific Hydraulic energy (E) = 500 J/kg. ▪ Turbine type = Pelton	▪ 3D digitization was used for erosion estimation. ▪ An optical scanning camera Comet L3D was used. ▪ The system's accuracy was within 20 µm, and the measurement time of 2.5 sec. ▪ Finnie model and Tabakoff models were used to simulate erosion in CFD software.	❖ **Measurements Via Weighing Balance:** Total Eroded Mass = 0.39 gm. ❖ **Measurements Via 3D Digitization:** Total eroded mass = 0.34 gm. ❖ The erosion depth varied up to 1.2 mm.
03	M.K. Phady [4]	▪ Silt particle size = 250-355, 180-250, 90-180, below 90 µm. ▪ Silt concentration: 5000, 7500, 10000 ppm. ▪ Jet velocity = ▪ 26.61, 28.23, 29.75 m/sec. ▪ Operating time = 8 hours. ▪ Material = Brass ▪ Turbine type = Pelton	▪ Experimental investigation ▪ Weight loss t & silt weight was measured via digital analytical balance (LC = 0.5 mg) and digital balance (LC= 0.5 g), respectively. ▪ A method proposed by Kline and McClintock was used to perform error analysis.	❖ Maximum erosion was found at the splitter and some portions on the notch of the buckets. ❖ **Silt Concentration:** Erosion rate increased with an increase in silt concentration (erosion rate was not the same for different silt size ranges). ❖ **Silt Size:** Erosion rate increased with an increase in silt size. ❖ **Jet Velocity:** The erosion rate obeyed power laws w.r.t jet velocity ($W \propto \boldsymbol{V^n}$).
04	M. Phady, R. Saini [25]	▪ Silt particle size = up to 355 µm ▪ Silt concentration: 5000-10000 ppm. ▪ Jet velocity = ▪ 26.62- 29.75 m/sec. ▪ Operating time = 8 hours. ▪ Material = Brass ▪ Turbine type = Pelton	▪ An experimental study. ▪ Turbine efficiency was measured using: $\eta_o = \dfrac{P_o}{\gamma \times H \times Q \times \eta_g} \times 100$ ▪ Measuring the mass of Buckets using the Basic volume method. ▪ A method proposed by Kline and McClintock was used to perform error analysis.	❖ **Percentage efficiency vs. Silt concentration:** For the given silt particle size, a 2 % percentage efficiency loss was observed for silt concentration in the range of 5000-10000 ppm. ❖ **Percentage efficiency vs. Jet velocity:** The percentage efficiency loss with a jet velocity varying between 26-30 m/sec was 0.25-0.40 %. ❖ **Percentage efficiency loss vs. Percentage Mass loss:** About 8 % efficiency loss was observed against 3.5 % mass loss of the bucket. ***Note:** Deviation of ±10 % between experimental and calculated data for efficiency loss was observed.
05	R. Thakur, S. Khurana [26]	▪ Silt particle size = 90, 150, 350, 450 µm. ▪ Silt concentration: 2000, 4000, 6000, 8000 ppm. ▪ Jet velocity = ▪ 25.46, 26.45, 27.2 m/sec. ▪ Operating time = 8 hours. ▪ Pressure = 0.5 KPa– 14 Mpa. ▪ Discharge head= 45-90 m. ▪ Material = Brass. ▪ Turbine type = Pelton	▪ Experimental Investigation. ▪ Head Measurement: computerized weight transducer (Pressure range = 0.5 KPa – 12 Mpa and accuracy = ±0.065 %). Stress analysis was carried out in ANSYS Workbench.	❖ Maximum erosion was observed at the splitter and notch of the bucket. Erosive wear was extraordinary at sharp edges and scores. ❖ **Silt Concentration:** the standardized erosive wear lied between 0.000078 – 0.00256 cm. ❖ **Silt Size:** An increase in erosive wear was observed with the silt size. **Stream Velocity:** Erosive wear was following a power law ($W \propto V^n$) w.r.t stream velocity (n = 1.94 approximately).

06	S. Khurana, [26]	▪ Silt particle size = 100, 200, 300, 370 µm ▪ Silt concentration: 1000, 3000, 5000, 8000 ppm. ▪ Jet velocity = ▪ 28.805 m/sec. ▪ Operating time = 6 hours. ▪ Material = Brass ▪ Turbine type = Pelton	• Small experimental study • Runner weight loss was measured by an electronic weighing balance having the least count of 0.5 g. • Silt weight was measured by an Electronic weighing balance having the least count of 0.5 m.	❖ **Normalized erosion vs. Silt size:** Normalized erosion increased with increasing silt size. ❖ **Normalized erosion vs. Silt concentration:** Normalized erosion was observed to be increased with the increasing silt concentration for the given range of silt sizes. ❖ **Normalized erosion vs. Jet diameter:** the wear rate was directly related to the jet diameter. ❖ **Percentage efficiency loss vs. jet diameter:** Percentage efficiency loss was directly related to the jet diameters. ❖ The deviation between experimental and analytical results was observed to be within ± 8 %.
07	Sandeep Kumar and Dr. Brajesh Varshney [12]	▪ Jet velocity = 4.65 m/sec ▪ Silt size = 150 micron ▪ Design discharge = 71.4 m^3/sec ▪ Design head = 147.5 m ▪ Installed capacity = 3×30 MW ▪ Turbine type = Francis	▪ Case study of HPP. ▪ A correlation was developed between mass loss due to erosive wear and silt concentration while keeping all other parameters constant. ▪ The analytical results obtained from the developed correlation were then compared with the erosive wear side data for validation.	❖ The rate of erosion increased with the silt concentration passes through the turbine. ❖ The correlation developed for the measurement of erosive wear in this research study: $W = 8.52C^{0.384}$ ❖ **Analytical Results:** The approximate value of eroded mass was varying from 746 kg to 1111 kg when silt load in the range of 114321 tons to 323041 tons passed through the turbine. ❖ **Experimental Results:** The approximate value of eroded mass was varying from 750 kg to 1125 kg when silt load in the range of 114321 tons to 323041 tons passed through the turbine. ❖ **Absolute Percentage Error:** Absolute percentage error varied from 0.52 to 1.52 in this research study.
08	S. Khurana, V. Goel [27]	▪ Silt size = 100, 200, 300, 370 µm. ▪ Silt concentration = 1000, 3000, 5000, 8000 ppm. ▪ Operating time = 6 h ▪ Jet velocity = 28.805 m/sec. ▪ Jet diameter = 7.2, 8.8, 12.5 mm. ▪ Material = Brass ▪ Rated head = 45 m ▪ Turbine type = Turgo Impulse turbine	▪ Experimental bench study ▪ An electronic weighing balance having the least count of 0.5 g was used to weigh the runner. ▪ An electronic weighing balance having the least count of 0.5 mg was used to measure the silt weight.	❖ **Normalized erosion vs. silt size:** Normalized erosion increased with increase in silt size. ❖ **Normalized erosion Vs. Silt concentration:** Normalized erosion was observed to be increased with the increasing silt concentration for the given range of silt sizes. ❖ **Normalized erosion Vs. Jet diameter:** It was observed that the wear rate is directly related to the jet diameter. ❖ **Percentage efficiency loss Vs. Jet diameter:** It was observed that percentage efficiency loss is directly related to jet diameters. ➢ **Note:** It was recommended to use multiple jets to meet the required discharge flow instead of a single jet to reduce erosion.
09	S. Khurana [28]	▪ Silt size = 50-150, 150-250, 250-350, 350-390 µm. ▪ Silt concentration = 3000, 6000, 9000, 12000 ppm. ▪ Jet velocity = 26.81, 27.88, 28.81 m/sec. ▪ Operating time = 8 hours ▪ Bucket material = Brass ▪ Turbine type = Turgo Impulse Turbine	▪ Experimental bench study ▪ the effect of silt concentration, size, and jet velocity on the erosion of Turgo impulse turbine blades was investigated.	❖ Maximum erosion was noticed along the depth of the blades and some portion on the notch of the blade. ❖ **Erosion Rate Vs. Silt concentration:** Erosion increased with increase in silt concentration, but the rate of increase was different for different silt sizes. ❖ **The erosion rate Vs. Silt size:** Normalized erosion increased with an increase in silt size while keeping all other parameters constant. The increase in erosive wear was significant for larger sizes and higher concentrations. ❖ **The erosion rate Vs. Jet velocity:** erosive wear was following power law ($W \propto \boldsymbol{V^n}$) w.r.t jet velocity. Where; n = 1.368 (selected from correlation figure) for this research study.
10	T. Bajracharya et al. [16]	▪ Min. and max. particle size = 0.05 & 0.15 mm, respectively ▪ Average particle size = 0.1 mm ▪ Mass flow rate inlet for jet = 4 kg/sec ▪ Particle mass flow rate = 0.001004 kg/sec ▪ Turbine type = Pelton	▪ It was an Experimental and CFD analysis using Ansys CFX to spot erosion-prone regions. ▪ Only three buckets were considered to improve computational cost. ▪ No sleep, smooth wall condition (Ensure better Jet Stability).	❖ Erosion-prone areas were a splitter, the buckets' inside and the backside area, and the bucket's tip. ❖ The highest pressure (1.317×10^5 Pa) detected at the splitter and PCD of the bucket. ❖ Experimental and numerical results showed the bucket's 69 and 82.5 mg mass loss, respectively. ❖ The difference between experimental and numerical results is below 20 %.

SUMMARY OF EROSION PREDICTION MODELS

S. No	Reference	Range of parameters	Turbine Type	Correlation Developed
01	M.K. Phady [10]	1) Silt concentration = 5000, 7500, 10000 ppm 2) silt size = 250-355, 180-250, 90-180, below 90 µm. 3) Jet velocity = 26.61, 28.23, 29.75 m/sec 4) operating time = 8 hours	Pelton Turbine	$W = 4.02 \times 10^{(-12)}.(S)^{0.0567}.(C)^{1.2267}.(V)^{3.79}.(t)$
02	R. Thakur, S. Khurana [26]	1) Silt size = 90,150, 300, 450 µm 2) silt concentration = 2000, 4000, 6000, 8000 ppm 3) jet velocity= 25.46, 26.45, 27.2 m/s 4) Operating time = 8 hours	Pelton Turbine	$W = 3.733 \times 10^{-11} S^{0.1159} C^{0.9096} \boldsymbol{V}^{2.285} t^{1.1317}$
03	Sandeep Kumar & Dr. Brajesh Varshney [12]	1) silt size = 150 micron 2) Jet velocity = 4.65 m/s 3) design discharge = 71.4 m^3/s 4) Design head = 147.5 m	Francis Turbine	$W = 8.52 C^{0.384}$
04	S. Khurana, V. Goel [27]	1) silt size = 100, 200, 300, 370 µm 2) silt concentration = 1000, 3000, 5000, 8000 ppm 3) jet velocity = 28.805 m/sec 4) operating time = 6 hours	Turgo Impulse Turbine	$\boldsymbol{W} = 9.41 \times 10^{4} \boldsymbol{D}^{0.187} \boldsymbol{S}^{-3.137} \boldsymbol{e}^{0.326 \ \boldsymbol{ln\ S}^{2}} \boldsymbol{C}^{-3.961} \times \boldsymbol{e}^{0.277 \ \boldsymbol{ln\ C}^{2}} \times \boldsymbol{t}^{0.540}$
05	S. Khurana [28]	1) Silt concentration = 3000, 6000, 9000, 12000 ppm 2) Silt size = 50-150, 150-250, 250-350, 350-390 µm. 3) Jet velocity = 26.81, 27.88, 28.81 m/s 4) operating time = 8 hours	Turgo Impulse Turbine	$W = 1.976 \times 10^{(-10)}.S^{0.118}.C^{0.967}.V^{1.368}.t^{1.117}$

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