ECONOMIC ANALYSIS OF SILT EROSION IN HYDRO TURBINES

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

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ALTERNATE HYDRO ENERGY SYSTEMS

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this dissertation work, entitled, "**ECONOMIC ANALYSIS OF SILT EROSION IN HYDRO TURBINES**", in partial fulfillment of the requirements for the award of the degree of **Master Of Technology** in "**Alternate Hydro Energy Systems**", submitted in Alternate Hydro Energy Center, Indian Institute of Technology, Roorkee is an authentic record of my own work carried out during the period from July 2009 to June 2010 under the supervision of **Dr.R.P.SAINI,** Associate Professor, Alternate Hydro Energy Center, and **Dr.ARUN KUMAR** , Head, Alternate Hydro Energy Center, Indian Institute of Technology, Roorkee, India.

I have not submitted the matter embodied in this dissertation for award of any other degree.

Date: June,28,2010

Place: Roorkee

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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RAHUL SINHA

ABSTRACT

Hydro turbine in a hydro power plant is one of the most important component. In case hydro turbine is not functioning properly or is out of order for maintenance or otherwise, plant suffers a huge loss of power generation and revenue. The function of turbine also affects the efficiency which may be reduced due to silt erosion/cavitation. Even one percent loss in efficiency of hydro turbine leads to perpetual loss of power and revenue.

Silt erosion in hydro turbines may be reduced to an economically acceptable level. Many investigators have studied the process of silt erosion in hydro turbines through experimental and analytical studies. Some of the investigators have reported that even design changes in the turbine components and using different materials and coatings to the turbine blades, the improvement in most cases are not significant. Hence, further experimental and theoretical studies are required for studying the effect of hydro abrasive erosion under different flow conditions.

In present study, the correlations available for estimating the silt erosion in different types of turbines are thoroughly studied. The existing co relations which can be used satisfactorily to determine the extent of erosion within the permissible range are verified using different values of correlation parameters. Based on these correlations, the trend of metal loss in turbines due to silt erosion has been obtained. Using other empirical equations, the power loss due to drop of efficiency under different working conditions may be a valuable tool in assessing a new runner design (to determine the lifetime operating cost). Cost analysis is carried out for the turbines affected due to erosion using cost of generation, cost of repair, maintenance cost and cost of mitigation which have been obtained from various turbine manufacturers. A methodology is evolved to analyze the economics of hydro turbines under such conditions. Such analysis shall be helpful for the turbine manufacturers and plant owners for comparative analysis to decide whether they should go for preventive measures for silt erosion in turbines or for maintenance of turbines.

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CHAPTER-1

INTRODUCTION

1.1 GENERAL

An energy crisis refers to the shortage of oil or shortage of electricity or other natural resources which is a bottleneck for economic growth. Energy crisis has become one of the major problems all over the world; especially the developed world needs more energy. Countries like USA, consumes 5 times more energy than the rest of the world, however the developing countries like India and China are also in raise of energy consumptions. It was estimated by the Energy Information Administration that in 2010 primary source of energy consisted petroleum 36.8%, coal 26.6%, and natural gas 22.9% amounting to an 86% share for fossil fuel in primary energy production in the world. Non –fossil sources included hydroelectric 6.3%, nuclear 6.0% and (geothermal, solar, tidal, wind wood waste) amounting 0.9%. World energy consumption is growing about 2.3% per year [1].

The production and use of fossil fuels raise environmental concerns. A global movement toward the generation of renewable is therefore under way to help meet increased energy needs. The burning of fossil fuels produces around 21.3 billion Tonnes (21.3 Gigatonnes) of carbon dioxide per year, but it is estimated that natural processes can only absorb about half of that amount, so there is a net increase of 10.65 billion Tonnes of atmospheric carbon dioxide per year (one Tonne of atmospheric carbon is equivalent to 44/12 or 3.7 Tonnes of carbon dioxide) [2].

1.2 RENEWABLE ENERGY SOURCES

Quantum of renewable energy source is determined by the amount of sunlight received. The Indian subcontinent being in tropical belt is endowed with a reasonably high amount of renewable energy. On an average earth receives 5x1015 kWh per annum. This is more than adequate to meet the world energy supply. The solar heat as well as light can be directly utilized for generation of electricity. Average flow on the Indian sub continent at ground lavel can be taken as 1.3 kW/m^2 as compared to 0.2 Kw/m^2 in USA. The total renewable energy resource potential that has been assessed in terms of technology is shown in table 1.1 [6].

Table 1.1 Estimate of potential of renewable energy [6]

Source/Technology	Approximate Potential
Bio mass	17000 MW
Solar energy	$5x10^{15}$kWh
Small hydro	10000 MW
Large hydro	150000 MW
Wind energy	45000 MW
Ocean thermal	50000 MW
Wave power	20000 MW
Tidal power	10000 MW
Geothermal	10000 MW

1.3 HYDROPOWER

Hydropower is a renewable, non-polluting and environmentally benign source of energy. It is perhaps the oldest renewable energy technique known to mankind for mechanical energy generation as well as electricity generation. The use of flowing water for various mechanical applications is pre-historic. The transition to electrical energy, however, could be made possible only by the 19th century after invention of dynamo. Development of hydro power in India dates back to 1897 with setting up of first hydro plant in India 130 kW capacity in Darjeeling known as Sidra pong small hydro power station to supply electricity to the local areas in decentralized manner. With the advancement of technology, and increasing requirement of electricity, the trust was shifted to big hydropower stations. The Sivasamudram Project of 4500 kW was the next to come up in Mysore district, Karnataka in 1902, for supply of power to the Kolar gold mines at 25 Hz. The pace of power development including hydro was rather tardy. The planned development of hydro projects in India was taken up in the post independence era. This means that the 1362 MW capacity (including 508 MW hydro) installed in the country before independence was mainly coming from small- and medium-sized projects. Since focus was laid on large-scale power generation through big hydro, thermal, and nuclear routes; the small hydro power (SHP) potential remained untapped. During the last 10–15 years, however, the necessity for development of SHP has been felt globally due to its various benefits particularly concerning environment, and it has assumed importance in the power development programme with time Realizing the fact that small hydropower projects can provide a solution for energy problem in remote and hilly areas where extension of grid system is comparatively uneconomical and also along the canal systems having sufficient drops, there is a renewed interest, internationally in the development of small hydro power projects[4]. The total installed capacity of hydropower in India is 36,836.40 MW which is 24.7% of total installed capacity of India [5].

1.4 KEY COMPONENTS OF SMALL HYDROPOWER SCHEME

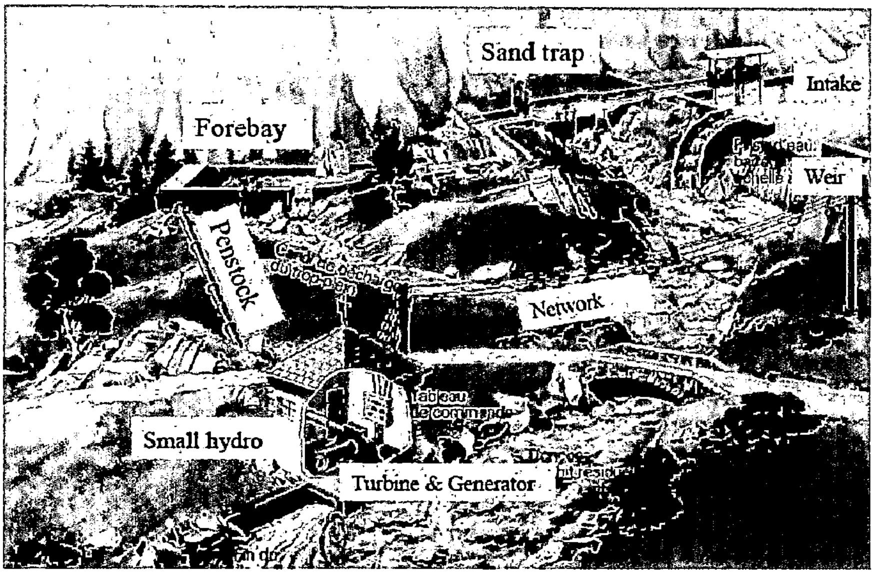


Fig. 1.1 Layout of SHP showing its basic components[46]

The key components of a hydro system are shown in Fig 1.1, and are described below.

1.4.1 Intake

The water intake must be located so it will always supply the necessary and adequate amount of water to the turbine. . It must include a screen to prevent debris, fish, or rocks from entering the turbine. A properly designed and constructed screen will be self-cleaning and require little maintenance. A poorly designed screen will require upkeep and will rob the system of power.

Fig. 1.2 Intake of a 3 MW plant. [3]

1.4.2 Desilting Tank

This serves as an area for the water from the intake to "decelerate" and for any fine materials such as sand and gravel that passed through the intake screen to settle and not flow into the turbine.

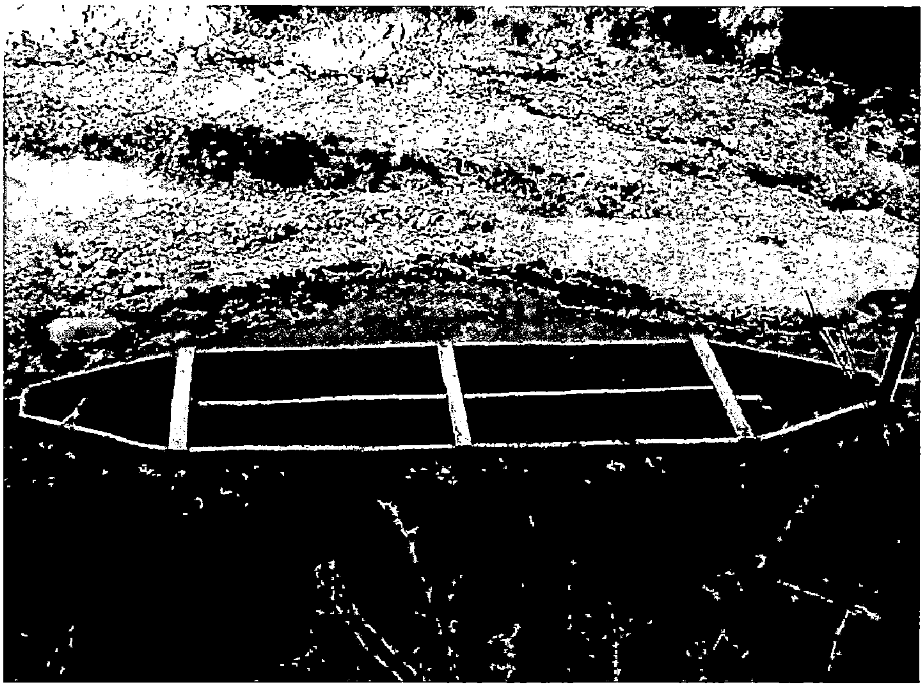


Fig. 1.3 Desilting tank [3].

1.4.3 Penstock

Penstocks for hydroelectric installations are normally equipped with a gate system and a surge tank. Flow is regulated by turbine operation and is nil when turbines are not in service.

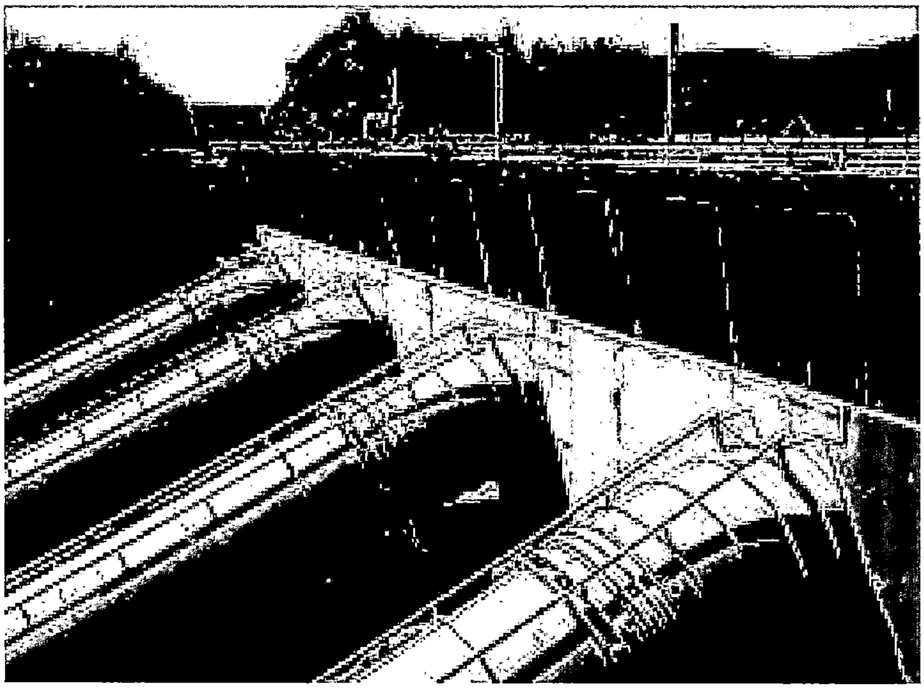


Fig. 1.4 Penstock [42].

1.4.4 Turbines

It is a machine which converts the energy of an elevated water supply into mechanical energy of a rotating shaft. Most old-style waterwheels utilized the weight effect of the water directly, but all modern hydraulic turbines are a form of fluid dynamic machinery of the jet and vane type operating on the impulse or reaction principle and thus involving the conversion of pressure energy to kinetic energy. The shaft drives an electric generator, and speed must be of an acceptable synchronous value.

1.4.5 Generator

Generator, in electricity, machine used to change mechanical energy into electrical energy. It operates on the principle of electromagnetic induction, discovered (1831) by Michael Faraday. When a conductor passes through a magnetic field, a voltage is induced across the ends of the conductor.

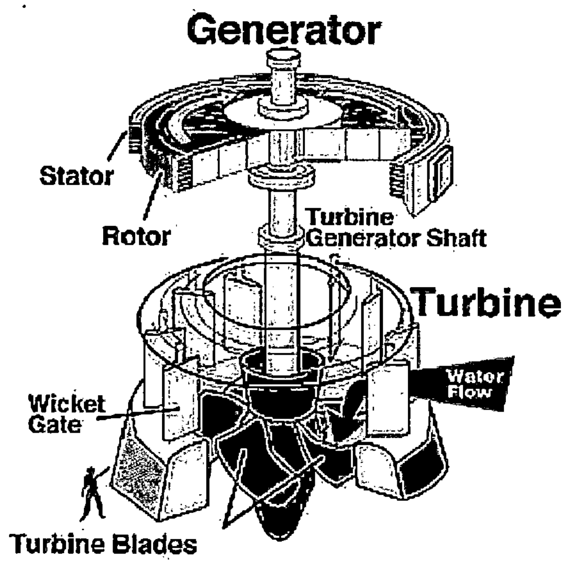


Fig. 1.5 Kaplan turbine and electrical generator cut-away view [42].

The generator is simply a mechanical arrangement for moving the conductor and leading the current produced by the voltage to an external circuit, where it actuates devices that require electricity.

1.5 IMPORTANCE OF TURBINE IN HYDRO POWER PLANTS

A water flow from an upper level to a lower level represents a hydraulic power potential. This power flow can be utilized in a water power plant by conversion to mechanical power on the shafts of turbines. Hydropower machine is the designation used for a machine that directly converts the hydraulic power in a water fall to mechanical power on the machine shaft. This power conversion involves losses that arise partly in the machine itself and partly in the water conduits to and from the machine.

The discharge and the net head for turbines differ in wide ranges from one power plant to another. This indicates that not only different types of turbines but also a very large register of sizes of turbines are needed.

The types of turbines in hydro power plants are distinguished in two main groups:

i. Impulse turbines
ii. Reaction turbines

This distinction is based on the difference between the two cases of energy conversion in these turbines. Briefly these two ways of energy conversion may be pronounced as follows.

i. Basically the flow energy to the impulse turbines is completely converted to kinetic energy before transformation in the runner. This means that the flow passes the runner buckets with no pressure difference between inlet and outlet. Therefore only the impulse forces being transferred by the direction changes of the flow velocity vectors when passing the buckets create the energy converted to mechanical energy on the turbine shaft. The flow enters the runner at nearly atmospheric pressure in the form of one or more jets regularly spaced around the rim of the runners. This means that each jet hits momentarily only a fraction or part of the circumference of the runner. For that reason the impulse turbines are also denoted partial turbines [7].

ii. In the reaction turbines two effects cause the energy transfer from the flow to mechanical energy on the turbine shaft. Firstly it follows from a drop in pressure from inlet to outlet of the runner. This is denoted the reaction part of the energy conversion. Secondly changes in the directions of the velocity vectors of the flow through the canals between the runner blades transfer impulse forces. This is denoted the impulse part of the energy conversion. The pressure drop from inlet to outlet of the runners is obtained because the runners are completely filled with water. Therefore this group of turbines also have been denoted as full turbines. [7]

The most commonly used turbines today are;

Impulse type: Pelton turbines

Reaction type: Francis turbines

Kaplan turbines

Bulb turbines

1.6 PROBLEM OF EROSION IN HYDRO TURBINES

Damages concerning water turbines are caused mainly by cavitation problems, sand erosion, material defects and fatigue. These problems are consequences essentially of high pressures, pressure variations and high water velocities which to some extent depend on the ever prevailing search for a minimizing of the costs of the investments.

The erosion in hydro turbines is majorly because of the two factors or it can be said that erosion in hydro turbine is of three types:

i. Cavitation erosion
ii. Silt erosion
iii. Combined Effect of Sand Erosion and Cavitation in Hydraulic Turbines

1.6.1 Cavitation

When the pressure in a liquid is lowered down to vapour pressure, cavities are created in the liquid, i.e., bubbles filled with air and vapour. This may occur in the low-pressure regions of the turbines, especially at the outlet of runners and inlet of the draft tube in reaction turbines. However, the cavity bubbles will again collapse when coming into regions of higher pressure. These collapses produce a strong characteristic noise, and bubbles collapsing on surfaces of runner blades, runner discs, draft tube wall and so on, may damage the surfaces by more or less terrific erosion. The whole range of turbine operation should therefore be free of cavitation. In practice that means to estimate maximum suction head.

1.6.2 Silt Erosion

Silt erosion or Sand erosion is designated as abrasive wear. This type of wear breaks down the flow guiding surfaces and partly make the surfaces uneven which may be origin also for cavitation erosion. Caused by the presence of solid silt particles in water, silt abrasion is particularly important in regions such as India, China and South America, causing severe damage to turbines and plant outages in extreme cases. In most cases, turbine silt abrasion results in lower turbine performance and shorter turbine operating life. In India in particular, with 80% of hydro power plants located in the Himalayan region, known for its fragile soils, silt erosion is an importantly increasing problem for most of this market. The critical period for power plant owners in this region is the monsoon period (June to September), when extremely high quantities of water are available for power generating. Research shows that during this period alone, up to 2.6 Mt* of silt can pass through the turbine. Sand erosion therefore may be both a releasing and contributing cause for damages which are observed in power plants with a large transport of wearing contaminants in the water flow.

1.6.3 Combined Effect of Sand Erosion and Cavitation in Hydraulic Turbines

A perfect hydraulic design of turbine components, in principle, should yield cavitation-free geometry. But when the surface integrity changes due to sand erosion even a cavitation-free design is found prone to cavitation. The reason is that both the phenomena are more likely to occur in high water velocity zones. Some of the eroded turbines have appearance of both sand erosion and cavitation. Study and analysis of the synergistic effect of erosion with cavitation is complex.

1.7 OBJECTIVE OF STUDY

Erosion in hydro turbines considered to be one of the most severe problems especially in case of Pelton and Francis turbines. It may be due to sand particles / cavitation and because of their synergetic action. Lot of work has been reported for determining the quantum of erosion for which the correlations are developed in order to assess the efficiency degradation due to erosion under different silt and working parameters. However no work has been reported on the economics aspect for maintenance of the turbines affected due to silt erosion. "Therefore an intensive study has been carried out to understand the erosion phenomena and silt erosion and the mechanism of erosion in hydro turbines in detail".

The objective of present dissertation is, to study the correlations available for estimating the silt erosion in different types of turbines. Based on existing co relations which can be satisfactorily used, to determine the extent of erosion within the permissible range will be then verified using different values of parameters constituting the correlation. Based on this correlation the trend of efficiency decay of turbine due to metal loss and finally the power loss with help of another empirical equation which could further be a valuable tool in assessing a new runner design, to determine the lifetime operating cost, is obtained. To carry out cost analysis for the turbines affected due to erosion based on energy generation and maintenance with the help of the cost of repair and maintenance obtained from various turbine manufacturers.

To develop a methodology to analyze the economics of hydro turbines under such conditions, which may be helpful for the turbine manufacturers to do the comparative analysis that whether to go for preventive measures of turbine erosion or to go for maintenance of turbines.

CHAPTER-2

LITERATURE REVIEW

A study by Finnie [8], explained that, the amount of surface material eroded by solid particles in a fluid stream depends on the conditions of fluid flow and on the mechanism of material removal. The paper first discussed some aspects of the fluid flow conditions which may lead to erosion and then analyses the mechanism of material removal for ductile and brittle materials. For ductile materials it is possible to predict the manner in which material removal varies with the direction and velocity of the eroding particles. The numerical magnitude of the erosion cannot be predicted with accuracy but does correlate with data from metal cutting tests. For brittle materials the conditions leading to initial cracking are deduced and ways of predicting the material removal are discussed. It was not found possible to develop an analysis as detailed as that for ductile materials. In addition, the influence of the properties of the abrasive particle on erosion was briefly considered.

Bitter [9] studied and found that, in fluid-bed systems, transport lines for solids, etc. heavy erosion may occur. This type of attack has been shown to comprise two types of wear, one caused by repeated deformation during collisions, eventually resulting in breaking loose of a piece of material, the other caused by the cutting action of the free-moving particles. In practice these two types of wear occur simultaneously. Formulae could be derived expressing erosion as a function of mass and velocity of the impinging particles, impingement angle mechanical and physical properties both of erosive particles and eroded body.

Neilson and Gilchrist [10] carried out a study in which erosion by a stream of solid particles has been discussed. In this work, experimental results were given for the erosive action of a particle laden gas stream on specimen materials which have widely different physical properties. The effects of particle shape, particle velocity and angle of attack were investigated and the parameters affecting particle deposition in the specimen surface were enumerated. A simple approach to a theoretical analysis of the problem is given and the relationships derived are used to correlate the experimental results.

Truscott [11], considered the factors affecting abrasive wear-the properties of the solid particles, the construction materials and the flow-and various types of wear. The main sources of information were from laboratory wear tests on materials and pumps, and from service experience on pumps and water-turbines. The effects of wear on performance and working life were also discussed. Finally, the main points emerging from the survey are listed.

The study carried out by, Hutchings and Winter [12], about mechanism of material removal. Metal targets were impacted at an oblique angle by 3 mm steel balls at velocities up to 250 m. The mechanism of metal removal were studied in detail.

Hutchings and Winter [13], studied and found that, Studies were made of the oblique impact of individual angular particles on lead and mild steel targets, and the influence of the particle orientation at the point of impact on the subsequent deformation determined. When the angle made by the leading edge of the particle to the surface is small, ploughing deformation can occur, similar to that found with spherical particles. At a sufficiently high impact velocity, material is removed from the surface. If the angle between the surface and the leading edge of the particle is larger, a micromachining action occurs. However, rather than scooping out material as a chip, the cutting edge of the particle tends to bury itself deeply into the specimen. Material can be removed as a result of a particle breaking up during its cutting action. Here, a lip raised during the early stages of the impact is subsequently cut off by fragments of the particle. It is shown that particle rotation can take place during impact and that when this happens the particle's effectiveness in removing material is diminished. Bands of intense deformation are visible in etched sections of craters in mild steel formed in some experiments. It is suggested that these are adiabatic shear bands.

A comprehensive model for the solid particle erosion of ductile materials is presented by Sundarajan [14]. The objective of the present paper was to develop a comprehensive theoretical model for erosion, valid for all impact angles, combining the concept of localization of plastic deformation leading to lip formation and the generalized Energy absorption relations valid for all impact angles and all shapes of eroding particles. Solid particle erosion of metallic materials at room temperature was extensively studied. However, a comprehensive theoretical model which can explain the experimental data is not yet available. The "cutting" or "micromachining" model of Finnie represents the pioneering effort in this regard. This model essentially computed the volume of the crater generated in the eroding material when it is impacted by a hard angular particle at a given velocity and angle of incidence, it was assumed that the crater volume or a proportion of it was removed causing weight loss, The cutting model, strictly valid for erosion at oblique impact angles and was capable of explaining the experimentally observed maximum in the erosion rate at intermediate impact angles and also predicts reasonably well the velocity dependence of the erosion rate.

A case study to understand the erosion in hydro turbines carried out by Chattopadhyay [15]. Turbine runners show an unusually high rate of wear in river water with high silt content. Cast ferritic stainless steel of CA6NM type was the normal turbine runner material. The Slurry erosion characteristics of stellite 6, lSwt. % Cr-lSwt.% Mn stainless steel, type 316L stainless steel and CA6NM were evaluated in specially designed equipment. The different wear rates of the alloys were explained in terms of the microstructure, hardness and work-hardening rate. The extremely high wear of cast CA6NM hydro turbine runners due to high silt contents in river water drastically reduced the power-generating capacities of several power plants [15].

Hydro abrasive erosion causes the destruction of a material surface as a result of impingement of solid particles carried within the fluid. To develop designs for the erosive environments, many manufacturers of hydraulic machinery have relied largely on experience and empirical data to estimate the damage likely to caused by abrasion, to specify intervals between the technical inspections, and to estimate component endurance. Grosse et al [16], presented the numerical methods which give the detailed understating of mechanism of erosion, and represent a design tool for the development of machines to operate in abrasive environments.

Meng and Ludema [17], reported that, Most wear models and equations in the literature were analyzed as to origin, content and applicability. No single predictive equation or group of limited equations could be found for general and practical use. The reasons include the perpetuation of erroneous and subjective expressions for the mechanisms of wear, the slow pace of translation of microscopic observations into macroscopic models of the wearing processes and the paucity of good experiments to verify proposed models.

In the study of Zhang *et al.* [18], Hydraulic damage tests carried out on five types of non-metallic coating materials in slurry water. A rotating disk test rig was used to simulate silt abrasion and cavitation erosion with natural silt at periphery speeds of 30 and 40 m SC'. The resistances of the various coatings to silt abrasion, and the combination of abrasion and cavitation, have been measured and compared under specified hydraulic conditions. The tests shown that among the five selected materials, epoxy resin reinforced by synthetic conmdum particles and castable polyether-based polyurethane rubber were the most resistant coatings to abrasion and the combined abrasion-cavitation damage, respectively. It was found that of the materials tested, high elasticity polyurethane had the greatest resistance to cavitation, whilst a brittle material, epoxy resin, had the least in high-silt-content water. The erosion rates of the coatings examined were generally proportional to the peripheral speed of the disk raised to the power of 3.1-4.5 under the given conditions. The synergistic effect of cavitation and abrasion on different coating materials was discussed.

Krause, Grein [19], reported in their study that, combating abrasion is a multidisciplinary engineering task. Although abrasion rates can be predicted reasonably accurately on the basis of research findings and empirical data, this is not sufficient. State-of-the –art research is now well on the way to preventive abrasion together.

Yan *et al.* [20], reported that, The development of china's enormous hydropower potential is hampered by its high silt content of many of its major rivers. China's two largest rivers, the Changjiang and Huanghe have hydraulic head of 5400 m and 4830 m respectively. The Hhangjiang has an annual average flow of 36600m^3/sec and for the Huanghe the annual average is 1900 m^3/sec. the silt content in the rivers of china is extremely high, with 42 of the major rivers transporting more than 140000 t of silt annually. The total amount of sand discharged into the sea is about 2x10^9 T. This silt content pass through the turbines and causes serious abrasion damage to hydro turbines. Mei Zu Yan discussed research on the abrasion phenomena and the Chinese approach to protection methods.

Erosion is a function of different parameters such as silt size, hardness, and concentration, quantity, shape, velocity and base material properties. In most cases, this can be minimized by controlling the above-mentioned parameters. During monsoon season, it becomes impossible to control these parameters which cause erosion. So, it is essential to know their effects. Wear, which occurs due to low and high-energy particle impact, can be controlled by velocity or by controlling silt size, shape and concentration. The low energy impact wear can also be controlled by providing suitable hard coatings. However, this becomes critical for high particle impact wear. An experimental study was undertaken by B S Mann [21], for understanding its nature. In the study, hard coatings such as hard chrome plating, plasma nitriding, D-gun spraying and Boronising were studied for high-energy impact wear resistance. Boronising appears to be excellent for this, followed by D gun sprayed WCq12Co coating. Based on this experimental study, Boronising is being field-tried on a component which is prone to erosion due to high-energy particle impacts.

Mack *et al.* [22], has studied that, Erosion in hydraulic power plants is caused by sand particles in the flow. This was one of the major problems that restricts the lifetime between overhauls of water turbines. Especially those parts of the hydraulic turbine which were exposed to high flow velocities bear a considerable risk of being damaged by erosion processes. Therefore, suitable methods for the prediction of erosion were necessary already in the design phase. The prediction of erosion, based on the Lagrangian calculation of particle paths in a viscous flow, were described for two components of a Francis turbine, for which results of field tests were available.

A microstructure study of slurry erosion of tungsten carbide–cobalt was studied in the by Pugsley, and Allen [23]. The slurry erosion performance of ultrafine WC–Co composites sintered from powder produced through the spray conversion process has been evaluated and compared to that of conventional materials. Slurry erosion testing were carried out using the jet impingement method and slurry composed of water and 500 mm diameter silica sand. The erosion resistance of WC–Co hard metals was seen to increase dramatically as the grain-size decreases below about 1 mm, with the result that ultrafine WC–Co may be up to three times more erosion resistant than the closest conventional material.

Bergeron [24], reported that, direct numerical simulations of quartz particles, given a turbulent stationary velocity field, are performed in "real time" on a Silicon Graphics workstation. Interaction of the surrounding flow on spherical particles is taken into account by a modified version of the Basset-Bossiness-Oseen equation, including nonlinear resistance. Boundary conditions (walls) are modeled with the use of reflection laws. Interactions between particles are neglected. The velocity field was pre-computed with the k–ε model over different geometries. Second-order accuracy numerical implementation and error estimation were discussed. Impacts on surfaces were accounted for by means of direction and kinetic energy of incident particles. The areas with the highest probability of damage were then mapped. Real-time high-quality interactive graphics were an important aspect of this useful numerical tool.

Mann [25], described wear characteristics against plasma nitriding and HVOF (High Velocity Oxy Fuel). He has described the abrasion and silt erosion characteristics of plasma nitriding and HVOF coatings along with commonly used steels in hydro turbines.

Again a comparison of slurry erosion characteristics of TiNi shape memory alloys and SUS304 stainless steel was done by Lin *et al.* [26]. The slurry erosion characteristics of three TiNi shape memory alloys and SUS304 stainless steel using the liquid/solid impingement were systematically studied. Experimental results showed that more resistant TiNi alloys and less resistant SUS304 stainless steel exhibit ductile behavior and the maximum erosion has observed at 30°.

Mann [27], have described that, the water jet impingement erosion characteristics of titanium alloy (Ti6Al4V), Hadfield steel, laser hardened, plasma nitrided and pack borided 12Cr steel along with most commonly used steels in hydro turbines. Round samples as per ASTM G73-98 were tested for water jet impingement erosion study. While testing, in the incubation period, plasma nitrided and pack borided 12Cr steel performed much better than 12Cr and 13Cr4Ni steels. Plasma nitrided 12Cr steel performed much better than pack borided 12Cr steel. It was due to the integrity of plasma nitrided layers and their ability to absorb shocks due to jet impingement. During incubation as well as in the long run, Hadfield steel and laser hardened 12Cr steel performed exceptionally well followed by 17Cr4Ni 'PH' steel. Based on this experimental study, a suitable criterion based on ultimate resilience (UR) for metallic materials and a composite modified resilience (CMR) for hard metallic coatings was discussed. Water jet impingement erosion test results along with the mechanical properties of materials and coatings, and their scanning electron micro structural details were reported.

The slurry erosion of two coatings applied by oxy fuel powder (OFP) and wire arc spraying (WAS) processes onto sand-blasted AISI 304 steel was studied by Santa, and Baena [28] and the results were compared to those obtained with AISI 431 and ASTM A743 grade CA6NM stainless steels, which were commonly used for hydraulic turbines and accessories. The coated surfaces showed higher erosion resistance than the uncoated stainless steels, with the lower volume losses measured for the E-C 29123 deposit. SEM analysis of the worn surfaces revealed intense plastic deformation in both coated and bare stainless steels, with little evidence of brittle fracture in the microstructure. The measured adhesive strength of the coatings was considered acceptable for the processes employed.

The behavior of erosion in hydro turbine steel was studied by Chauhan and Goel [29]. The martensitic stainless steel (termed as 13/4) is currently being used for fabrication of underwater parts in hydroelectric projects. There was, however, several maintenance problems associated with the use of this steel. A nitrónic steel (termed as 21–4–N) has been developed as an alternative with the specific aim of overcoming these problems. A comparative study was made on the erosion behavior of 13/4 and 21–4–N steels by means of solid particle impingement using gas jet.

Sand erosion of pelton turbine nozzles and buckets was studied by carrying out a case study of Chilime Hydropower Plant by Bajracharya *et al.* [30]. Detailed studies were conducted and erosion analysis was carried out in this case study. Sieve and mineral content analyses were systematically carried out and sediment load was calculated. By doing this, erosion rate and efficiency reduction were established using already known methodology and scenario for similar hydropower plants. The flow analysis through surface of needle was established by drawing flow net diagrams. This detrimental damage led to efficiency reduction of 1.21% consequently resulting in loss of power generation. A wear rate of 3.4 mm/year was estimated for the needle and the bucket after a systematic analysis.

Chauhan *et al.* [31], made a comparative study on the erosion behavior of as cast 13/4, and as cast and hot rolled 21-4-N steels by means of solid particle impingement using gas jet. It was observed that the hot rolled 21-4-N nitronic steel possesses excellent resistance to erosion followed by as cast 21-4-N and 13/4 steels. The austenitic matrix of the hot rolled 21-4-N steel possessed high hardness coupled with ductility, high tensile toughness and work hardening ability, which result in higher erosion resistance. The erosion damages were in agreement with studies of eroded surfaces on scanning electron microscope (SEM).

Erosive wear of hydro turbine runners depended upon different 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. Padhy, and Saini [32] showed the effect of these parameters on erosion in actual conditions experimentally. An extensive experimental study was carried out on a small scale Pelton turbine. Based on the experimental data collected for different parameters, correlations were developed for wear rate of Pelton turbine buckets as a function of critical parameters, i.e., size and concentration of silt particles and jet velocity.

Padhy, and Saini [33], reviewed the silt erosion in hydro turbines and reported that, Erosive wear of hydro turbine runners is a complex phenomenon, which depends upon different parameters such as silt size, hardness and concentration, velocity of water, and base material properties. The efficiency of the turbine decreases with the increase in the erosive wear and final breakdown of hydro turbines. Various researchers conducted experiments to study the effect of these parameters on erosive wear, but most of these experiments are on small-size samples in different types of test rigs to simulate the flow conditions in the turbine, but actual flow conditions and the phenomenon of erosive wear are too complex to simulate. In the present paper, studies undertaken in this field by several investigators have been discussed extensively. Based on literature survey various aspects related to silt erosion in hydro turbines, different causes for the declined performance and efficiency of the hydro turbines and suitable remedial measures suggested by various investigators were discussed.

Thapa *et al.* [34], studied and found, a perfect hydraulic design of turbine components, in principle, should yield cavitation-free geometry. But when the surface integrity changes due to sand erosion even a cavitation-free design was found prone to cavitation. The reason was that both the phenomena are more likely to occur in high water velocity zones. Some of the eroded turbines have appearance of both sand erosion and cavitation. Study and analysis of the synergistic effect of erosion with cavitation was complex.

Pande, and Rao [35], briefly described the methodology adopted to develop an inherently silt resistant Francis turbine runner. Erosion on a runner is numerically evolved using the modern CFD tools and its performance parameters are also evolved. A new runner with performance parameters quite similar to the original runner and silt erosion reduced by almost 40% has been developed.

Winkler and Pande [36] studied that, Due to the extensive problems with a high concentration of hard particles in the water going through turbines in India the paper gave an overview over the mechanisms and solutions from the design and the protection point of view. The different damaging mechanisms of particles depending on the size and the location of abrasion on a profiled surface were being described, showing the influence of the boundary layer for the two extremes of quasi-laminar or turbulent condition. After that a short overview of different optimisation processes to minimise the wear were given. Here also examples of design changes are given

In another study of Pande [37] reported that, Lagrangian Particle Tracking (LPT) module is a powerful tool to counter silt menace. The numerical analysis method takes in to account the turbulence function while solving the Navier Stoke equation. The LPT takes in to account both interaction of liquid on the particle and particle on the liquid while tracing the track of the particle hitting the metal boundary. An erosion rate coefficient was generated which is a function of the particle relative velocity and the angle of impact. Suitable macros developed evaluate the erosion.

CHAPTER -3

SILT EROSION IN HYDRO TURBINES

3.1 GENERAL

Hydraulic abrasion of the flow passage components of hydraulic machines should be interpreted as a gradual alteration in state and shape taking place on their surface. The process develops to the action of incoherent solid abrasive particles suspended in the water. In a number of hydroelectric stations operating with water which contains a great amount of sediment matter, the components associated with flow passage portion in the hydro turbines were affected with considerable erosion. This results first, in a decline of efficiency in these units and , second, reduce the inter repair time operation .i.e. the operation interruptions, needed to provide maintenance service, become more frequent, the amount of rebuilding overhaul is greatly increased. The erosion intensity can be characterized by an efficiency fall in turbines, which, for example, amounted nearly 10% in the course of one year operation, of one of the water power station in Trans-Causcasus [43]. Such a significant drop in efficiency can be mainly accounted for a failure in the runner and labyrinths packing of the device.

Silt erosion is a result of mechanical wear of components on account of dynamic action of silt flowing in the water coming in contact with the wearing surface. However the mechanism of erosion is complex due to interaction of several factors like sediment particles size, shape, hardness, velocity, impingement angle, concentration, properties of material and so on. The silt laden water passing through the turbine is the root cause of silt erosion of turbine components which consequently leads to a loss in efficiency thereby output, abetting of cavitation , pressure pulsations , vibrations , mechanical failures and frequent shut downs Since silt erosion damage is on account of dynamic action of silt with the component, properties of silt, mechanical properties of the component in contact with the flow and conditions of flow are therefore jointly responsible for the intensity and quantum of silt erosion. Therefore silt characteristic, velocity of silt laden water are the important factors to understand erosion intensity or extent of damage on hydro turbines. Fig. 3.1 shows such a Kaplan runner damaged by silt erosion and Fig. 3.2 shows the damaged guide vanes due to silt erosion. This problem is more severe in medium and high head turbines. Fig. 3.4 and 3.4 shows the eroded blades of a Francis turbine and eroded spears of a Pelton turbine.

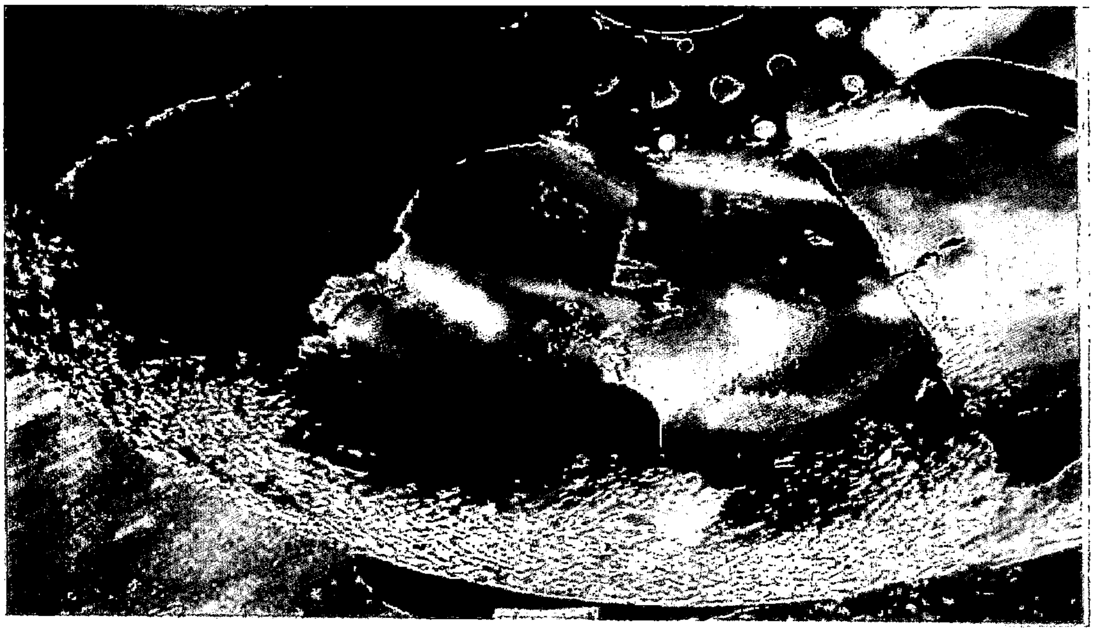


Fig. 3.1 Severely damaged Kaplan runner by the impact of silt [38]

Fig. 3.2 Silt erosion damage on the guide vanes [38]

Fig. 3.3 Eroded Francis runner from silt [45]

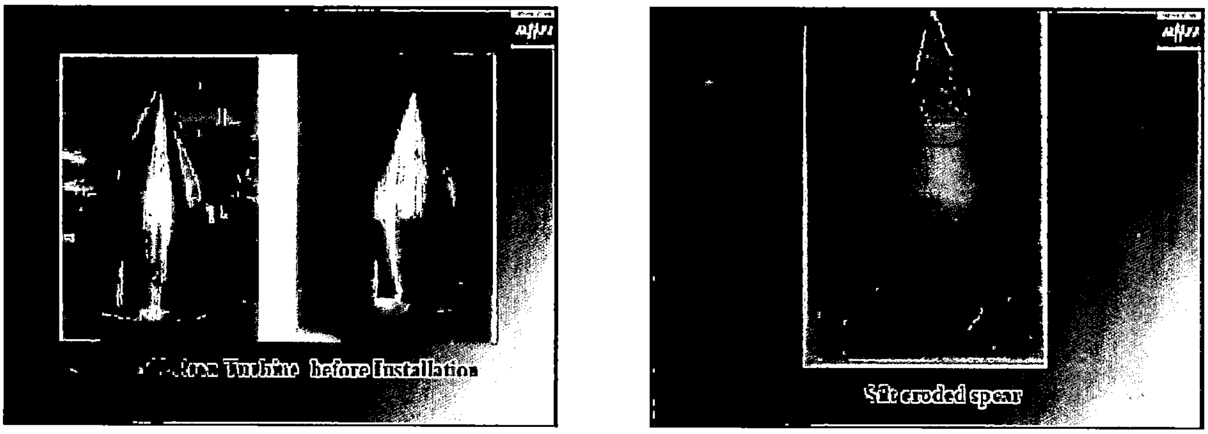


Fig. 3.4 Spear of a Pelton Turbine before installation and after being eroded.[45]

3.2 SILT PARTICLE EROSION MECHANISM

Silt erosion involves all the three modes erosion i.e. Chiseling, Hammering and Grinding. Chiseling is the cutting of a hard material such as wood stone and metal by a tool with a characteristically shaped cutting edge of blade on its end. Hammering is a normal attack by the eroding body. Its action is equivalent to a series of hammer blows. To resist this type of action, the material again has to be as hard as possible, and has to prevent the spreading of cracks. Grinding is a metal cutting process by the help of a no. of abrasive particles to give a metal surface a desired finish or shape.

3.3 DAMAGING MECHANISM

While the hardness of the stainless steel in general used for runners lies at 5.5 on the Mohs scale, the hardness of quartz lies at 7 and above. Other components, which are under risk, are sometimes also made from stainless steel but often also carbon steel with an even lower hardness is being used. But not only the hardness of quartz is responsible for the damaging effect but especially when the particles present have a sharp-edge form, as shown in Fig. 3.5, the damage these particles can wreak is much higher compared to round-edged particles. This is the case in most hydro power plants in India as due to the nearness of the Himalaya the quartz has not been rounded but still retained its sharp angular shape.

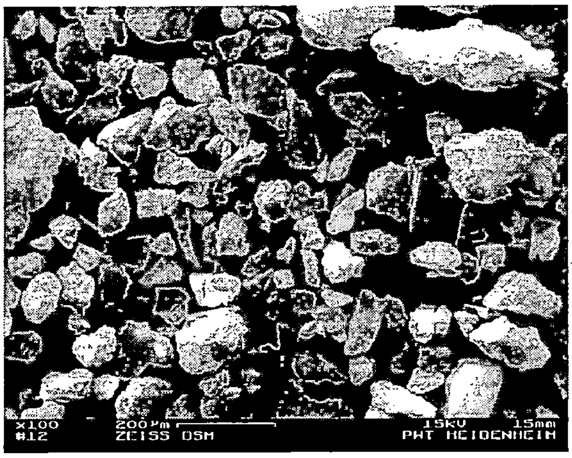


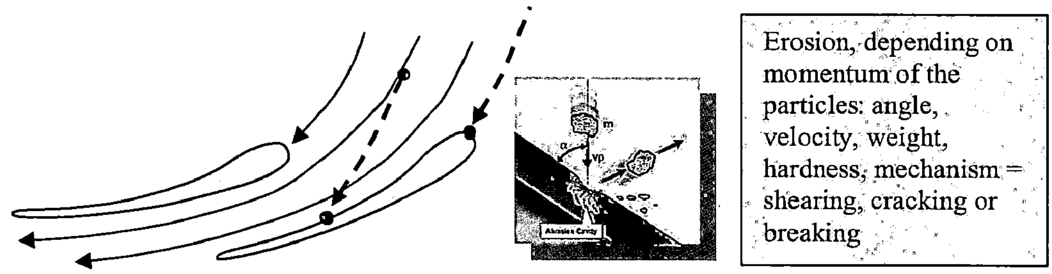
Fig. 3.5 Sharp-edged sand particles (from India) [36]

Particles damage mainly those areas where a high velocity is present as only there the abrasive forces reach a certain height needed for damaging the base material. These areas can be divided into two main groups as:

i. Profiled passages with relatively high velocity, which are mainly found on the runner and the guide vanes.

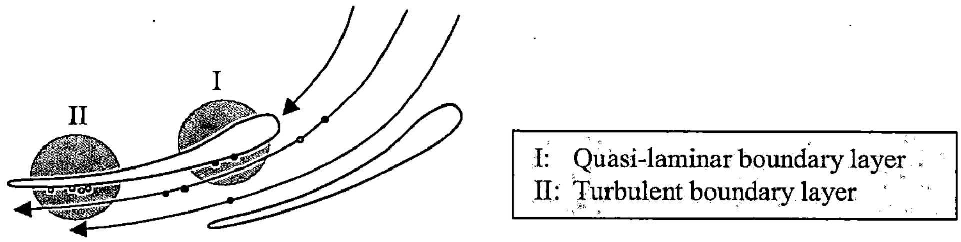
ii. Recesses like clearances of runner labyrinth and between guide vanes and facing plates. These are characterized by high velocity and slit cavitation.

When focussing on the profiled passages, larger particles follow the mass forces and the abrasive erosion is dependent on the angle, velocity, weight and hardness of the particles when impacting with the eroded part and shearing, cracking or breaking takes place. Finer particles,



a) Behaviour of large particles

which are smaller than 0,2 mm diameter follow the main flow. For these particles the flow conditions in the boundary layer are determining the damages, which they can havoc.



b) Behaviour of small particles

Fig. 3.6 Behavior of particles dependent on the size in a profiled passage[36]

When looking at the flow conditions in the boundary layer of a blade, two conditions can be found as shown in figure 3.6 b, which influences the damaging mechanisms especially for smaller particles as:

i. Quasi-laminar boundary layer in the entrance area of the blade, and

ii. Turbulent boundary layer in the outlet area

In Fig.3.7 the flow velocity and the turbulence grade for the boundary layer of a blade are shown. While the relative flow velocity is at the entrance area of the blade highest, the flow in this area is mainly quasi laminar. Due to this the relative flow velocity in the boundary layer is quite small. Further towards the outlet edge the relative velocity is slightly dropping but the-

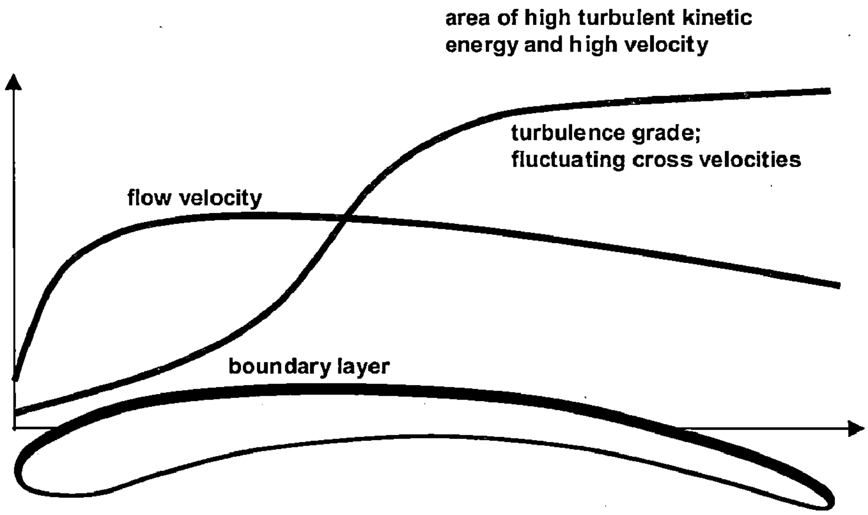


Fig. 3.7 Flow velocity and turbulence grade dependent on the location of the blade [36]

-turbulence grade in the boundary layer increases, so that the real velocity in the layer can be increases compared to the overall velocity, making these conditions very critical for hydro-abrasive erosion if hard particles are in the water.

In the quasi-laminar condition the abrasion is not very high, as the particles roll or slide over the surface. Rounded particles have here the advantage of rolling, while sharp edged particles can damage the surface slightly as when the raking angle of a sharp-edged particle and the material surface is in a certain range it might come to a small amount of shearing.

In the turbulent layer the abrasion is dependent on the fluctuating cross velocity, weight, shape and hardness of the particles. Due to the cross velocities, the particles are not just moving along in the direction of the overall water flow but they can move perpendicular to the surface and can be hammered onto the surface and due to the turbulences can even move backwards. The damaging mechanism is gouging or hammering as shown in 3.8. While for the impact of particles moving perpendicular to the surface the shape is a small influence, especially when the angle of the particle movement and the surface is getting small the influence of the particle shape on the erosion mechanism is increasing as rounded particles have more of a ploughing 3 nuclei and have an influence in advancing of the inception of cavitation. Due to this and also as soon as the first damages occur the profile often changes in a way that a significant increase in cavitation occurs, which damages the surface further, so that the material's strength is reduced and erosion is significantly enhanced. Also if not stainless steel is used the combination of all three damaging processes of cavitation, corrosion and hydro-abrasive erosion has to be taken into account.

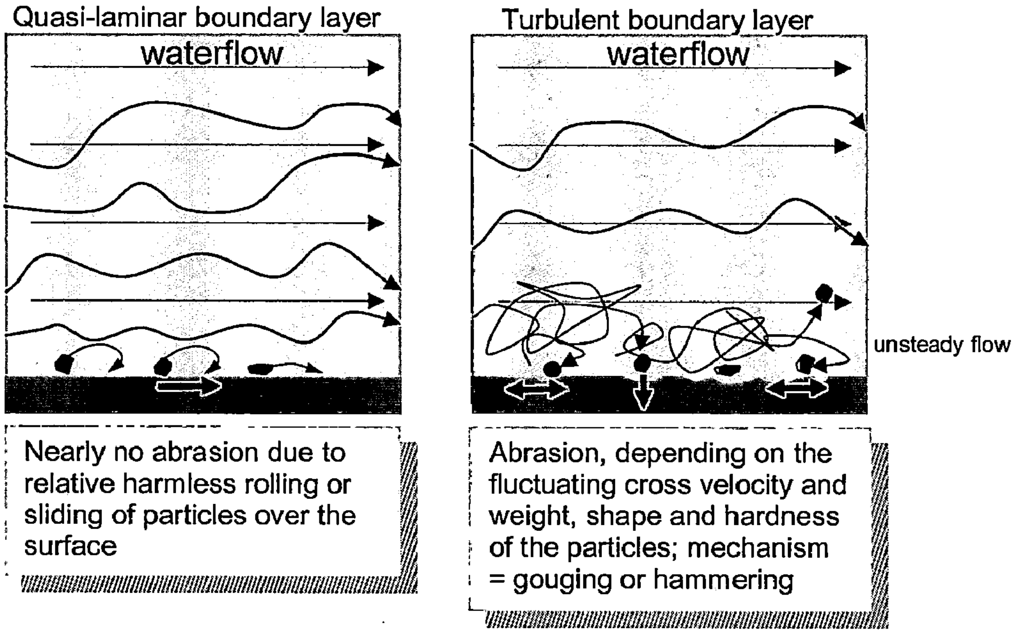


Fig. 3.8 Comparison of particle movement in different boundary conditions [36]

3.4 FACTORS RESPONSIBLE FOR AFFECTING INTENSITY OR SILT EROSION RATE

3.4.1 Silt Characteristics

The physical properties of sand particles may be defined in many ways, such as grain size (equivalent diameter), shape (round or sharp edges), geological structure mainly hardness) and grading (distribution of varying sizes) and concentration.

The intensity of erosion is directly proportional to the size of the particles. Particle sizes above 0.25mm are extremely harmful. It has been found that particles larger expressed in parts per million (ppm). Its cut-off values for damage to be significant are: 200 ppm for low and medium head machines (up to 150 m). And 150 ppm for high head machines than 0.25 mm, even with a hardness of less than 5 on .Moh's scale, cause wear. Similarly fine silt (less than 0.1 mm) containing quartz can erode under water components. Fine silt is especially dangerous if the turbine is operating under a high head. Sharp and angular particles cause more erosion compared with rounded ones the intensity of erosion is also directly proportional to the hardness of the particles (irrespective of their size). Particles with Moh's hardness of more than 5 are harmful. Himalayan silt is 90 per cent (7 on Moh`s scale compared with 10 for diamonds). The silt concentration is the most dominating factor influencing erosion intensity linearly. It is generally expressed in parts per million (ppm). Its cut off values for damage are: 200 ppm for low and medium head turbine (upto 150m), and 150 ppm for high head machines [20].

3.4.2 Velocity of Silt-Laden Water

The intensity of erosion is usually proportional to the cube of the velocity V of the water carrying silt particles in suspension. This is particularly true for Francis runners. Any decrease in velocity, therefore would substantially reduce erosion damage. For instance, a 10 per cent decrease in water velocity could reduce erosion by 27 per cent.

3.4.3 Machine Flow Pattern

Intensity of silt abrasion is closely related to the local flow pattern in a machine i.e. same specimen materials can suffer different degrees of damage when placed in different locations with different types of flow. On the other hand, same type of abrasion can occur for each kind of material when placed at different locations, but with the same type of flow pattern [20].

3.4.4 Power Plant Design Criteria

Intensity of damage due to silt at different power stations may vary even where silt conditions are identical which clearly indicates that equipment design has a significant role to play in influencing the intensity of erosion .Power plant design necessarily includes water passage, rotation speed and number of runner blades etc.

When a turbine is designed to handle high concentrations of silt, selection of a conservative specific speed is advisable. The adverse effect of silt is reduced in oversized machines. The rotation speed should be lower than the synchronous speed selected for a machine to be used in clean water. Experience also shows that design optimization is possible to mitigate silt erosion of critical zones. From the basic principles of hydrodynamics, the energy transfer by hydrofoils results from their angle of incidence, curvature and shape. These parameters create differential velocities over the blade surface, and the rate of change of velocity depends on the curvature and length of the blade. It has been found that the peak velocity can be moderated by increasing the blade length, and the wearing life can be increased by increasing the thickness of the blades, especially towards the tip section. The turbine runner needs to be designed taking account of the following boundary conditions [39];

1. Minimum curvature of the blade profiles towards the tip in the case of Kaplan units, a towards the outlet edge nearer the skirt in the case of Francis machines;
2. Point of maximum curvature as near as possible to the inlet edge in the case of Francis un and near to the hub in the case of Kaplan units, as well as reduction of curvature towards t outlet edge in both cases;
3. Minimum angle of incidence;
4. Long blade profiles and a flat rear section;
5. Minimum number of blades; and,
6. Blade profiles to be as thick as possible with appropriate thickness distribution.

3.4.5 Wear Resistance of Material

In case of ductile materials, the material removal is through cutting and ploughing, while in case of brittle materials it is through fragmentation and removal of flakes. A ductile material suffers maximum erosion at an impact angle of about 20° and offers good erosion resistance to normal impact (90°), whereas brittle materials suffer severe erosion under normal impact, but offer good erosion resistance at low angles. During impact, when the yield strength of the materials is locally exceeded, plastic deformation takes place in the vicinity of the impact. After multiple impacts, a plastically deformed surface layer may form near the eroded surface and, therefore, the yield strength of the material increases due to work hardening. Continued work hardening causes embrittlement and fragmentation of target surface [40].

3.5 ABRASION CRITERION FOR HYDRAULIC TURBINES

The product of operating head H and content of harmful sediments S_d (d>0.05mm) that essentially represents the energy content of the particles is selected as a measure of abrasion intensity. $HS_d=7$ is roughly the dividing line between moderate damage and serious damage [20]

3.6 THEORIES FOR EROSION MECHANISM

To understand the mechanism of erosion on hydro turbines by silt particles one can take help of the various mechanistic theories developed for the material removal when a ductile metal target is eroded by solid particles (usually harder than the target) which are described as follows.

(i) Erosion by cutting: Finnie (1958), Hutchings (1977), Hutchings *et al.* (1976),

Erosion by cutting has been observed using high-speed photography by Hutchings (1977); it is the result of a sharp cornered projectile machining a chip of material from the target surface. Each impact leading to the removal of a chip is considered to be independent and the total amount of erosion is the sum of the contributions from each micromachining impact. This theory, which evolved from the study of the machining process on lathes, is both quantitatively and qualitatively successful. However, not all eroding particles are angular and not all impacts give rise to detached chips of material and therefore this theory appears to be unable to deal with these exceptions.

(ii) Erosion by deformation wear: Bitter (1963a, b).

When a projectile impinges upon the surface of a ductile target it loses some kinetic energy. Most of this lost energy is transformed into plastic deformation and then into heat within the target. If this heat is generated sufficiently quickly and within a small enough volume of the target then the temperature there can reach the melting point. Target material can then be removed more easily due to its much reduced cohesive strength.

Qualitative observations which indicate that melting has occurred have been restricted to scanning electron microscopy of eroded target surfaces (Smeltzer *et* aZ1970, Shewmon 1979). This kind of evidence cannot be accepted as proving that melting is a dominant mechanism of erosion. In support of the theory Neilson and Gilchrist (1968) and Uetz and Gommel (1966) have measured a rise in the temperature of a target during erosion. Clearly erosion by melting can be either a cooperative or an independent effect of the eroding projectiles.

(iii) Erosion by target melting: Neilson and Gilchrist (1968), Smeltzer *et al.* (1970),

Suh's (1973) theory of abrasion by delamination wear has been extended by Jahanmir (1980) to include erosion. The target is considered to be composed of a matrix containing harder inclusions. The projectile interacts with the surface by sliding across it but not directly removing material. Delamination can only occur when subsurface cracks start to extend parallel to the target surface. These cracks are nucleated by voids which can form at the interface between the matrix and the inclusions. In order to nucleate a void, there must be present around an inclusion both a large shear stress and a large hydrostatic stress. This latter stress is not present initially. However, repeated sliding across the same portion of the target surface apparently gives rise to large residual stresses and these are considered to be the source of the hydrostatic stresses. Clearly, the mechanism of delamination is a cooperative effect.

(iv) Erosion by delaminating wear: Suh (1973), Jahanmir (1980).

Bitter (1963a, b) assumed that the removal of material from the surface of a target occurs by the joint action of two mechanisms: cutting, which only occurs when the projectile strikes the target at grazing incidence; and deformation wear, which predominates at normal impingement. Unfortunately he did not explain clearly how material was removed by deformation wear. It may be that it is low-cycle fatigue (Hutchings 1979) or, indeed, delamination wears. However, Jahanmir (1980) discusses delamination in terms of a projectile sliding across a surface and sliding is impossible at normal impingement.

Bitter (1963a, b) was careful to point out that deformation wear is characterized by repeated bombardment, by which he implies that it is a cooperative mechanism.None of these theories is capable of explaining all of the effects normally observed in erosion experiments. Two effects, which remain largely unexplained, are the influence of the duration and magnitude of the eroding flux on the amount of erosion.

3.7 TURBINE EFFICIENCY IN SILTY WATER

It is important for new machine designs to undergo appropriate model testing with silty water to determine efficiency. The turbine efficiency is extremely sensitive to increased clearances between the guide vanes and their holding rings, besides runner labyrinth clearances. Even before any wear has taken place, the overall efficiency in silty water is reduced in proportion to the solids content.

Hydraulic performance tests on a Francis turbine model with sediment- laden flow, conducted in Japan; showed that the turbine's best efficiency decreased almost in direct proportion to the increase in solids concentration or the specific gravity.

The reduction in peak efficiency (η) is expressed [39] as:

$$\eta_m = (1 - 0.085\ C_w)\ \eta_w$$

η_m = turbine peak η with sediment laden flow (mixture);

η_w = turbine peak η with clean water; and,

C_w = fraction of solids by weight.

The critical cavitation coefficient was also found to be influenced by the presence of silt in the flow; it increases in direct proportion to the mixture concentration at each unit speed.

3.8 SILT EROSION / CAVITATION SYNERGY

As mentioned earlier, the extent of material removal depends on the velocity and force with which the particles act over the surface if blade curvature is relatively high; the resulting higher centrifugal force on the particles increases the intensity of erosion. Over a period of operation in silty water the surface becomes irregular, which, in turn induces local cavitation. Subsequently. The destruction is faster as a result of the combined effects a turbine component completely free from cavitation when operating in clean water is affected by cavitation in silty water. Furthermore, a component already eroded by silt erosion is much more prone to cavitation pitting. The combined effect can be very severe and can be understood as follows:

With the hydraulic design parameters adopted these days (high specific speed), cavitation is considered to be largely responsible for the initiation of damage. Generally, removal of metal from a runner (excluding other underwater parts), is limited to 0.1 D^2 kg per 1000 h of operation, where D is the throat diameter of the runner in meters. For the sake of economy in manufacturing costs of turbines and generators, manufacturers do permit limited cavitation to take place.

Turbine settings are thus fixed by the manufacturers, so that cavitation remains within the guaranteed limits. Some restrictions on operating conditions are also imposed. The above is generally based on the assumption that turbines will be operated in fairly clear water and thus no major damage is expected.

When cavitation does take place, the affected area develops pumiceous and honeycomb like pits, and the metal is weakened. Because of this, the water flow is locally disturbed. If the water is clean, there is generally no serious problem as a result of this limited cavitation. However, when silt-laden water passes over this, the spongy area is rapidly removed as a result of sliding abrasion. The fresh runner area develops a similar pumiceous spongy surface (from cavitation) and is again removed by the grinding action of the sand, which is present in the water. The rate of removal depends on the size, hardness, roughness, silt concentration and velocity of the water. Thus, the outlet edges of the turbine blades, where velocities are higher, become thinner. Vibration takes place and, as a result of fatigue, cracks develop and ultimately, pieces of the runner wash out. The lost pieces of the runner blade greatly disturb the flow condition, and severe damage occurs.

If the turbines operate in clear water, it takes a much longer time for the water to remove the cavitation-affected spongy areas. The presence of silt accelerates the damage. The damage caused by a combination of cavitation and abrasion is therefore much more rapid and severe compared with damage caused by either of them separately.

Some well-known facts about cavitation erosion and sand abrasion are:

i. The viscosity of particle-laden flow is higher than clear water, especially when the water contains very fine grains such as ash and clay. As the critical vaporizing pressure is raised, the inception of cavitation is delayed.

ii. The intensity of cavitation erosion is related to the velocity of the flow in the sixth power or higher..

iii. The intensity of sand erosion is roughly proportional to the third power of flow velocity.

iv. There is an evident incubation period with cavitation erosion. The rate of damage may be identified with stages of incubation, acceleration, deceleration and equilibrium. Sand erosion has no incubation period damage is simply proportional to time.

Damage to metal surfaces where there is interaction between cavitation and erosion is much more serious than each attack alone.

CHAPTER-4

STUDY OF CORRELATIONS AVAILABLE FOR ESTIMATION OF SILT EROSION

4.1 GENERAL

Silt erosion is a result of mechanical wear of components on account of dynamic action of silt flowing in the water coming in contact with wearing surface. Therefore, silt flowing with water passing through the turbine is the root cause of silt erosion of turbine components. While passing through the generating units, suspended silt in water is subjected to the force of gravity, viscosity, inertia, turbulence and cavitation. Combination of these forces makes silt movement highly complex under varying velocity profiles and pressure gradient.

The process of hydraulic abrasion, within the components forming the flow passage portion of hydraulic machines and affected by attack of solid particles suspended in the flow, is influenced by a number of factors, namely: an average motion velocity of the particles; the mass of particles; the concentration of abrasive particles in the fluid; size distribution of the particle and their average grain size; the incidence angle of impingement as related to the surface; the time interval of attack affected by the particle (of specified size and concentration) on the surface flown about by the fluid; the erosion resistance of the structural material used.

Most wear models and equations in the literature were analyzed as to origin, content and applicability. No single predictive equation or group of limited equations could be found for general and practical use. In searching the literature for models and equations over 300 equations were found for friction and wear. Two publications were surveyed: the journal Wear between 1957 and 1992 and the Wear of Materials (WOM) conferences from 1977 to 1991. The total number of papers surveyed was 5466 (4726 in Wear, 740 in WOM) and the total number of individual authors was 5325.[17] A significant number of equations relate to wear but were not particularly amenable to analysis, so were left out of later consideration. There remained 182 wear equations for the many types of wear. Wear equations have changed character or emphasis since 1957, undoubtedly following the trend in all other fields of technology. No equation was found to have been developed strictly from the fundamental and intrinsic quantities of science, although a few approached this goal. The truly fundamental equations carry the hope that if they are complete enough they will "predict" wear rate or wear amount with useful numerical accuracy.

4.2 AVAILABLE CORRELATIONS FOR ESTIMATING THE EXTENT OF EROSION

Based on literature survey various models, equations and correlations developed by various authors to estimate wear and its effects on different parameters of hydro turbines are examined critically and discussed as follows;

i. The actual mechanism of erosive wear was not fully understood. Most common expression for the erosive wear was based on experimental experiences. The hydro-abrasive wear was commonly quantified by means of wear rate W, defined by loss of mass per unit time and generally expressed as [33];

$$W = f(\textit{properties of eroding material, properties of base material and operating conditions}) \quad (4.1)$$

ii. The experimental results and the analyses of Finnie and Bitter indicate that the Following factors should be accounted for in any relationships for erosion damage.

a) The normal component of kinetic energy of the impacted particles is absorbed in the specimen surface and accounts for deformation wear.
b) For certain hard materials, subjected principally to deformation wear, there is a limiting component of velocity normal to the surface below which no erosion takes place. This limiting value is dependent on particle shape.
c) The kinetic energy component parallel to the surface is associated with cutting wear.
d) For cutting wear and large angles of attack the particles come to rest in the surface and the total parallel component of kinetic energy contributes to cutting wear. For small angles of attack, however, the particles may sweep into the surface and finally leave again with a residual amount of parallel kinetic energy.

If one assumes that for cutting wear units of kinetic energy must be absorbed by the surface to release one unit mass of eroded material and that the corresponding parameter for deformation wear is ε, then the above factors immediately lead to the following relationships [8].

$$W = \underset{\mathbf{A}}{\frac{0.5M(V^2cos^2\alpha - v_p^2)}{\varphi}} + \underset{\mathbf{B}}{\frac{0.5M(Vsin\alpha - K)^2}{\varepsilon}} \qquad \alpha < \alpha_0 \quad (4.2)$$

and

$$W = \underset{\mathbf{C}}{\frac{0.5(V^2cos^2\alpha)}{\varphi}} + \underset{\mathbf{B}}{\frac{0.5M(Vsin\alpha - K)^2}{\varepsilon}} \qquad \alpha > \alpha_0 \quad (4.3)$$

Where, *W* is the erosion produced by *M* pounds of particles at angle of attack α and particle velocity *V*. *K* is the velocity component normal to the surface below which no erosion takes place in certain hard materials and v_p is the residual parallel component of particle velocity at small angles of attack. Part B accounts for deformation wear and parts A and C account for cutting wear at small angles of attack and large angles of attack respectively. α_0 is the angle of attack at which v_p is zero so that at this angle eqns. (4.2) and (4.3) predict the same erosion.

iii. Bein et al have attempted to develop a correlation for the estimation of erosion rate based on extensive data collected on a bench scale test rig. The general form of correlation can be represented as,

$$W = KV^{\beta}d^{\gamma}C^{\varphi} \qquad (4.4)$$

where W is erosion rate, V is velocity of particle, d is particle size, C is solid concentration, and K, β, γ and φ are constants whose values depend on the properties of the erodent as well as the target material. For different erodents, the effect of particle size has been normally considered as a parameter affecting the wear and the exponent value 'γ' was found to lie between 0.3 and 1.6 [33].

iv. Silt erosion rate can generally govern by the formula,

$$w = S_1S_2S_3S_4M_rV^X \qquad (4.5)$$

Where S_1 is coefficient of silt concentration, S_2 is coefficient of silt hardness, S_3 is coefficient of silt particle size, S_4 is coefficient of silt particle shape, M_r is coefficient of wear resistance of base material, and v is relative velocity of water. The values suggested for the exponent X are: 3 for Francis runner, 2.5 for guide vanes and pivot ring liner, 2.5 for Pelton nozzle and 1.5 for Pelton runner buckets [33].

v. Krause and Grein reported that the abrasion rate on conventional steel Pelton runner made of X5CrNi 13/4 was as given below,

$$\delta = pqcv^{3.4}f(d_{p50}) \tag{4.6}$$

Where δ is abrasion rate (μm/h), p is a constant, q is quartz content, c is mean sand concentration, and v is relative jet velocity; f (d_{p50}) is function defining particle size [33].

vi. The turbine abrasion was expressed by Asthana as,

$$TA = f(PE, V^z) \tag{4.7}$$

Where PE is modified suspended sediment content, v is relative velocity between flowing water and turbine parts where abrasion is severe, and z is exponent for relative velocity. The modified sediment content (PE) is expressed by the following equation:

$$PE = P^{\alpha}a^{\beta}k_1k_2k_3 \tag{4.8}$$

Where P is the average annual suspended sediment content in gm/l. It is based on the long-term measurements in the river; 'α' is exponent of 'P' representing correction factor for suspended sediment concentration. It is taken as 1 for concentration up to 5 g/l; a is average grain size coefficient of suspended sediment with a base of 0.05 mm; β is exponent of 'a' representing correction factor for average particle size, which was taken as 1 for particle up to 0.6mm and curved flow; k_1, k_2, k_3, represent the coefficient to account for shape, hardness and abrasion resistance of base metal, respectively. k_1 is taken as 0.75, 1.0 and 1.25 depending on irregularities ranging from few to severe, k_2

was taken as 1 for hardness greater than 3 (on Moh's scale) and 0.5 for less than 3, k_3 was taken as 1 for 13Cr4Ni steel [33].

vii. Schneider and Kachele proposed that wear rate, W was a function of a multitude of parameters as shown in the following algebraic relation:

$$W \sim cqf(d_{50})v_f^n \quad (4.9)$$

Where c (kg/m3) is sand concentration, q (kg/kg) is hard particle contents, d50 (m) is median Particle size, and vf (m/s) is flow velocity. The authors suggested that the value of n varied considerably from about 2.1 to more than 3. This range of values was reported to reflect the limitations of the algebraic relation, which considered neither the material parameters of the eroded body nor the flow parameters or the various material parameters of the silt particles [33].

viii. Bajracharya et al. established erosive wear rate of spear and efficiency reduction relationships from the field survey of Chilmi Hydro Electric Plant (CHEP), a Pelton turbine based hydro electric plant in Nepal. They proposed a relationship between the erosion rate and the particle size at different quartz content levels which is presented as;

$$Erosive\ wear\ rate \propto a(size)^b \quad (4.10)$$

Where; erosive wear rate is in kg/year, and a=351.35 and b=1.4976, for quartz content of 38%; a=1199.8 and b=1.8025, for quartz content of 60%; and a= 1482.1and b=1.8125, for quartz content of 80% [30].

ix. Generally the expression for erosion of hydro turbine is given as a function of velocity, material hardness, particle size, and concentration. The most general relation for erosion purpose is:

$$W = K_{mat}K_{env}cV_nf(\alpha) \quad (4.11)$$

Here, *W* is the erosion rate (material removal) in mm/year, K_{mat} the material constant, K_{env} a constant depending on environment, *c* the concentration of particles, *f*

(α) a function of impingement angle α, 'V' the velocity of particles and 'n' is the exponent of velocity [33].

x. The erosion models are basically developed for specific purpose or condition. Truscott presented the equation of Bergeron to predict the erosion rate of pump with simplified assumptions such as pure sliding of spherical particles over the surface. He presented equation for erosion as:

$$Erosion \propto \frac{V^2}{D}(\rho_p - \rho)d^3p^K \quad (4.12)$$

Where 'V' is the characteristic velocity of liquid, D the characteristic dimension of the machine, 'ρ_p' the density of particle, d the diameter of particle, 'p' the number of particles per unit surface area, 'ρ' the density of liquid and 'K' is the experimental coefficient depending upon nature of abrasive particles. This equation is proportional to experimental coefficient, which is dependent on abrasive nature of particles [33].

xi. Tsuguo established the relationship of factors concerning erosion of turbines based on 8 years erosion data of 18 hydropower plants. The repair cycle of turbine is determined according to calculation of turbine erosion from equation, which gives erosion rate in term of loss of thickness per unit time (W):

$$W = \beta c^x a^y k_1 k_2 k_3 v^n \quad (4.13)$$

Where 'β' is the turbine coefficient at eroded part, 'c' the concentration of suspended sediment and 'V' is the relative velocity. The term 'a' is average grain size coefficient on the basis of unit value for grain size 0.05 mm. The terms 'k_1' and 'k_2' are the shape and hardness coefficient of sand particles and 'k_3' is the abrasion resistant coefficient of material. The x, y and n are exponent values for concentration, size coefficient and velocity, respectively. The value of x and y are close to the unity and any deviation of this linear proportionality is determined from plot of wear versus parameter. The values of 'n' are proposed for different turbine components based on relation between relative velocity and erosion. Minimum value of 'n' is proposed as 1.5 for

Pelton bucket and maximum value is 3 for Francis turbine runner. Similarly, for Francis turbine guide vanes and Pelton turbine needle, this value is proposed as 2.5 [33].

xii. I. Finnie gave a simple expression for the volume of material, Q, removed by a single abrasive grain of mass, m, and velocity, V, by integrating over cutting period [8].

$$Q = \frac{mV^2}{p\psi K}(sin2\alpha - \frac{6}{k}sin^2\alpha) \qquad \text{if } \tan\alpha \leq \frac{K}{6} \tag{4.14}$$

$$Q = \frac{mV^2}{p\psi K}(\frac{KCOS^2\alpha}{6}) \qquad \text{if } \tan\alpha \geq \frac{K}{6} \tag{4.15}$$

We can see that$\psi = \frac{l}{y_t}$. The two expressions predict the same weight loss when tan 2α= K/6 and the maximum erosion occurs at the slightly lower angle given by tan 2α = K/3. The first equation, which applies for lower angles, corresponds to the case in which the particle leaves the surface while still cutting. The second equation, which applies to higher angles, corresponds to the case in which horizontal motion of the particle tip ceases while cutting. By analogy to metal cutting experiments17 a value of y = 2 is selected. Finally, free from further assumptions, we may write the volume removal due to a mass M of angular abrasive grains as [8]:

$$Q \approx \frac{MV^2}{8p}[sin2\alpha - 3sin^2\alpha] \qquad \alpha \leq 18.5 \tag{4.16}$$

$$Q \approx \frac{MV^2}{24p}cos^2\alpha \qquad \alpha \geq 18.5 \tag{4.17}$$

xiii. Expression for the dimensionless erosion rate (E,) is obtained as:

$$E_n = 2V_d\rho F(t)\Delta \in / \in_c \tag{4.18}$$

Where E_n, is the ratio of the mass loss suffered by the eroding material to the mass of the particles causing that loss, V_d, is the volume of the plastic zone underneath the impacting particle, .Δ∈ is the strain increment introduced in the plastic zone during each impact, m is the mass of the particle, $\rho$is the density of the eroding material, $\in_C$ is the critical strain for lip formation and F(t) is a numerical constant which accounts for the fact that numerous impacts are required at the same location to accumulate the critical strain and also for the fact that a strain gradient exists within the plastic zone [14].

xiv. Barwell suggested that wear rates may be typified by one of three curves of the type:

(1) $$V = \frac{\beta}{\alpha}\{1 - e^{-\alpha t}\} \quad (4.19)$$

(2) $$V = \alpha t \quad (4.20)$$

(3) $$V = \beta e^{\alpha t} \quad (4.21)$$

Where V is the volume loss, α is a constant and t is time. The parameter $'\beta'$ is one of the mysterious terms, identified as "some characteristic of the initial surfaces", probably not describing a predicted effect but rather reflecting an effect noticed by an alert observer. These equations simply describe the shape of a curve for V vs. t or V vs. p, the latter quantified in some way [17].

xv. Rhee found that the total wear of a friction material (polymer-matrix) is a function of the applied load '*F*', speed 'V' and time 't' according to:

$$\Delta W = KF^a V^b t^c \quad (4.22)$$

Where 'ΔW' is the weight loss of the friction material and *K*, *a*, *b* and c are empirical constants [17].

xvi. Contact-mechanics-based equations were common in the years 1970-1980. They usually begin as models of a system, assuming simple relationships among working conditions. Some account is often taken of the topography of the contacting surfaces as well in order to calculate the local region of contact. Many of these equations are based on the assumption that a conventional material property (of the author's choice), usually Young modulus '***E***' or hardness 'H', will be important in the wear process.

$$W = K_s \frac{P}{P_m} \quad (4.23)$$

Where 'W' is the worn volume, s is the sliding distance, 'P' is the applied load, $'P_m'$ is the flow pressure (approximately equivalent to hardness) of the softer material and the ratio of the last two is often taken as the real contact area. 'K' is stated to be a constant related to the probability that an encounter of two asperities will produce a wear particle [17].

xvii. Bitter suggested in his paper, a study of erosion phenomena that [17]:

$$\in_{VT}=\in_{VD}+\in_{VC} \tag{4.24}$$

$$\in_{VD}=\frac{0.5M(Vsin\alpha-K)^2}{\delta} \tag{4.25}$$

$$\in_{VC1}=\frac{2MV(Vsin\alpha-K)^2}{(Vsin\alpha)^{1/2}}\left(Vcos\alpha-\frac{C(Vsin\alpha-K)^2}{(Vsin\alpha)^{1/2}}\chi\right) \quad \text{for } \alpha \geq \alpha_{po} \tag{4.26}$$

$$\in_{VC2}=\frac{0.5M[V^2cos^2\alpha-K_1(Vsin\alpha-K)^{1.5}]}{\chi} \quad \text{for } \alpha < \alpha_{po} \tag{4.27}$$

Where, $\in_{VT}$ is total volume erosion rate, $\in_{VD}$ isvolume of material removed by deformation mechanism, $\in_{VC}$ is volume of material removed by cutting mechanism, α is impact angle, V is particle velocity, K is velocity normal to surface below which no erosion takes place, δ is deformation wear factor, α_{po} is impact angle at which horizontal velocity component has just become zero.

xviii It was found by Padhy and Saini that regression of experimental data, which was carried out by them on a Pelton runner, deals with the first order. From the first order regression of the data on log–log scale, the value of the constant and the exponents for S, C, V and t are found to be as 4.02E_ 12, 0.0567, 1.2267, 3.794 and 1 respectively. The final form of the correlation for normalized erosive wear rate is obtained as follows:

$$W = 4.02 * 10^{-12} * S^{0.0567} * V^{3.79} * C^{1.2267} * t \tag{4.28}$$

Where, ‘S’ silt particle size (m), ‘t’, operating hour, ‘V’ velocity of flow (m/s) ‘W’ is wear (gms) .

4.3 TREND OF METAL LOSS IN VARIOUS CORRELATIONS DUE TO EROSION

Here the values of different parameters used in the correlations are varied within the permissible range to observe the trend metal loss with the variation in the parameters. The correlation developed by M K Padhy and R P Saini [32], has been considered and the nature of this correlation has been found out.

$$W = 4.02 * 10^{-12} * S^{0.0567} * V^{3.79} * C^{1.2267} * t \qquad (4.28)$$

Different parameters of this equation have been varied and the trend of metal loss has been obtained. Velocity ‘V’ is varying with the metal loss at ‘S’ = 0.00025 m,‘t’ = 8000 hrs, and ‘C’ = 1000, 2000 and 3000 ppm shown in Table 4.1, and corresponding nature of the curve is shown in Fig.4.1.

Table 4.1 variation of erosion with flow velocity at different silt conc. in equation (4.28)

V(m/s)	24	26.4	28.8	31.2	33.6	36	38.4	40.8	43.2	45.6	48	50.4
W(gms)at 1000ppm	16.37	24.35	44.26	58.61	76.13	97.22	122.3	151.9	186.5	226.5	272.5	325.0
W(gms)at 2000ppm	38.32	54.99	76.48	103.58	137.1	178.2	227.5	286.3	355.6	436.4	530.0	637.7
W(gms)at 3000ppm	63	90.4	125.8	170.3	225.6	293	374.2	470.8	584.7	717.7	871.7	1049

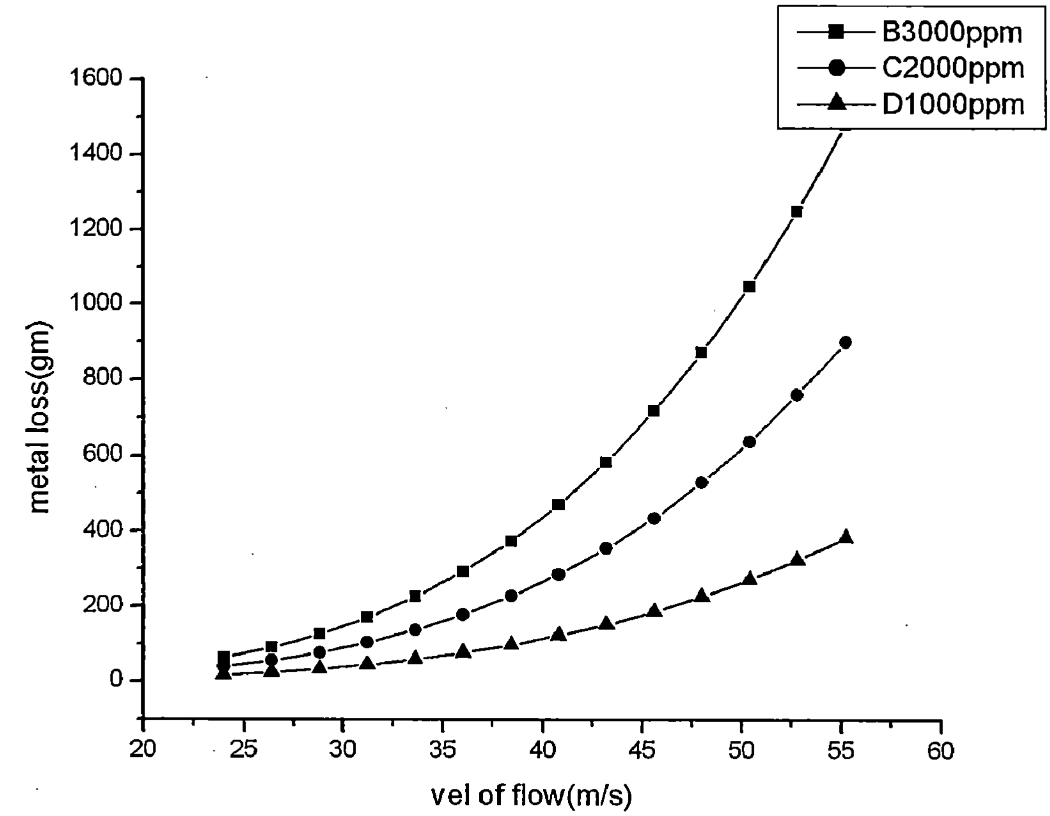


Fig. 4.1 curves showing variation of metal loss with flow velocity at different silt conc. eq.(4.28)

Then the metal loss was varied with time of operation at different particle size shown in table 4.2, and corresponding nature of curve is shown in Fig. 4.2.

Table 4.2 variation of erosion with time of operation in equation (4.28)

t(hrs)	3000	6000	9000	12000	15000	18000	21000	24000	27000	30000	33000	36000
W(gms) at 0.25m	11.0	22.0	33.0	44.0	55.0	66.1	77.1	88.11	99.12	110.1	121.2	132.2
W(gms) at 0.4mm	11.3	22.6	33.9	45.3	56.6	67.9	89.9	90.5	101.2	113.1	124.4	135.7
W(gms) at 0.6mm	11.6	23.2	34.7	46.3	57.9	69.5	81	92.6	104.2	115.7	127.3	139

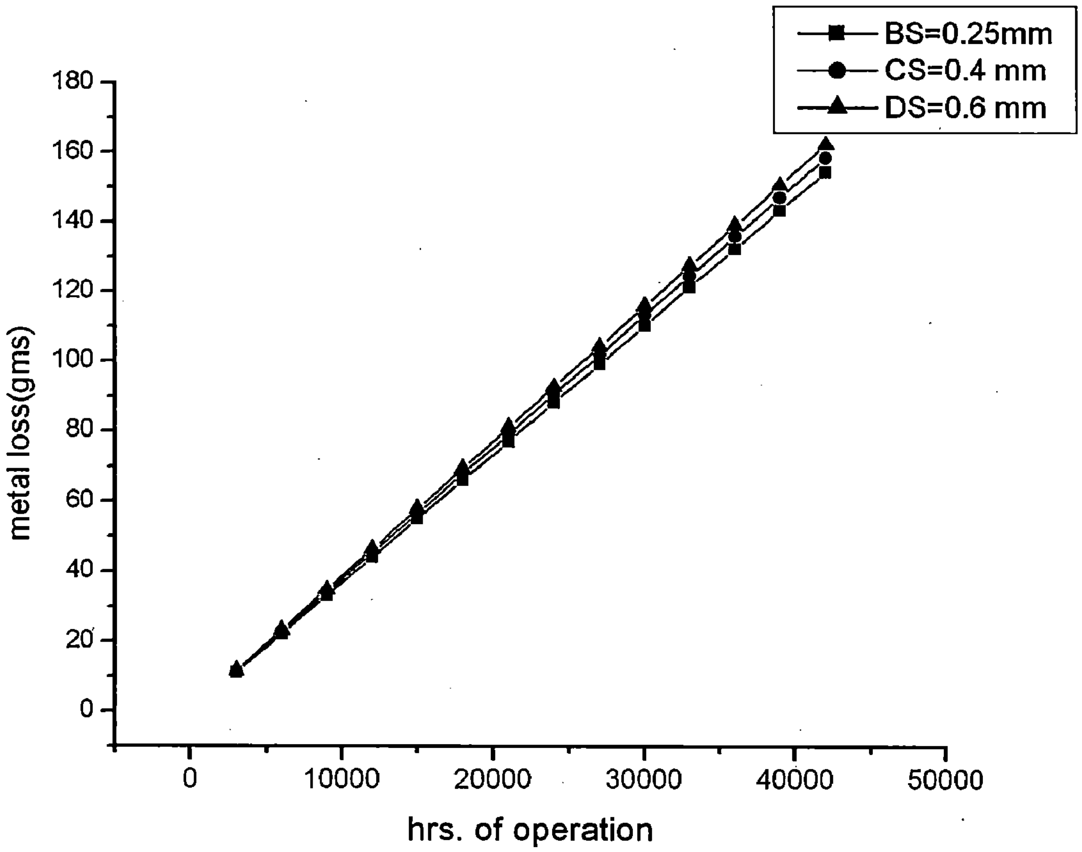


Fig. 4.2 curves showing variation of metal loss with flow velocity at different silt size, eq.(4.28)

From above, this was observed that, the trend of metal loss obtained in the case of increasing concentration of silt as well as increasing particle size, is similar. The metal loss increases with increase in silt concentration and with increase in silt size also. This correlation covers wide range of parameters on which the erosion of turbine depends. The parameters constituting this correlation are practically easier to obtain.

Another correlation is considered which was developed by Krause and Grein [19]. This correlation is analyzed by varying its parameters within the permissible range and the trend of abrasion is found out.

$$\delta = pqcv^{3.4}f(d_{p50}) \tag{4.6}$$

Where, 'δ' is abrasion rate (μm/h), 'p' is a constant, 'q' is quartz content, 'c' mean sand concentration, ' v' relative jet velocity, $f(d_{p50})$ is function defining particle size.

Parameters of this equation were varied to find the trend of metal loss. Here the relative velocity of jet is varied with the metal loss at different silt concentrations of 100 ppm, 2000 ppm and 3000 ppm and 'p' = 0.98 and 'q' = 0.90. Table 4.3 shows variation of relative jet velocity with erosion at different concentration of silt for equation (4.6), and Fig. 4.3 shows the the trend of metal loss for the same.

Table 4.3 variation of erosion with relative jet velocity in equation (4.6)

v(m/s)	30	31	32	33	34	35	36	37	38	39	40	41
W(mm/h) at 1000ppm	20.62	23.06	25.7	28.52	31.57	34.84	38.34	42.08	46.08	50.33	54.86	59.66
W(mm/h) at 2000ppm	41.2	46.1	51.3	57	63.1	69.6	76.6	84.1	92.1	101	110	119
W(mm/h) at 3000ppm	61.8	69.1	77	85.5	94.6	104	115	126	138	151	164	179

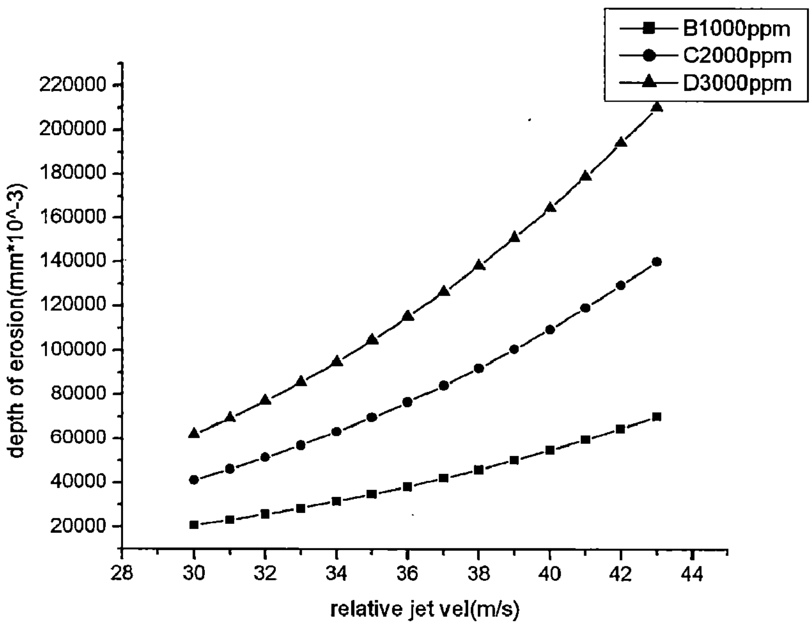


Fig. 4.3 curves showing variation of erosion depth with flow velocity at different silt conc. eq.(4.6)

Then the relative jet velocity was varied with erosion depth at different values of quartz content which is shown in the table 4.4 and Fig. 4.4 shows the trend of metal loss with varying relative jet velocity for the same case.

Table 4.4 variation of metal loss with relative jet velocity at different quartz content in eq. (4.6)

v(m/s)	30	31	32	33	34	35	36	37	38	39	40	41
W(mm/h) at 90% quartz	20.62	23.06	25.7	28.52	31.57	34.84	38.34	42.0	46.0	50.3	54.8	59.6
W(mm/h) at 80% quartz	18.3	20.5	22.8	25.3	28	30.9	34	37.4	40.9	44.7	48.7	53
W(mm/h) at 70% quartz	16	18	20.1	22.2	24.5	27.1	29.8	32.7	35.8	39.1	42.6	46.4

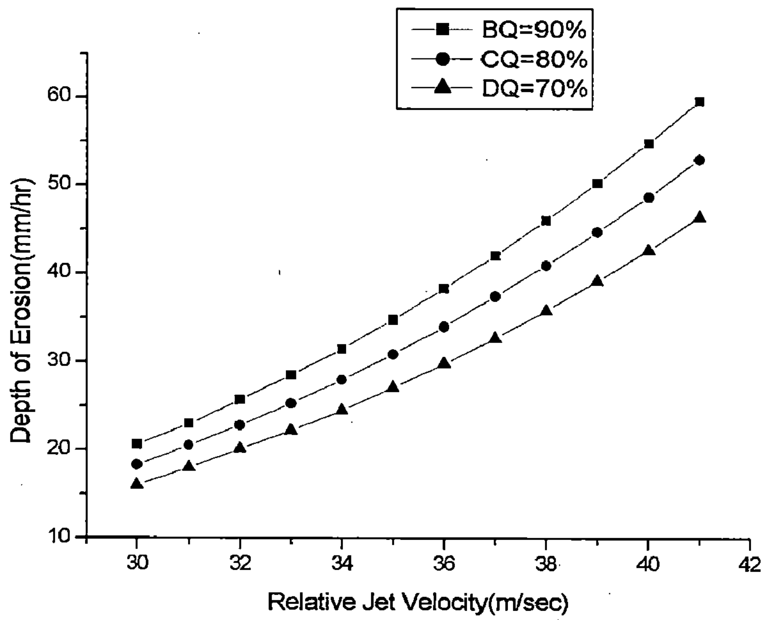


Fig. 4.4 curves showing variation of erosion depth with flow velocity at different quartz content eq.(4.6)

It was observed from above analysis that the parameters constituting this correlation are main factors upon which the silt erosion depends. The quantum of quartz in silt is very important factor which is also included in the correlation. The trend shows that the erosion of turbine increased with the increase in silt concentration as well as with increase in quartz content. The parameters used are easily available or predictable, which made this correlation appropriate for further analysis.

Another correlation is considered which was developed by Bein et al [33]. This correlation is analyzed by varying its parameters within the permissible range and the trend of abrasion is found out.

$$W = KV^{\beta} d^{\gamma} C^{\varphi} \tag{4.4}$$

Where 'W' is erosion rate (kg/h), 'V' is velocity of particle (m/s),'d' is particle size(m) 'C' is solid concentration (kg/m^3) and K, β, γ and φ are constants.

The parameters of this equation were varied and the trend of metal loss was found out. Here the velocity of the particle was varied with metal loss at different silt concentrations and the value of 'k', 'β', and 'φ' is 0.98, 1.1 and 0.85 respectively and, γ = 0.92 [33]. The variation of metal loss with particle velocity is shown in table; 4.5 and corresponding trend of metal loss with change in particle velocity at different concentration of silt is shown in Fig. 4.5.

Table 4.5 variation of mass loss with particle velocity at different conc. of silt for eq. (4.4).

V(m/s)	20	22	24	26	28	30	32	34	36	38	40	42
W(g/h) at conc=1..0kg/m^3	10.4	11.6	12.8	13.9	15.1	16.3	17.5	18.7	19.9	21.2	22.4	23.6
W(g/h) at conc= 1.2kg/m^3	12.2	13.5	14.9	16.3	17.7	19.0	20.5	21.9	23.3	24.7	26.2	27.7
W(g/h) at conc= 1.4kg/m^3	13.9	15.5	1 7	18.6	20.1	21.7	23.3	24.9	26.6	28.1	29.8	31.5

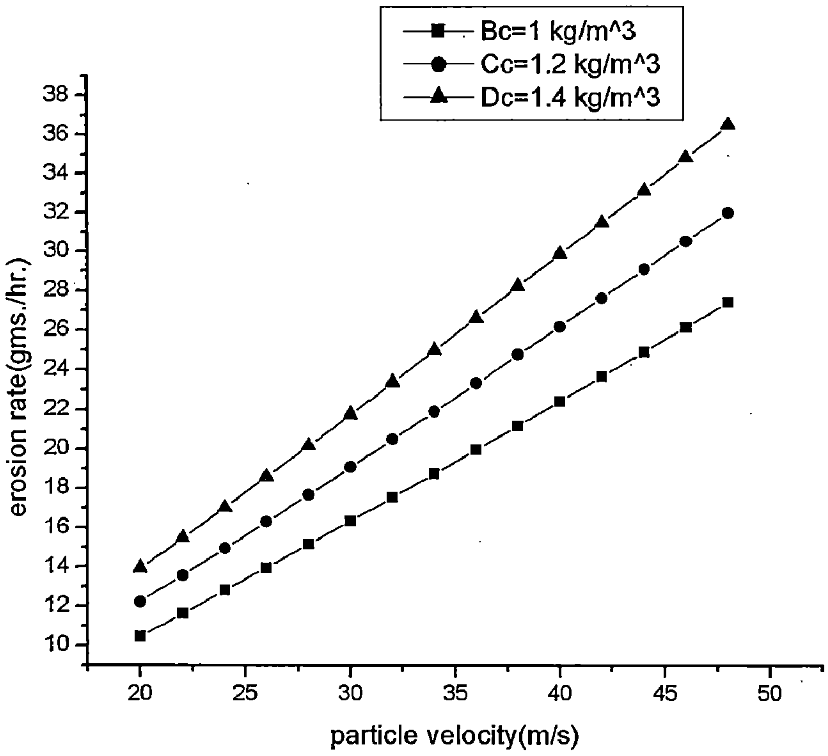


Fig. 4.5 curves showing variation of erosion rate with flow velocity at different silt conc. eq(4.4)

Then the particle velocity varied with erosion rate at different values of silt size which is shown in the table 4.6 and Fig. 4.6 shows the trend of metal loss with varying particle velocity for the same case.

Table 4.6 variation of mass loss with particle velocity at different silt size for eq. (4.4).

V(m/s)	20	22	24	26	28	30	32	34	36	38	40	42
W(g/h) at d=0.2mm	12.2	13.5	14.9	16.3	17.7	19	20.4	21.8	23.3	24.7	26.2	27.6
W(g/h) at d=0.22mm	13.3	14.8	16.3	17.8	19.3	19.0	20.8	22.3	23.8	25.4	27	28.5
W(g/h) at d=0.24mm	14.4	16	17.6	18.6	19.4	20.9	22.5	24.2	25.8	27.5	29.2	31

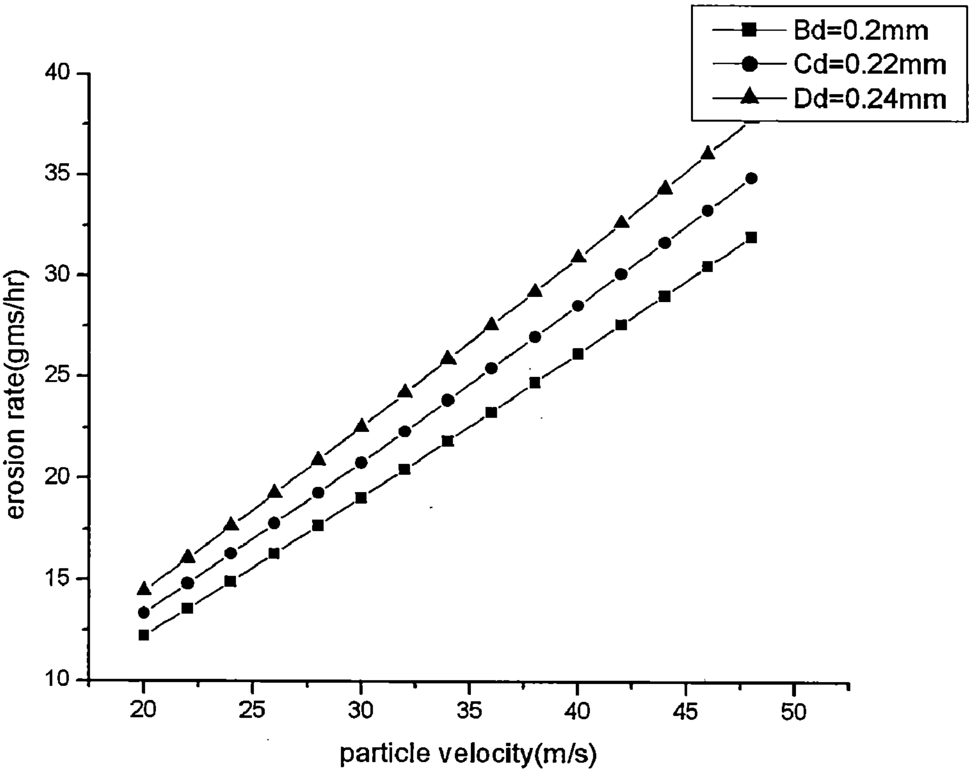


Fig. 4.6 curves showing variation of erosion rate with particle velocity at different silt size, eq(4.4)

Above analysis was again showing increase in erosion with an increase in silt concentration and silt size. The trend of metal loss is also similar for change in various parameters. This correlation considered a wide range of factors on which the silt erosion depends. Constants were also used in the correlation which depends upon various factors.

Another correlation is considered which was developed by Tsuguo [32]. This correlation is analyzed by varying its parameters within the permissible range and the trend of abrasion is found out. The correlation was given as:

$$W = \beta c^x a^y k_1 k_2 k_3 v^n \tag{4.13}$$

Where 'β' is the turbine coefficient at eroded part, 'c' the concentration of suspended sediment and 'V' is the relative velocity. The term 'a' is average grain size coefficient on the basis of unit value for grain size 0.05 mm. The terms 'k_1' and 'k_2' are the shape and hardness coefficient of sand particles and 'k_3' is the abrasion resistant coefficient of material. The x, y and n are exponent values for concentration, size coefficient and velocity, respectively.

The parameters of this equation were varied and the trend of metal loss was found out. Here the velocity of the particle was varied with metal loss at different silt concentrations and the value of 'β','x' and 'y' are 0.98, 0.97 and 0.98 respectively and, 'k_1', 'k_2' and 'k_3' are equal to 0.92, 0.95 and 0.96 respectively. The value of 'n' is considered as 1.5, The variation of metal loss with particle velocity is shown in table; 4.7 and corresponding trend of metal loss with change in particle velocity at different concentration of silt is shown in Fig. 4.7.

Table 4.7 variation of mass loss with particle velocity at different conc. of silt for eq. (4.13).

V(m/s)	22	24	26	28	30	32	34	36	38	40	42	44
W(mm/h) at 1000ppm	0.020	0.023	0.026	0.029	0.032	0.036	0.039	0.042	0.046	0.050	0.054	0.057
W(mm/h) at 2000ppm	0.039	0.045	0.05	0.057	0.063	0.07	0.076	22.3	0.083	0.090	0.097	0.010
W(mm/h) at 3000ppm	0.059	0.067	0.076	0.085	0.094	0.010	0.011	0.012	0.013	0.014	0.015	0.016

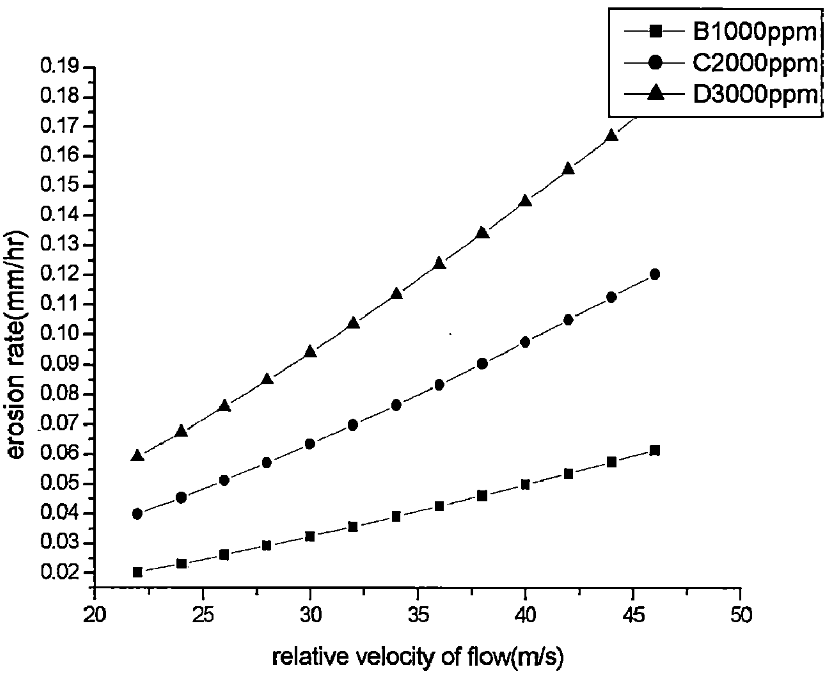


Fig. 4.7 curves showing variation of erosion rate with relative flow velocity at different silt conc. eq.(4.13)

Then the particle velocity varied with erosion rate at different values of silt size which is shown in the table 4.8 and Fig. 4.8 shows the trend of metal loss with varying particle velocity for the same case.

Table 4.8 variation of mass loss with particle velocity at different silt size for eq. (4.13).

V(m/s)	22	24	26	28	30	32	34	36	38	40	42	44
W(g/h) at d=0.2mm	0.016	0.018	0.021	0.023	0.026	0.029	0.031	0.034	0.037	0.040	0043	0.046
W(g/h) at d=0.22mm	0.018	0.020	0.023	0.026	0.028	0.031	0.034	0.037	0.040	0.044	0.047	0.050
W(g/h) at d=0.24mm	0.019	0.022	0.025	0.028	0.031	0.034	0.037	0.040	0.044	0.047	0.051	0.055

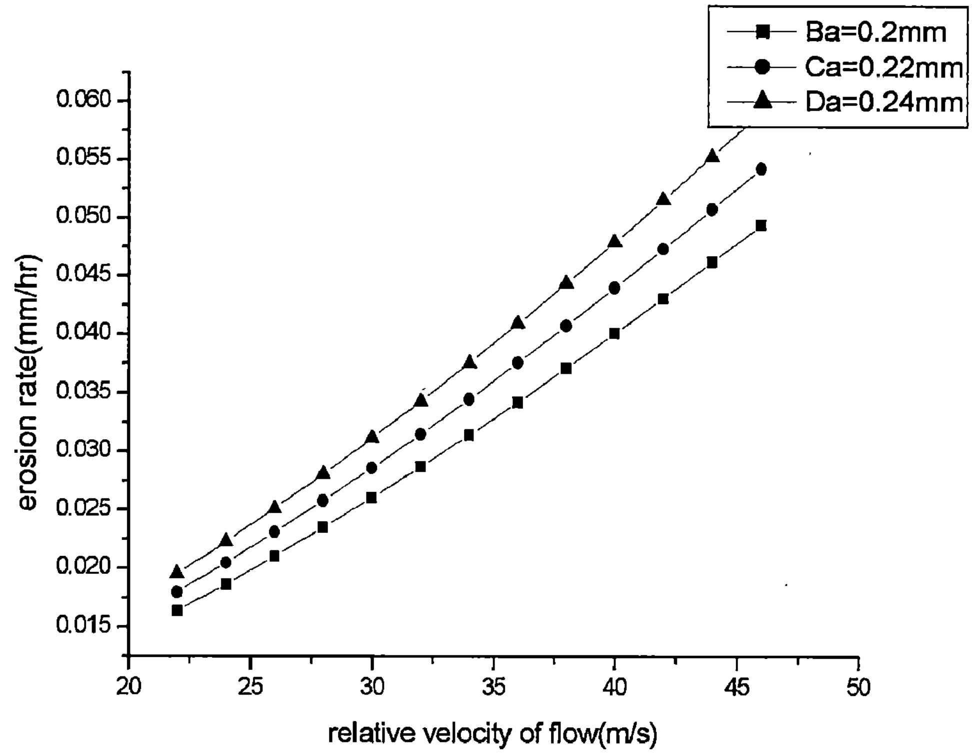


Fig. 4.8 curves showing variation of erosion rate with particle velocity at different silt size, eq(4.13)

The variation of parameters of above correlation gave a trend of metal loss which was again similar in nature. The silt erosion extent increased with an increase of silt concentration and size of silt particle. The trend of increment was also similar. Lots of factors were considered in this correlation upon which the silt erosion depends. Many coefficients and contents were also involved in this correlation.

From above analysis, it was found that, almost all the correlations available for estimating the silt erosion in different types of turbines follow the similar trend of metal loss. The correlations available considered many factors on which the erosion depends. There were various factors and coefficients used in correlations which depends upon working conditions. The correlations were developed by different authors on two bases, i.e. experimental and theoretical.

In the present study, the analysis of Pelton turbine has been carried out, with the help of two correlations. One of these correlations was developed on the basis of experiments on Pelton turbine and another one was on the theory for the same type of turbine. These two correlations were applied to the same conditions and the results were compared. Then on the basis of the erosion extents obtained from these two correlations, the economic analysis was carried out.

CHAPTER-5

ECONOMIC ANALYSIS

5.1 GENERAL

In chapter 4, various correlations developed by different authors to assess the extent of metal loss due to silt erosion, reviewed and analyzed. The correlations covering all important factors upon which silt erosion depends were considered. By varying the values of parameters within the permissible range, the trend of metal loss were obtained and found that, in most of the cases it was similar. Therefore, any of these correlations could be utilized for carrying out economic analysis of silt erosion in hydro turbines. Such two correlations were selected for estimating the metal loss. Both correlations were developed to estimate the metal loss in Pelton turbines. The selected correlations were equation (4.6), and equation (4.28).

Equation (4.6) was developed analytically by Krause and Grein. This correlation was developed for estimating the abrasion rate on conventional steel Pelton runner made of X5CrNi 13/4 .Erosion rate at different power plants were measured. The expected wear rate obtained from this equation were very close to the measured value of wear rate.

Equation (4.28) was developed by Padhy and Saini by carrying out an extensive experimental study on a small scale Pelton turbine. Based on experimental data collected for different parameters, correlation was developed for wear rate of Pelton turbine buckets as a function of critical parameters, i.e., size and concentration of silt particles and jet velocity.

In this chapter above said two co-relations were selected from the analysis carried out in chapter 4 with the help of which the extent of erosion in hydraulic turbines was estimated for different period of time of operations a particular power plant. The details of the power plant were obtained from the manufacturer (Voith Hydro) by visiting their office. Erosion of hydro turbine causes a considerable declination in the efficiency of the turbines, and thus, loss of revenue. Therefore the loss of revenue due to efficiency reduction was calculated. The hydro turbine erosion also causes the loss of revenue which is spend in the repair of turbines. The cost of repair of turbines was calculated with the help of both the correlations with the rate obtained from the manufacturers. Thus the total loss of revenue is obtained due to erosion in hydro turbines from both correlations.

As there are methods available to combat the sever effects of erosion in hydro turbine, the cost of these preventive measures is also calculated. These are generally, providing a coating to the erosion prone area and change in the blade profile by CFD analysis. A comparative study is made between the cost of preventive measure of hydro turbine erosion and loss of revenue due to hydro turbine erosion.

5.2 COST OF REPAIR AND PREVENTIVE MEASURE FROM SILT EROSION IN HYDRO TURBINES

For this purpose a visit was made to the turbine manufacturers in India. Most of the turbine manufacturers do not deal with the repair work of turbines except a few. So as, coating of turbine parts is also not being done in most of the manufacturers. In India, BHEL, VOITH Hydro, and ALSTOM, do the various types of coating work. Generally, hard coating is very popular for this purpose which is also known as HVOF (high velocity oxy fuel). Now VOITH has invented a different coating known as soft coating which is eliminating some drawbacks of hard coating.

A visit was made on 05/05/10 to VOITH HYDRO office. The cost of various process mentioned above were obtained which is as:

5.2.1 Repair Cost

(a). Smaller Turbines (less than 25 MW plants)

Repair cost of these turbines generally depends upon the man power and the no. of hours they work. Such turbines can be repaired on site locally, by welding and grinding. In small hydro, increasing the life of the turbine is main issue, though such repair work increases the life of the turbine up to some extent but it does not ensure the recovery of efficiency occurred due to erosion. Since in this range of generation the life of turbine accounts more, developers go for such repair work.

For repairing,

i. **welding cost is = Rs. 500/kg of turbine material**
ii. **grinding cost is =Rs. 400/100 mm^2**

(b). Bigger Turbines (more than 25 MW plants)

The turbines in this range are sent to the specialized manufacturers, e.g. BHEL, VOITH HYDRO, ALSTOM etc. They monitor the damage properly. With proper application of required technologies they do the repair work. In this range of the turbines, the efficiency after maintenance is also taken care because, small reduction in efficiency cause a huge loss of revenue in such range, therefore expertise are required for such works.

Two types of runners lie in this range:

1. **Coated Runner**: repairing such runners is very tedious task, as for repair operation the coating has to be removed, which again ask for high skilled operating personnel. High velocity water jet is used to remove the coating already there to repair it again. About 5 mm of base material is removed from the base material to remove the previous coating which makes it a costly affair. Very few people in the world are specialized to do this work. This becomes very costly again.

2. **Uncoated Runner:** uncoated runner is easier to repair than a coated one. The damage is easily monitored and the repair work can be directly done on the surface of runner which is cost and time saving.

For repairing,

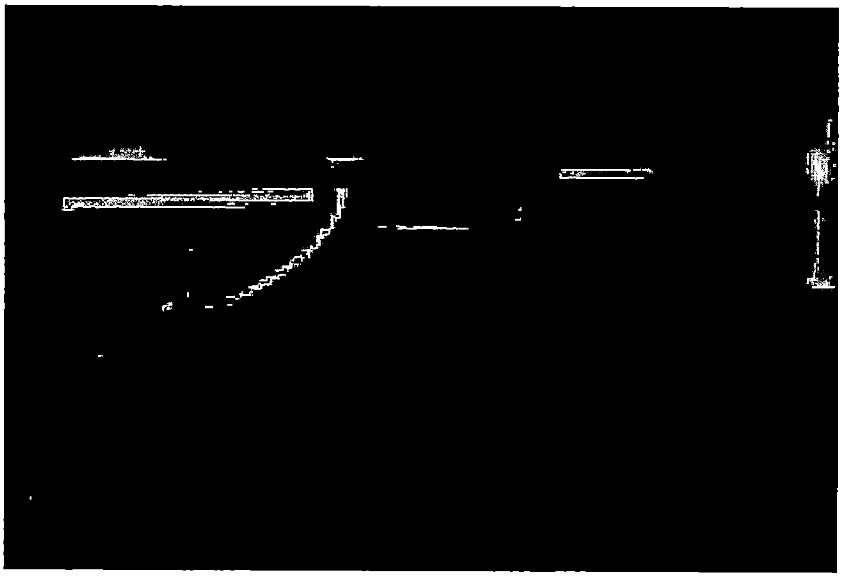
i. **The cost is = 35 to 40% of the runner cost. (uncoated runner)**

ii. **The cost is = 40 to 50% of the runner cost. (coated runner)**

5.2.2 Cost of Coating

Coating of turbine components is a very effective option to prevent the damaging effect of erosion. This technology is particularly well suited to runners with easy blade access, enabling coating to be sprayed onto all surface areas manually or using a robot. The high abrasion and fatigue resistance of the HVOF coating is achieved using a metal substance embedded with tungsten carbide ceramic powder. The application technique used creates a high-density layer of coating with very strong bonding capabilities, which is on average 0.3 mm thick. The cost of hard coating is same for the larger capacity turbines also. The difference comes where the coating is done by robots. With robot arms a better finish is provided. The spray gun is required to be maintained at an angle of 90 degree with a ±15 degree. The cost of coating is more in robot arm coating than the manual coating. In larger capacity turbines, replaceable liners are provided at the top and the bottom of blades which are also be coated, which again increases the cost. The coating of a spear and a robot arm used for coating is shown in figure 5.1 and 5.2 respectively

Fig. 5.1 HVOF coating of a Pelton turbine spear. [45]



Fig, 5.2 Robot arm is being used for coating. [44]

The cost of coating (HVOF) is = Rs. 0.2 Million /m^2 at a thickness of 0.3 mm.

5.2.3 Cost of Analysis Work Required to Change the Profile of Blades In Order To Minimize Erosion

(a). Smaller Turbines: Generally smaller turbines do not go through the design change as, it becomes more expensive exercise for such capacity plant.

(b). Bigger Turbines: In these turbines the high velocity zones are identified and an analysis is carried out to reduce the velocity at those points in order to minimize erosion. Erosion is directly proportional to 3rd power of velocity, therefore, as the velocity increases the erosion increases to its third power. The profile is kept such that the velocity becomes minimum without affecting the efficiency. This analysis is done by software known as CFD (Computation Fluid Dynamics).

The cost of this analysis is = approx. Rs. 25 to 30 Million/ 100 hrs.

5.3 COST ANALYSIS USING DIFFERENT CORELATIONS

The process of hydraulic abrasion, within the components forming the flow passage portion of hydraulic machines and affected by attack of solid particles suspended in the flow, is influenced by a number of factors, namely: an average motion velocity of the particles; the mass of particles; the concentration of abrasive particles in the fluid; size distribution of particle and their average grain size; the incidence angle of impingement as related to the surface ; the time interval of the attack effected by the particles on the surface flown about by the fluid; the erosion resistance of the material used.

There is no comprehensive formula presently capable of evaluating hydraulic abrasion quantitatively with due consideration of the particular values characterizing the afore mentioned parameters. There is, however, a number of theoretical and experimental data enabling to reveal the relationship mechanism of abrasive erosion.

The correlation to provide agreement between theory and practice is given by Krause and Grein, and It gives abrasion rate on conventional steel Pelton runners made of X5CrNi 13/4 as:

$$\delta = pqcv^{3.4} f(d_{p50}) \text{ ....}(4.6)$$

Where,

δ= abrasion rate (μm/h)

p= constant

q= quartz content

c= mean sand concentration

v= relative jet velocity

$f(d_{p50})$ = function defining particle size distribution

For the analysis work the specifications of two power plants; Sorang and Loharinagpala were obtained from the manufacturer of the turbines of these plants i.e. Voith Hydro. These plants are located in Himachal Pradesh and Uttarakhand respectively. Specifications of Sorang Hydro Power Plant are given in table 5.1.

Table 5.1 Specifications of Sorang hydro power plant

Power output	120.15 MW
No. of units	two
Discharge	20.48 cumecs
Head	670.17 meters
Type of turbine	Pelton
No. of buckets	21
Diameter of runner	1.7 m
Speed	600 rpm
Jet diameter	161 mm
Weight of buckets	110kg/bucket
No. of jets	5

With the help of correlation (4.6), abrasion is calculated for different period of time at different concentrations. Erosion for different period of time at a silt concentration of 1000 ppm is shown in table 5.2.

Table 5.2 Total erosion in mm in different time period at c= 1000 ppm, eq. (4.6)

t(hrs)	2190	4380	6570	**8760**	10950	13140	15330	**17520**	19710	21900	24090	**26280**
Erosion (μm)	181	362	543	**724**	904	1090	1270	**1450**	1630	1810	1990	**2170**
Erosion (mm)	0.181	0.362	0.543	**0.724**	0.904	1.09	1.27	**1.45**	1.63	1.81	1.99	**2.17**

Above table shows the erosion in mm per 0.25 years. Erosion after one year is highlighted.

Bajracharya et al, have reported that, the relation between the erosion rate and the reduction in efficiency is given by: [30]

$$efficiency\ reduction\ \alpha\ a(erosion\ rate)^{b} \text{ ....(a)}$$

Where a = 0.1522 and b = 1.6946, and erosion rate is in mm/year. Putting the erosion rate from above table in this equation we get:

$$efficiency\ reduction\ =\ 0.1522(0.724)^{1.6946}$$

$$= 0.088\%$$

Therefore reduction in power generation is:

$$P = 9.81 * 20.48 * 670.17 * (0.92 - 0.00088) * 0.97$$

$$= 120040.52 \text{ kW}$$

Therefore loss of energy units is:

= (120155.45-120040.52) x8760

= **1006786.8 units/year**

Table 5.3, shows erosion of buckets at a concentration of 2000ppm for different time periods.

Table 5.3 Total erosion in mm in different time period at c= 2000 ppm, eq. (4.6)

t(hrs)	2190	4380	6570	**8760**	10950	13140	15330	**17520**	19710	21900	24090	**26280**
Erosion(μm)	362	724	1090	**1450**	1810	2170	2530	**2890**	3260	3620	3980	**4340**
Erosion(mm)	0.362	0.724	1.09	**1.45**	1.81	2.17	2.53	**2.89**	3.26	3.62	3.98	**4.34**

Putting the erosion rate from above table in equation (a) we get:

$$efficiency\ reduction = 0.1522(1.45)^{1.6946}$$
$$= 0.285\%$$

Therefore reduction in power generation is:

$$P = 9.81 * 20.48 * 670.17 * (0.92 - 0.00285) * 0.97$$
$$= 119783.23\ kW$$

Therefore loss of energy units is:

= (120155.35 – 119783.23) x8760

= [illegible] **units/year** 3260581.07

Table 5.3.4 shows erosion of buckets at a concentration of 3000ppm for different time periods.

Table 5.4 Total erosion in mm in different time period at c= 3000 ppm, eq. (4.6)

t(hrs)	2190	4380	6570	**8760**	10950	13140	15330	**17520**	19710	21900	24090	**26280**
Erosion (μm)	543	1090	1630	**2170**	3260	3800	4340	**4880**	5430	5970	6510	**7050**
Erosion (mm)	0.543	1.09	1.63	**2.17**	3.26	3.8	4.34	**4.88**	5.43	5.97	6.51	**7.05**

Putting the erosion rate from above table in equation (a) we get:

$$efficiency\ reduction = 0.1522(2.17)^{1.6946}$$
$$= 0.566\%$$

Therefore reduction in power generation is:

$$P = 9.81 * 20.48 * 670.17 * (0.92 - 0.00566) * 0.97$$
$$= 119416.24\ kW$$

Therefore loss of energy units is:

= (120155.45 – 119416.24) x8760

= [illegible] **units/year** 6475479.6

Now Erosion affected area of a bucket = dxd

= 0.161 x 0.161

= 0.0259 sq. m

Total erosion affected area for all the buckets of two units

= 0.0259 x 21 x 2

= 1.088 sq. m.

Considering all three cases of different sand concentrations we will calculate the mass loss taking a density of X5CrNi 13/4 as, 7,800 kg/ cubic meter.

For(c) = 1000 ppm:

Mass loss 'M' = 1.088 x0.724 x 10^-3 x 7800

= **6.14 kg/year**

Total cost of repair = cost of welding+cost of grinding of affected area, two units:

= [(6.14x500) + (10880x40)]

= **Rs. 438272**

On calculating the loss of revenue due to reduction in energy units by taking the cost of one unit as Rs. 4.00/-, we get:

= 4 x 1006786.8

= **Rs.** 4027147.2

Total loss of revenue in one year is:

= (total cost of repair) + (total loss of money due to reduction in efficiency)

= (438272+4027147.2)

= **Rs.** 4465419.2

The cost of preventive measures (coating) to the affected area was calculated, as:

= 1.088 x 200000

= Rs.**217600**

For coating of spear by taking the tip angle as 60 degree, the surface area of the tip comes out to be:

= 0.5*π*d^2

= 0.040 sq. m.

Total surface area to be coated on spears

= 5 x 0.040 x2

= 0.4 sq. m.

Total cost of coating the spear

= 0.4x200000

= **Rs. 80000**

Total cost of coating of turbine components:

= (cost of coating of buckets) + (cost of coating of spear)

= (217600) + (80000)

= **Rs 297600**

For(c) = 2000 ppm:

Mass loss 'M' = 1.088 x1.45 x 10^-3 x 7800

= **12.30 kg/year**

Total cost of repair = (cost of welding) +(cost of grinding of affected area), of two units:

= [(12.30x500) + (10880x40)]

= **Rs. 441352**

On calculating the loss of revenue due to reduction in energy units by taking the cost of one unit as Rs. 4.00/-, we get:

= 4 x 3260581.07

= **Rs.** 13042324.28

Total loss of revenue in one year is:

= (total cost of repair) + (total loss of money due to reduction in efficiency)

= (441352+13042324.2)

= **Rs.** 13483676.28

On calculating the cost of preventive measures (coating) will be same as above, as the erosion prone area is same and will be:

= **Rs 297600**

(Assuming the thickness of coating is 0.3 mm sufficient for all three concentrations of silt.)

For(c) = 3000 ppm:

Mass loss 'M' = 1.088 x2.17 x 10^-3 x 7800

= **18.41 kg/year**

Total cost of repair = (cost of welding) + (cost of grinding of affected area), of two units:

= [(18.41x500) + (10880x40)]

= **Rs. 444405**

On calculating the loss of revenue due to reduction in energy units by taking the cost of one unit as Rs. 4.00/-, we get:

= [illegible] 4 × 6475479.6

= **Rs.** [illegible] 25901918.4

Total loss of revenue in one year is:

= (total cost of repair) + (total loss of money due to reduction in efficiency)

= (444405+25901918.4)

= **Rs.** [illegible] 26346323.4

On calculating the cost of preventive measures (coating) will be same as above, as the erosion prone area is same and will be:

= **Rs 297600**

(Assuming the thickness of coating is 0.3 mm sufficient for all three concentrations of silt.)

Another correlation to assess the extent of erosion is given by, Bajracharya et al, is as:

$$W = 4.02 * 10^{-12} * S^{0.0567} * V^{3.79} * C^{1.2267} * t \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (4.28)$$

Where,

'S' silt particle size (m).

't', operating hour (h)

'V' velocity of flow (m/s)

'W' normalized wear (g/g) per unit discharge (m3/s)

Above correlation is used to assess the metal loss in the turbine of the same plant as above and hence the cost of repair and mitigation were calculated.

Table 5.5, shows the erosion for different period of time at a concentration of silt of 1000ppm.

Table 5.5 Total erosion in kg in different time period at c= 1000 ppm, eq. (4.28)

t(hrs)	2190	4380	6570	**8760**	10950	13140	15330	**17520**	19710	21900	24090	**26280**
W(kg)	1.54	3.08	4.61	**6.15**	7.69	9.23	10.8	**12.3**	13.8	15.4	16.9	**18.5**

Above table shows the erosion in mm per 0.25 years. Erosion after one year is highlighted.

We know that the density of turbine material is 7800 kg/ cubic meter. Therefore we can get the volume of the eroded metal as we have the mass of the same:

Volume of eroded material = mass/density

= 6.15/7800

= 0.000788 cubic meter

Now we calculate the affected area due to erosion on one bucket:

= dxd

= 0.161x0.161

= 0.0259 sq. m.

Total affected area = 0.026x21x2

= 1.088 sq. m

Erosion depth per year = volume of metal removed/affected area

= 0.000788/1.088

= 0.72 mm/yr.

Using the equation **(a)**, we can evaluate the reduction in efficiency due to the erosion we have calculated above:

$$efficiency\ reduction = 0.1522(0.72)^{1.6946}$$

$$= 0.087\ \%$$

Therefore reduction in power generation is:

$$P = 9.81 * 20.48 * 670.17 * (0.92 - 0.00087) * 0.97$$

$$= 120041.83\ \text{kW}$$

Therefore loss of energy units is:

= (120155.45-120041.83) x8760

= [illegible] **units/year** 995311.5

Table 5.6, shows the erosion for different period of time at a concentration of silt of 2000ppm.

Table 5.6 Total erosion in kg in different time period at c= 2000 ppm, eq. (4.28)

t(hrs)	2190	4380	6570	**8760**	10950	13140	15330	**17520**	19710	21900	24090	**26280**
W(kg)	3.6	7.2	10.8	**14.4**	18	21.6	25.2	**12.3**	28.8	32.4	36	**39.6**

Volume of eroded material = mass/density

= 14.4/7800

= **0.00185 cubic meter**

Now we calculate the affected area due to erosion on one bucket:

= dxd

= 0.161x0.161

= 0.0259 sq. m.

Total affected area = 0.026x21x2

= 1.088 sq. m

Erosion depth per year = volume of metal removed/affected area

= 0.00185/1.088

= **1.7 mm/yr.**

Using the equation **(a)**, we can evaluate the reduction in efficiency due to the erosion we have calculated above:

$$efficiency\ reduction = 0.1522(1.7)^{1.6946}$$

= 0.374 %

Therefore reduction in power generation is:

$$P = 9.81 * 20.48 * 670.17 * (0.92 - 0.00374) * 0.97$$

= 119667 kW

Therefore loss of energy units is:

= (12015546-119667) x8760

= [illegible] **units/year** 4278822

Table 5.7, shows the erosion for different period of time at a concentration of silt of 3000ppm

Table 5.7 Total erosion in kg in different time period at c= 3000 ppm, eq. (4.28)

t(hrs)	2190	4380	6570	**8760**	10950	13140	15330	**17520**	19710	21900	24090	**26280**
W(kg)	5.92	11.8	17.8	**23.7**	29.6	35.5	41.4	**47.3**	53.3	59.2	65.1	**71**

Volume of eroded material = mass/density

= 23.7/7800

= **0.00303 cubic meter**

Now we calculate the affected area due to erosion on one bucket:

= dxd

= 0.161x0.161

= 0.0259 sq. m.

Total affected area = 0.026x21x2

= 1.088 sq. m

Erosion depth per year = volume of metal removed/affected area

= 0.00303/1.088

= **2.78 mm/yr.**

Using the equation **(a)**, we can evaluate the reduction in efficiency due to the erosion we have calculated above:

$$efficiency\ reduction = 0.1522(2.78)^{1.6946}$$

$$= 0.86\ \%$$

Therefore reduction in power generation is:

$$P = 9.81 * 20.48 * 670.17 * (0.92 - 0.0086) * 0.97$$

$$= 119032.26\ kW$$

Therefore loss of energy units is:

= (12[illegible]119667) x8760

= [illegible] **units/year** 9839144.4

Now for c = 1000 ppm

Welding cost = 6.15x500

= Rs. 3075

Grinding cost = 10880x40

= Rs. 435200

Total cost of repair = (cost of welding) + (cost of grinding of affected area)

= **Rs. 438275**

Now on calculating the loss of revenue due to reduction in energy units by taking the cost of one unit as Rs. 4.00/-, we get:

= 4 x 995311.2

= **Rs** 3981244.8

On calculating the cost of preventive measures (coating) to the affected area, we get:

Total area of buckets affected by erosion = 9.136 sq m.

Cost of coating on buckets = 1.088x 200000

= **Rs. 217600**

Now we calculate the affected area due to erosion on the spear, considering tip angle as 60 deg.:

$= 0.5*\pi*d^2$

= 0.04 sq. m.

Total spear area affected due to erosion:

= 0.04x2x5

= 0.4 sq m.

Cost of coating on spear:

= 0.4x200000

= **Rs. 80000**

Total cost of coating = (cost of coating of bucket) + (cost of coating of spear)

= (217600) + (80000)

= **Rs. 297600**

Total loss of revenue due to erosion:

= (loss of revenue due to reduction in efficiency) + (repair cost)

= (438275) + (3981244.8)

= **Rs.** 4419519.8

Now for c = 2000 ppm

Welding cost = 14.4x500

= Rs. 7200

Grinding cost = 10880x40

= Rs. 435200

Total cost of repair = (cost of welding) + (cost of grinding of affected area)

= Rs. 442400

On calculating the loss of revenue due to reduction in energy units by taking the cost of one unit as Rs. 4.00/-, we get:

= 4 x 4278822

= **Rs** 17115288

Preventive measures (coating) cost will remain same:

= **Rs. 297600**

Total loss of revenue due to erosion:

= (loss of revenue due to reduction in efficiency) + (repair cost)

= (422400) + (17115288)

= **Rs.** 17557688

Now for c = 3000 ppm

Welding cost = 23.7x500

= Rs. 11850

Grinding cost = 10880x40

= Rs. 435200

Total cost of repair = (cost of welding) + (cost of grinding of affected area)

= Rs. 447050

On calculating the loss of revenue due to reduction in energy units by taking the cost of one unit as Rs. 4.00/-, we get:

= 4 x 9839144.4

= **Rs.** 39356577.6

Preventive measures (coating) cost will remain same:

= **Rs. 297600**

Total loss of revenue due to erosion:

= (loss of revenue due to reduction in efficiency) + (repair cost)

= (447050) + (39356577.6)

= Rs. 39803627.6

5.4. VARIOUS COSTS CALCULATED ABOVE:

Above, the economics of a power plant "Sorang" was studied on the basis of silt erosi with help of two correlations, which were studied in chapter 4. The metal loss in each case w calculated and corresponding costs of repair and mitigation measures were calculated f different concentrations of silt and time of operation. These costs are shown in table 5.8 and tab 5.9 for equation (v) and (xviii), respectively;

Table 5.8 Showing various costs calculated for a power plant of Sorang from eq. (4.6)

concentrations	cost of repair	loss of revenue due to loss in energy units	cost of coating	Total loss of revenue
conc. = 1000 ppm	Rs. 438272	Rs. 4027147.2	Rs 297600	Rs. 4465419
conc. = 2000 ppm	Rs. 441352	Rs. 13042324.28	Rs 297600	Rs.13483676.28
conc. = 3000 ppm	Rs. 444405	Rs. 25901918.4	Rs 297600	Rs. 26346323.4

Table 5.9 Showing various costs calculated for a power plant of Sorang from eq. (4.28)

concentrations	cost of repair	loss of revenue due to loss in energy units	cost of coating	Total loss of revenue
conc. = 1000 ppm	Rs. 438275	Rs 3981244.8	Rs. 297600	Rs. 4419519.8
conc. = 2000 ppm	Rs. 442400	Rs 17115288	Rs. 297600	Rs. 17557688
conc. = 3000 ppm	Rs 447050	Rs. 39356577.6	Rs. 297600	Rs.39803627.6

Fig. 5.3 and Fig. 5.4, shows the variation of mass loss at different concentration of silt with total loss of revenue in correlation (4.6) and correlation (4.28).

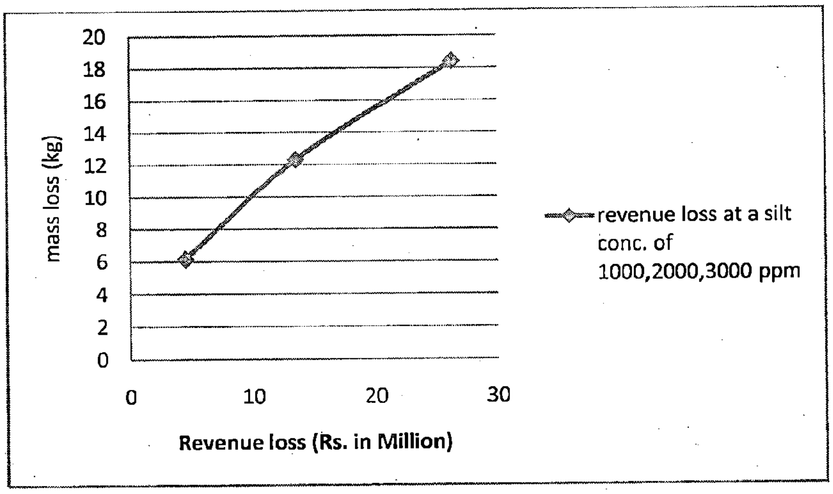


Fig. 5.3 Showing variation of revenue loss with mass loss at different silt concentrations i eq. (4.6)

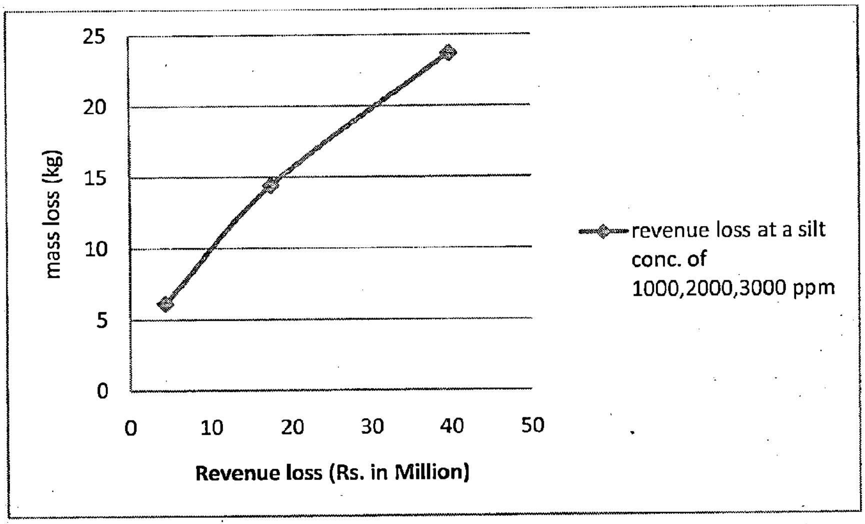


Fig. 5.4 Showing variation of revenue loss with mass loss at different silt concentrations in eq. (4.28)

From above analysis, we can see that, both correlations give the results in almost same range in case of mass loss of buckets of a Pelton runner of a particular hydro power plant. The cost of repair in three cases of concentrations of silt in water was calculated and the loss of revenue due to reduction in efficiency is also calculated. The cost of mitigation measure which is generally considered as coating was also calculated. The analysis shows that, if the mitigation measures are applied to the plant, a great saving in money can be made, as it ensures an efficient operation of runner and reduces the time period between the repair cycles. The cost of coating may vary w site specifications. Larger size particles and higher silt concentration in water may ask for thic coatings which will become a costly exercise. But from analysis it is observed that for lo concentrations the cost of coating is approximately 14 times less than total losses, where as higher concentrations it is approximately 130 times less than total loss of revenue. The t savings in case of coating drawn from correlations (4.6) and (4.28) are shown in table; 5.10 5.11.

Table 5.10 Total saving of money in case of coating from eq. (4.6)

Total loss of revenue/yr	Cost of coating	Total savings/yr.
Rs. 4465419	Rs. 297600	Rs. 4167819
Rs. 13483676.28	Rs. 297600	Rs. 13186076.28
Rs. 26346323.4	Rs. 297600	Rs. 26048723.4

Table 5.11 Total saving of money in case of coating from eq. (4.28)

Total loss of revenue/yr	Cost of coating	Total savings/yr.
Rs. 4419519.8	Rs. 297600	Rs. 4121919.8
Rs. 17557688	Rs. 297600	Rs. 17260088
Rs. 39803627.6	Rs. 297600	Rs. 39506027.6

CHAPTER-6

CONCLUSIONS & SCOPE OF WORK IN FUTURE

6.1 CONCLUSIONS

Many researchers have worked in the field of erosion of metal including erosion in hydro machinery caused by silt erosion as well as cavitation. Their damaging effects on hydro turbines, their mitigation measures, and their overall effect on whole power plant has also been studied and reported by many researchers. But still, no work has been carried out to study the erosion of hydro turbines economics considerations of power plant.

Present dissertation is an attempt to relate the silt erosion in hydro turbines and economics of power plants with help of various correlations developed by different authors who have worked in this field. Based on analysis following conclusions were drawn:

i. There are various models available to estimate the metal loss due to impingement of particles on the surface, developed by different authors, from which some correlations can be utilized for estimating the extent of metal loss in hydro turbines due to silt erosion.

ii. The wear equations developed by various authors, which can be utilized to estimate the hydro abrasive erosion, were identified and analyzed. It was found that all the correlations follow almost the same trend while giving the metal loss for different values of the parameters.

iii. Equations developed by "Padhy and Saini" and "Krause and Grein" have been used to assess the erosion of a particular plant of 120 MW. Both correlations give the metal loss in similar range, for equal period of time of operation.

iv. The total loss calculated for one year from correlation (4.6) is Rs. 4.4 Million, Rs. 13.4 Million, and Rs. 26.3 Million for a silt concentration of 1000, 2000, and 3000 ppm respectively, and from correlation (4.28) is Rs. 4.4 Million, Rs. 17.5 million, and Rs. 39.8 million for a silt concentration of 1000, 2000, and 3000 ppm respectively.

v. The analysis shows that, the cost of coating the silt erosion prone areas is less than the loss of revenue caused by erosion. The cost of coating may vary with type and size of turbine and silt concentration and size. Bigger particles and higher silt concentration demand for thicker coatings therefore costs more, since the cost of coating is about 130 times lesser than the loss of revenue, even a thicker coating will cause good saving of money.

vi. A methodology has been developed for economic analysis of silt erosion in hydro turbines turbine which will help the plant owner and turbine manufacturer for analyzing and taking the decision on replacement or repair of hydro turbine.

6.2 SCOPE OF WORK IN THE FUTURE

More studies are recommended to estimate the metal loss due to silt erosion in all types of hydro turbines in practice. Correlations are required to be developed covering all factors responsible for erosion. The range or the values of these factors should be well defined for different working conditions. These correlations can be used to estimate the metal loss in hydro turbines more accurately resulting more accurate cost of repair. An analysis may be taken up to develop a direct relation between the cost of repair, metal loss and, cost of mitigation measures which will be very helpful for power plant owners and turbine manufacturers.

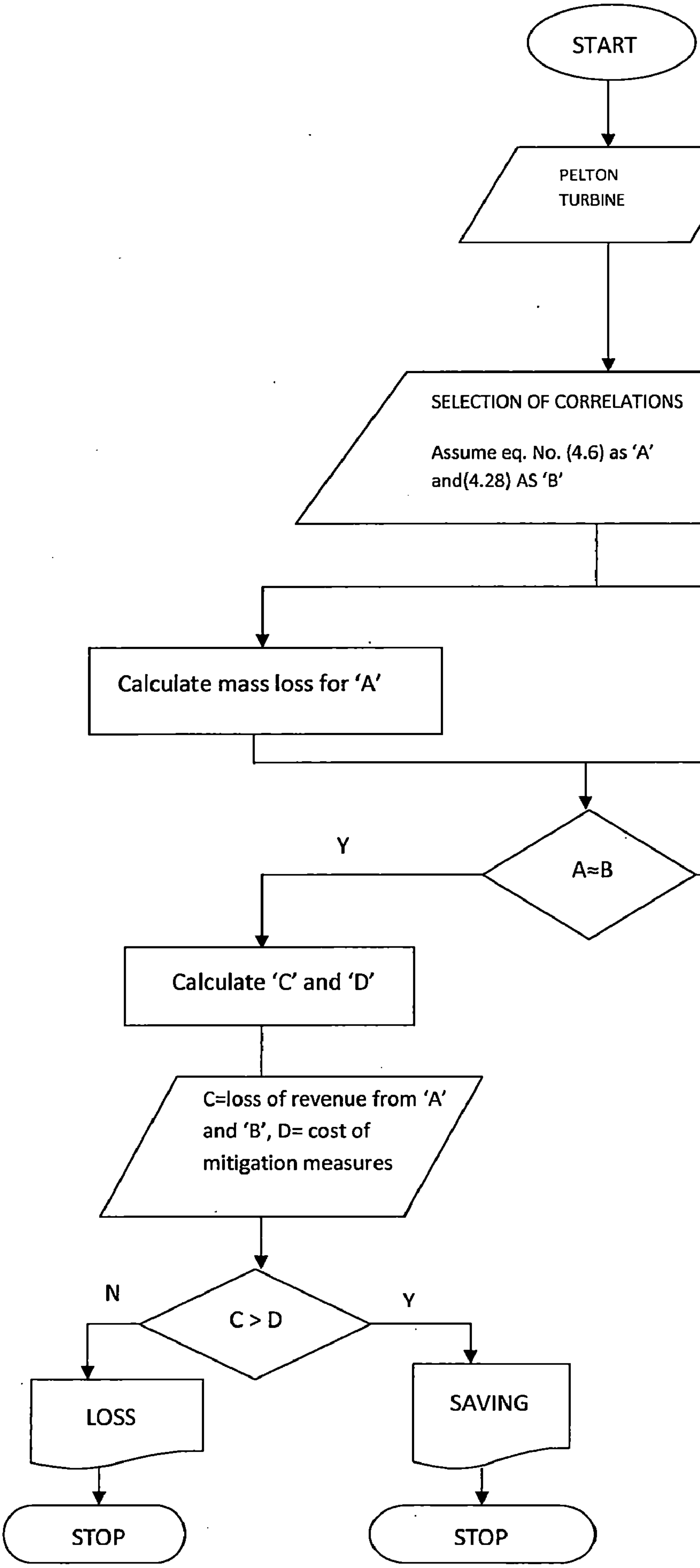


Figure.6.1; Methodology adopted in study to carry out economic analysis of turbine erosion.

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