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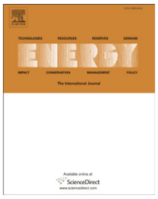

A methodology for assessment of erosive wear on a Francis turbine runner

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ABSTRACT

This study addresses the problem of erosive wear of Francis turbine runner of a typical power station located in northern Himalayan belt of India. Wear damage is determined using the erosion models of IEC-2009, IEC-2013, empirical assessment of Thapa and a methodology proposed in this research work. The proposed model introduces effect of relative velocity of turbine instead of characteristic velocity and also the effect of curvature of the blades by incorporating a parameter referred to as geometrical factor. The results obtained from the proposed model of erosive wear of the Francis turbine have been calibrated against Jhimrukh Hydropower Centre(*JHC*).

The study also includes petrographic analysis of the sediment taken from the site of power station to obtain the parameters related to concentration(C), size (K_{sz}), hardness (K_{hd}) and shape (K_{sh}). Effect of these parameters have been introduced into the wear models used in this investigation. The erosive wear assessment reveals that damage is severe at the runner outlet due to the high relative velocity(45.5 m/s against 15.5 m/s at inlet) and presence of hard minerals. The average loss of thickness for runner is 1.3 mm/year of operation, which agrees within 10% of the measured values from site of the power station.

1. Introduction

Erosion of turbine runner used in hydropower plants occurs because of sediments *i.e* due to the fragments of rock (loosened from earths' surface due to weathering processes and the impact of rain and snow)usually present in flowing water [1]. The sediment(as high as 20,000 ppm) is present in water and it becomes difficult to remove all such matter before passing through the turbine. The silt mainly consists of quartz (70%–98%), which is extremely hard (hardness 7 on Moh's scale) causes severe damage to the turbine components as cited in Ref. [2]. This poses a challenge to many hydropower stations resulting in severe erosion of turbines leading to the loss in energy generation [3].

The process of erosion of turbines is influenced by factors like shape, size, hardness, concentration, average speed of silt particles, the incidence angle of such particles (and the time interval of the attack by the silt particles on the surface of hydraulic turbine). The erosive wear also depends upon the properties of turbine material [4]. Desale *et al.* [5] investigated the effect of sediment particle shape, density and hardness.

Effect of shape and size: Hutchings [6] showed that erosion rate for the irregular and sharp edged particles was more as compared to blunt particles with round edges. Bahadur and Badruddin [7] characterize the erodent particles with different dimensions. Lynn [8] determined the rate of erodent particle impact on unit area of the surface on which erosion occurred as mean mass removed for each particle impact. Padhy [9] investigated (experimentally) the effect of shape of silt particles on the erosive wear of Pelton turbine bucket. The erosion damage dependence on silt particle size has been studied by several researchers [10–12] wherein wear rate has been shown to increase with particle size.

Effect of hardness: erosion is directly affected by hardness of impinging particle. The erodent particles with hardness more than 5 on Moh's scale are considered detrimental. Goodwin *et al.* [11] performed several tests with various grades of very fine sand under dry conditions and found that erosion rate varied with hardness and also depended on the amount of quartz present.

Effect of concentration: concentration of the silt (which is the total silt mass present in the unit mass of the fluid) is one of the dominating factors for erosive wear [13]. Some researchers as

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quoted in Ref. [13] suggested that erosive wear was proportional to concentration by a power law. Most of the materials, when tested for longer duration have resulted in the exponent value close to unity. Hence, considering erosion rate as directly proportional to concentration is a satisfactory approximation [14].

Effect of velocity: effect of velocity of the sediment particle on erosion rate is generally found to be proportional to power law of velocity by an exponent *n*, which depends upon the factors like material of impacting surface or wall and operating conditions. Any decrease in velocity (say by 10%) would substantially reduce the damage by 27% [15]. Goodwin [11] found *n* to be 2.3 for materials tested(both metals and plastics). The most common value of index reported is 3 as given in Ref. [13].

Effect of material being eroded: material used in the turbine is important as far as the amount of erosion rate by the sediment is concerned. The main turbine components like runner and guide vanes are susceptible to erosion damage [16]. The erosion resistance of stainless steels is good compared to other materials. Naidu [15] recommended materials for the critical turbine components (runner and guide vanes) to be 13% Cr, 4% Ni, stainless steel. Several experimental studies on various chromium nickle and manganese based stainless steel and their respective coatings were reported by Chattopadhyay [17], Mann [18–20].

Effect of impingement angle: erosion may be accompanied by plastic deformation. The material damage due to plastic deformation depends on velocity and impingement angle of erodent particles with respect to material surface together with other parameters [21]. Bergeron as cited in Ref. [13] defines effect of impingement angle of erodent particles and erosive wear for pure sliding and oblique impact. Bitter [22] [23] defines the erosion as deformation and cutting wear. Finnie [24–27], Neilson and Gilchrist [28] discuss impingement angle of erodent particle effects on the wear. Zhong [29] used the Bitter's [22,23] model to clarify the effects of particle impinging velocity and angle, particle size and concentration on wear of a pump casing. Bukhaiti [30] presents a series of systematic erosion tests to study the effect of impingement angle of erodent particle on 1017 steel and characterize three erosion regions as (*i*) *shallow rolling and particle rolling*,(*ii*) *micro cutting and deep ploughing*, (*iii*) *indentation and material extrusion*.

Effect of curvature: curvature of the wall surface (at which erosion occurs) is also an important factor along with the impingement angle that affects the erosion, as the flow direction changes along the wall surface. Hence particles hit the wall at the particular impingement angle depending upon the radius of curvature of surface. Therefore, a large radius of curvature at the location where the flow direction changes will tend to minimize the number of erodent particles which hit the wall surface. Bovet as cited in Ref. [13] showed that the radius of curvature has inverse relation with erosion from the wall surface. Wang [31–33] studied the effects of elbow radius of curvature on erosion rates by flow modeling and particle tracking. Edwards [34] studied the particle fluid interaction and the resulting particle wall impingement (direct and random impingement) and it was found that geometry selection caused gradual change in flow direction (and where length of impingement zone is more) and contributed to the reduction in erosion rate. Thapa [35] reported the effect of different shapes of blade angle distribution on erosion factor(ratio of the erosion rate of new design with respect to the reference design) along the blade surface from inlet to outlet. Khanal [36] reported a methodology for designing Francis runner blade by changing the blade profile and curvature towards trailing edge.

Mathematical and empirical models: many mathematical and empirical models have been by researchers [2,4,14,15,22,23,28,37–44] for the prediction of erosion rate in hydraulic turbines. Such models identified certain parameters/factors on which the erosive wear rate was dependent. Thapa [45] used the models of IEC-2009 [39] and Bajracharya [41] to predict erosion rate of Francis runner. Since the Bajracharya [41] model is particularly based on the Pelton runner, therefore prediction of erosion rate for Francis runner can be modified by including effects of geometrical factor of runner and the relative velocity of Francis runner (at the inlet and the outlet). Thapa [46] studied the effect of different parameters on erosive wear of turbine blade and predicted that one of the solutions to prevent the erosion of hydro turbine is to reduce relative velocity.

Need for proposed model: the present investigation proposes a novel idea of incorporating the relative velocity of turbine blade instead of characteristic velocity (due to inherent limitation of use of characteristic velocity to correctly predict the erosive wear at inlet and outlet of the blade of Francis runner of different power stations). The present work is focused on the prediction of erosive wear rate of Francis runner using the model of IEC-2013 [40] by incorporating the relative velocity of Francis runner instead of characteristic velocity. The discrepancy in the characteristic velocity in IEC-2013 [40] model (which shows variations in its values) at inlet and outlet of runner for different power stations with similar design specifications, is effectively removed by replacing the characteristic velocity with the relative velocity. The difference between predicted and experimental values of erosive wear (regarding the more erosive wear at inlet than at outlet of the blade of Francis runner) is attributed to be the use of characteristic velocity (which is one of the parameters in calculations of erosive wear in the IEC-2013 [40] model). This investigation also introduces a parameter referred to as geometrical factor based on radius of curvature of blade. The radius of curvature of runner blade includes its angles at inlet/outlet, which have influence on erosion rate. The curvature has influence on erosion both at inlet and outlet of the blades of Francis runner.

Generic contour plots have been obtained wherein erosion rate can directly be read corresponding to the design parameters of turbine and particle load of sediment present in river for any power station. Calibration of the proposed model has been performed on the Jhimrukh Hydrocentre(*JHC*) for which specifications and silt properties were already available in the literature [47] and also with the *on site measurements* obtained at Uri Power Station(UPS) of Jammu and Kashmir state of India. The erosion rate of *JHC* obtained from proposed model agrees well (within less than 15% of the experimental results of Thapa [48]) and also the results obtained for UPS from this study agrees within 10% of *on site measurements* of the runner thickness obtained during the maintenance period of power station.

2. Erosive wear models

Various erosive wear models have been proposed in literature [4,13,21–23,30,37,39–41] in which the wear rate has been given as a function of velocity, hardness, size and shape of impinging particle. These models pertain to ductile and brittle materials and for single and multiple erosive wear particles. Some of these models describe general erosion related problems while several models are completely based on the erosion of turbines. The general erosive wear models cannot be directly used for prediction of wear rate of turbines. There are some common parameters in *general erosive wear models* and *turbine erosive wear models e.g*, velocity, concentration, size, shape, hardness of sediment particles and materials eroded. However, there are some other parameters *e.g*, design specifications of turbine, which are particularly suitable for *turbine erosive wear models*.

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