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A Review of Slurry Erosion in Hydropower Turbines and Its Control using Protective Coatings

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Abstract **- Hydropower is one of the most stable and widely used renewable energy sources. However, in rivers with high silt content, especially in the Himalayas, slurry erosion severly damages hydro turbine parts. This damage leads to loss of efficiency, frequent maintenance, and shorter life span. Slurry erosion occurs due to the high speed impact of hard abrasive particles, like quartz, often combined with cavitation. This review paper presents outlines of slurry erosion mechanisms, factors that influence it, affected turbine parts, and ways to reduce its effects, focusing mainly on surface coating techniques. It critically reviews various coating techniques, including plasma spray, detonation gun (D-Gun), high velocity oxy-fuel (HVOF), high velocity air fuel (HVAF), and cold spray. The paper emphasizes carbide-based, oxide-based, metallic, and nano-composite coatings found in existing literature. It also discusses recent experimental studies, challenges, and future research directions.**

Keywords: ***Slurry erosion, Hydropower turbines, HVOF coating, Thermal spray, Cavitation erosion***

I. INTRODUCTION

Hydropower plays an important part in meeting the world's electricity demands, due to its efficiency, cost-effectiveness, and eco-friendly nature. In India, the abundance of rivers and mountainous landscapes offers significant opportunities for hydropower development. Despite these advantages, hydropower

Facilities especially those located along Himalayan Rivers face persistent problems with slurry erosion.

This occurs when water loaded with silt and sand flows through turbines. Glacial rivers, in particular, transport high levels of abrasive minerals like quartz, feldspar, and mica, which can rapidly wear down turbine parts during operation. The impact of slurry erosion is significant, causing substantial damage to critical turbine components such as runners, guide vanes, nozzles, facing plates, and draft tubes. Over time, this damage leads to reduced efficiency, mechanical imbalance, unwanted vibrations, and unexpected plant shutdowns. In India, the financial burden from erosion-related repairs and lost productivity is estimated to reach millions of dollars every year. Traditional materials like carbon steel and stainless steel often fail to withstand such abrasive environments. As a result, engineers are increasingly turning to surface engineering techniques, especially the use of protective coatings, to help safeguard equipment and reduce erosion.

II. SLURRY EROSION MECHANISM

Slurry erosion is defined as the progressive material loss that occurs due to the impact of solid particles suspended in a liquid medium on a solid surface in repetitive manner. The erosion mechanism depends on material properties, particle characteristics, and flow conditions.For ductile materials, erosion is dominated by cutting, ploughing, and plastic deformation, with maximum erosion occurring at low impingement angles (20°–30°). In contrast, brittle materials experience erosion primarily through crack initiation and propagation, with the greatest erosion occurring at normal impact (90°). In hydropower turbines, both ductile and brittle erosion mechanisms coexist due to complex flow conditions.Slurry erosion is further accelerated by Cavitation with generation of microjets and shockwaves during bubble collapse. The joint action of cavitation and slurry erosion leads to coating failure and rapid surface degradation if not properly designed.

III. FACTORS AFFECTING SLURRY EROSION

The intensity of slurry erosion in hydropower turbines is influenced by several parameters:

A. Particle Characteristics

Particle size, shape, hardness, and density significantly affect erosion rate. Angular and hard quartz particles cause

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severe micro-cutting and fracture. Larger particles generally increase erosion, while very fine particles may reveal a cushioning effect.

B. Slurry Concentration

An increase in silt concentration leads to higher particle surface interactions, thereby increasing erosion. However, beyond a critical concentration, particle to particle collisions may decrease effective erosion.

C. Impact Velocity and Angle

Erosion rate increases exponentially with particle velocity. Impact angle governs the dominant erosion mechanism and material response.

D. Material Properties

Hardness, toughness, microstructure, and bonding strength play a vital role in erosion resistance. Coatings with a balanced combination of hardness and toughness show excellent performance.

IV. TURBINE COMPONENTS SUSCEPTIBLE TO SLURRY EROSION

Slurry erosion affects several critical components of hydropower turbines, including:

- Runner blades and buckets
- Guide vanes and stay vanes
- Nozzles and spear tips (Pelton turbines)
- Facing plates and draft tubes

Localized erosion leads to efficiency loss, increased clearances, vibration, and premature component failure, necessitating frequent repair or replacement.

V. MITIGATION STRATEGIES

A. Silt Control Measures

Silt management techniques such as desilting chambers, settling basins, and catchment area treatment are commonly employed. Although effective to some extent, complete removal of fine silt particles is unrealistic.

B. Surface Engineering Approaches

Surface modification using protective coatings has appeared as the most effective strategy to reduce slurry erosion. Coatings act as sacrificial layers and significantly enhance component life.

VI. COATING TECHNOLOGIES FOR SLURRY EROSION RESISTANCE

A. Plasma Spray Coatings

Plasma spray coatings are widely used to deposit ceramic and cermet materials. These coatings offer good hardness and wear resistance. However, it relatively offers higher porosity that may reduce their erosion performance.

B. Detonation Gun (D-Gun) Coatings

D-Gun coatings are distinguished by high density, low porosity, and excellent adhesion. They provide superior erosion resistance. However they are limited by equipment complexity and cost.

C. High Velocity Oxy-Fuel (HVOF) Coatings

HVOF coatings have gained widespread acceptance in hydropower applications due to their dense microstructure, low oxidation, and high bond strength. Carbide-based HVOF coatings such as WC–Co and Cr_3C_2–NiCr exhibit excellent slurry erosion resistance.

D. High Velocity Air Fuel (HVAF) Coatings

HVAF is an advanced variant of HVOF that operates at lower flame temperatures and higher particle velocities. These conditions result in coatings with minimal oxidation, higher density, and improved erosion resistance.

E. Cold Spray Coatings

Cold spray coatings are deposited at relatively low temperatures, preserving feedstock properties and minimizing oxidation. Although it is promising, but further research is required for hydropower applications.

VII. COATING MATERIALS

A. Carbide-Based Coatings

WC–Co, WC–CoCr, and Cr_3C_2–NiCr coatings are extensively used for slurry erosion resistance due to their high hardness and wear resistance.

B. Oxide-Based Coatings

Oxide ceramics such as Al_2O_3, Cr_2O_3, and ZrO_2 exhibits good corrosion resistance but may suffer brittle fracture under high-impact erosion.

C. Metallic and Alloy Coatings

Ni-based and Co-based alloys offer higher toughness and corrosion resistance, making them suitable for joint erosion and corrosion environments.

D. Nano-Composite Coatings

Recent studies indicate that nano-structured and grapheme or CNT-reinforced coatings offers significantly improved erosion resistance. It enhances toughness and reduces porosity.

TABLE 1

COMPARATIVE ASSESSMENT OF COATING TECHNIQUES USED IN HYDROPOWER TURBINE PROTECTION

Coating Technique	***Particle Velocity***	***Coating Density / Porosity***	***Typical Coating Materials***	***Key Advantages***	***Limitations***	***References***
Plasma Spray (APS)	Moderate	Medium / High porosity	Al_2O_3, Cr_2O_3, ZrO_2	Thick coatings, wide material range	Higher porosity, lower bond strength	[9], [14], [16]
D-Gun Spray	Very High	Very dense / Low porosity	WC–Co, Cr_3C_2–NiCr	Excellent hardness and adhesion	High cost, complex setup	[10], [14], [16]
HVOF Spray	High (Supersonic)	Dense / Low porosity	WC–Co, WC–CoCr, Cr_3C_2–NiCr	Superior erosion resistance, good adhesion	Limited ceramic deposition	[10], [13], [16], [23]
HVAF Spray	Very High	Very dense / Very low porosity	WC–Co, WC–CoCr	Minimal oxidation, high toughness	Limited industrial availability	[11], [16]
Cold Spray	High (Solid-state)	Dense	Al, Cu, Ni-based alloys	No thermal degradation, low	Limited ceramic use	[11], [15]

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TABLE 2
COMMON COATING MATERIALS AND TYPICAL PROPERTIES

Coating Material	*Typical Hardness (Vickers, Hv0.5)*	*Key Properties*	*Common Application*	*References*
WC–Co	1100–1400	Very high hardness, good toughness	Runners, guide vanes	[10], [13], [16]
WC–CoCr	1000–1300	Improved corrosion resistance	Silt-laden rivers	[10], [11], [16]
Cr_3C_2–NiCr	800–1000	High temperature stability	Pelton nozzles	[10], [14], [16]
Al_2O_3	900–1200	Excellent hardness, brittle nature	Facing plates	[9], [14], [15]
Cr_2O_3	1100–1300	High wear & corrosion resistance	Guide vanes	[9], [16], [17]
NiCrBSi	500–750	Good toughness, corrosion	Repair coatings	[6], [15], [16]
Nano-WC composites	1200–1500	Enhanced toughness & erosion resistance	Advanced turbines	[12], [17], [18]

VIII. CHALLENGES AND FUTURE SCOPE

Despite surfacing technology has advanced significantly since its early days, numerous hurdles still hinder the entry of surfacing into mass production in many industrial sectors. To begin with, an accurate determination of how long coatings will last under actual working conditions is an important area that continues to challenge manufacturers, as there is a notable lack of adequate methods for predicting coating characteristics under various types of mechanical, chemical, and thermal stress factors acting together. Secondly, scaling up the production of nano-composite coatings from a lab-based scale to a full production scale presents major challenges, particularly in the areas of retaining micro structural homogeneity, reducing variations in repeatability and ensuring that the functional integrities of the nano-composite coatings are maintained over larger surface areas. Thirdly, cost-effectiveness also represents a major hindrance to wider acceptance of nano-composite coatings and multifunctional coatings since the production of such products typically requires expensive raw materials in conjunction with complex manufacturing processes. Consequently, only manufacturers with large financial resources can afford to use advanced technology for surfacing, limiting its use by the majority of manufacturers.

Going forward, it is recommended that research efforts be focused on the creation of multifunctional coatings that can resist both cavitation and corrosion in addition to slurry erosion, and facilitate increased operational performance and reduced maintenance requirements. Additionally, the use of computational models to evaluate coating performance in realistic working conditions will allow designers to optimise the performance characteristics of the coatings before placing them into the field. Lastly, the implementation of real-time condition monitoring enables the proactive development of maintenance programs that can regularly monitor the health multifunctional coatings during service, decreasing the incidence of sudden failures and increasing overall system reliability.

IX. CONCLUSIONS

Hydropower turbines are faced with a significant risk from slurry erosion due to the high silt levels in the water where they operate, as these highly abrasive materials continually strike against the turbine components, which may ultimately result in the loss of material, degradation of the surface of these components, and reduced efficiency, thereby shortening the service life of a turbine. Advanced surface coatings, which are deposited using either the High-Velocity Oxy-Fuel (HVOF) or High-Velocity Air-Fuel (HVAF) coatings, can enhance the performance of turbines by using hard carbide-based and nano-composite coatings that exhibit superior adhesion, density and resistance to wear, thus improving the longevity of turbines and reducing the need for maintenance. Although there has been significant success with the application of these coatings, a great deal of additional research is needed to determine the optimal composition, microstructure and deposition parameters of these coatings for the specific operating conditions to which they will be subjected in the field. Integrating both experimental studies and numerical modeling will allow for an improved understanding of the erosion mechanism and also provide guidance to manufacturers regarding the design of custom-made coatings that will support sustainable hydropower generation.

Future research on improved coatings should focus on coatings that will provide resistance to slurry erosion, cavitation and corrosion. Utilizing numerical modelling to ensure optimum coating performance and real-time condition monitoring techniques to predict failures in order to minimize the amount of maintenance required. The development of these coatings will therefore assist in closing the gap between laboratory research and commercial applications, and enable such coatings to be manufactured at both a high-performance and cost-effective level.

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