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Tribological Models for Erosive Wear in Slurry Flow: A Review: Part I

Mechanistic mathematical modelling for accurate slurry erosion prediction

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Slurry erosion is a mechanically induced wear observed in various industries transiting the mixture of liquid and erodent particles, either naturally or affectedly. The equipment and pipelines need frequent monitoring and slurry erosion prediction to check the severity of erosion for implementing preventive measures to minimise the damage of erosion wear. Experimental investigation and online condition monitoring are very high priced and provide a fair idea about the extent of slurry erosion wear; nevertheless, precise prediction of slurry erosion wear requires *in situ* operating conditions. To minimise expenditure on slurry erosion testing or monitoring and accurate slurry erosion prediction, tribological modelling of slurry erosion wear by mathematical approach or computer-based simulations has proved to be an excellent approach by numerous researchers to foresee the slurry erosion wear and control its severity. Several authors in the past have aligned their efforts in this direction. This two-part review is an attempt to estimate the progress in the variety of tribological modelling (primarily mathematical models) of slurry erosion for its forecasting, monitoring and to suggest the apt approach for the modelling of slurry erosion wear, especially for hydroturbine components. This article covers the research studies pertaining to mathematical wear models for solid particle erosion recommending a commencing approach for slurry erosion wear modelling.

Keywords

slurry erosion, solid particle erosion, mathematical modelling

1. Introduction

Erosive wear in slurry flow is a significant phenomenon encountered in various industrial processes involving the transport of solid-liquid mixtures. Understanding and predicting the erosion of materials under such conditions is crucial for optimising equipment design and maintenance strategies. Tribological models for erosive wear in slurry flow play a key role in this domain by providing theoretical frameworks to analyse and quantify erosion mechanisms. These models typically aim to describe the complex interactions between the solid particles in the slurry, the fluid dynamics of the carrier liquid and the material surface being eroded. By integrating principles from tribology, fluid dynamics and materials science, these models offer insights into erosion rates, particle impact velocities and surface damage mechanisms.

Slurry erosion wear primarily depends upon the quantum of particles hitting the target surface, their morphology, striking velocity and incident angle, in addition to it, some other parameters such as comparable hardness of particles and exposed surface, also contribute to slurry erosion. Flow conditions of slurry decide the values (speed and direction of particles) of some of these parameters such as: velocity, incident angle at the instant of striking the surface open to mobile mixture of erodent particles and liquid because the striking particles and fluid as a matter of course do not share the same direction and speed in flow. Experimental investigations of the slurry erosive flows play a major and important role for identification and quantification of the factors having influence on the transportation of slurry particulate materials in many applications such as slurry pipelines in many industries, hydroturbines in hydropower plants and pumps and thereby, wear due to slurry erosion phenomenon. In another earlier study (1), experimental investigations for slurry erosion wear under different categories of materials, either modified with various methods such as coatings, reinforcements, heat treatments, thermomechanical processes or unmodified have been reported, discussed and reviewed. This kind of *in situ* investigations are very high-priced, laborious and time-engrossing to follow under slurry erosive original conditions in applications concerned to complex industrial processes of various slurry handling equipment and transportation systems like mining, power generation in hydropower plants, chemical processing and dredging. Rapid changes in flow conditions as in the case of turbine blades or pipe bends or elbows turn the erosion sometimes, severe. Understanding the severity of erosion wear and to avert exorbitant outlays on experimental investigations, more convergence is required on expansion of the wear models and corresponding wear equations having potential to foresee the extent of erosion wear. Precisely, it is to be done in terms of mass or volume loss of materials befitting the wide ranged operating conditions in correlation to the real-life slurry erosion applications. The contemporary advancements in the dynamic modelling algorithms of fluid-particles and high-pitch accomplished computing technologies have constituted numerical methods an attainable choice for investigating and studying the particle laden slurry erosive flows. Inherently, a wear model is the inclusion of equivalent parameters or variables, which impulse directly or indirectly in the equations for forecasting the wear accompanied by their enumeration and depiction. Wear equations are generally referred as accumulation of these parameters or variables in the analytical form (2). Several factors influence the mass loss due to slurry erosion. Some of them: velocity and angle of impingement, shape and size, load intensity, hardness, stiffness and density are associated with the impacting particles. Some principal ones such as ductility and hardness are associated with the target material (3).

In the past six to seven decades, many authors have unfolded the wear models; conversed about in forthcoming sections and corresponding equations predicting the quantity of wear for absolute solid particle erosion and subsequently by some authors, for erosion due to slurry flow. Still, there is a paucity of mathematical wear models which can predict the erosion wear in more accurate manner to the existing models and which might encompass all the influential operating variables or parameters. This two-part review narrates the approach correlating the number of possibilities, for modelling the wear due to slurry erosion for its prediction. This detailed compilation comprises of mathematical modelling, mechanistic and empirical ones. A few other wear models using computer-based simulations are also analysed under this review. The mathematical mechanistic wear models for absolute solid particle erosion have also been considered, focused and covered in this analysis as these models facilitate the path for advancement in modelling of slurry erosion wear.

2. Modelling Aspects of Slurry Erosion

Numerous researchers have modelled the wear due to solid particle erosion and very few of them have focused on slurry erosion wear. Authors have pursued different features, views and perceptions for modelling the wear due to slurry. Various authors have modelled for erosion wear with due consideration of speed and direction of motion of erodent particles of slurry striking the target surface identical to that of flow of the liquid carrying the slurry particles. In most of the research, the speculation for same speed and direction of flow was turned out to be approximately in consonance of the experimental outcomes, whenever the modelling for erosion wear was accomplished for jet type of slurry erosion testers. Many researchers have executed and followed this pattern of wear modelling. In reality, it is not precise and genuine for experimental investigations to be performed on slurry erosion testers of types other than jet types. Such hypothesis is not supposed to be advantageous and helpful for wear modelling. Consequently, slurry erosion prediction before experimental investigations in slurry pot testers is intricate and troublesome because to presume the speed and direction of slurry particles may culminate into erroneous impressions. Slurry erosion pot testers are generally applicable for comparison of slurry erosion resistance of different categories and types of materials under identical operating conditions. For modelling the wear for pot testers, the influence of velocity, direction, drag, fluid viscosity, Reynolds number and flow type of slurry liquid on the trajectories of mobile slurry particles are taken into consideration and comprised of relevant equations intended for erosion wear estimation. Subsequently, revealing these equations bring about the realistic values of impact velocities and few other relevant parameters imperative for mass loss computation (similar to (4)). As long as the pragmatic values of associated parameters are recognised and noted, wear modelling of slurry erosion seems to be almost similar and identical practice to the erosion modelling of solid particle impingement as executed by numerous researchers. The same can be initiated *via* acknowledging various fundamental and few other erosion models updated, amended and re-tailored every so often by researchers. But their accuracy after being modelled would depend upon the degree of precision of liquid impact determination on slurry particles close to the actual effect. Wong *et al*. utilised some fluid mechanics concepts: Navier-Stokes equations and Newton's second law to ascertain the field of slurry flow and trajectories of the slurry particles, respectively (4). Eulerian approach, in which the velocity and acceleration of particles are described at fixed points as function of the space coordinate of the points and time, might be useful for these values corresponding to solid particles in flow field. Lagrangian approach, in which solid particles are being traced in flow field, is disregarded due to complex mathematical integrations. Some researchers (5) incorporated the influence of particle rotation; moment of inertia of solid particles about the centre of gravity. Few (6) have included the effect of both moment of inertia of slurry particles and centrifugal force, especially for slurry flow in pipelines. Generally, particle oscillation and inconstancy in velocity depends on liquid flow and is dominated by liquid fluctuation and variation in flow velocity, but slurry particles with considerable moment of inertia are deflected from the liquid wavering. Few authors incorporated the effect of particle densities (3, 6–12) and target material densities (10, 12) in modelling. Very few (10, 12) of them included the densities of both erodent particle and target materials.

For pipeline flow, Huang *et al.* also incorporated the effect of liquid density. The authors also considered and discussed about lateral motion of solid particles in pipe, influenced and governed by momentum of inertia of particles, liquid turbulence, buoyant, centrifugal and gravitational effects. They modelled the liquid flow correlating the liquid turbulence. The effect of liquid viscosity and the influence of Reynolds number of liquid as well as slurry particles on loss due to wear were also considered (6). Reynolds number portrays the flow pattern of slurry, tending to deviate from Laminar to turbulent at its higher values. Few authors (3, 5, 13–15) have taken the plastic flow of pressure in wear modelling, responsible for flow of stress; indent creation or volume loss between the solid particles and target material into consideration. Some authors figured the indentation term in modelling in the form of hardness (8), volume (3, 7, 8, 10, 16) and depth (7, 17) of indentation of the exposed target material. In other ways, Tilly considered the extent of disintegration of solid particles in the course of impact and established that the particle breakage into fragments depends upon its initial size and velocity. The author categorised the wear loss by primary and secondary erosion, without and with fragmentation, respectively during strike. Extent of fragmentation and inceptive kinetic energy directly affects the extent of erosion (16). Some authors had taken the threshold values; below which materials remain elastic and no erosion takes place, for example, size (16) and velocity (14–16, 18–20) of particles. Authors infrequently defined the cutting (11, 12) and deformation characteristics velocity (12, 18) and elaborated in modelling. Cutting characteristics velocity is a character for target and solid particle's material characteristics, while deformation characteristic velocity demonstrates the erosion potential in the direction of deformation. Several authors (3, 18–20) expressed the erosion as composite contribution of deformation and cutting wear, while Wang *et al*. (21) advised the wear as the combination of cutting, deformation and fatigue and followed accordingly in wear modelling. Few authors focused the energy indispensable in wearing out unit volume of target materials and so utilised the deformation (12, 18–20) and cutting wear factors (18–20) for deformation and cutting wear, respectively. Scanty authors included the effect of fracture toughness in wear modelling for brittle materials (9) and thermal spray coatings (17), exhibiting the behaviour identical to brittle materials. Fracture toughness of the material of interest can be directly correlated to the size and density of cracks. Crack propagation in brittle materials is only yielded to flow further, if the level of stress around the crack is excelled to the limiting or critical stress value pertaining to critical stress intensity factor or fracture toughness. Deportment of these kinds of cracks can be well predicted with the aid of basic concepts related to fracture mechanics. Many authors (9, 17, 22) utilised the assistance of contact fracture theory and fracture mechanics for erosion prediction.

Very few authors (3, 10) considered and applied the idea of critical plastic strain correlating the erosion ductility of target materials to ascertain the point of time of removal of material due to erosion. Whenever the collision of a spherical body to another spherical body is considered, Hertzian equation for a pure elastic collision is usually applicable. One spherical body can be assumed flat surface considering its radius as infinite for forming suitability and applicability of Hutching contact theory to model the slurry erosion wear. Hertz elaborated the theory perspective to the macroscopic elastic stress distribution for plastic deformation, elastic stress fields, fracture or fatigue, contact pressure between the colliding bodies and relevant elastic modulus (reduced modulus). Many authors (7, 17–19, 22) utilised the basic concepts related to Hertzian contact theory for wear modelling, thereby for prediction of erosion. Some authors, therefore focused to consider in modelling; the elastic-plastic properties (18, 19), Poisson’s ratio (7, 12, 17–19) and Young’s modulus (7, 12, 17–19, 23) of materials pertaining to the erodent and target. Similarly but in a slight different manner, Wang *et al.* (21) emphasised the comparative strength of erodent and target materials by taking the ratio of their stiffness into the modelled equation for wear prediction. In a specific consideration, the authors (23, 24) took the ratio of velocity of rebound and approach of impacting particles as the coefficient of restitution (e).

Various authors developed the correlations for slurry erosion wear using the experimental outcomes. Empirical modelling performed in such manner can be valid and utilised only for erosion wear prediction for specific combinations or categories of target and erodent materials, exclusively along with selected parameters. Apart from this, many of the authors executed the development of mechanistic erosion modelling in which mechanics of forces, pressures and other relevant parameters in between the erodent particles and target materials during their interaction on contact or impact were considered. These types of developed erosion wear models are universal in their approach to predict wear for intended class of operating parameters, erodent and target materials. This review includes all kinds of modelling, such as statistical, mechanistic and some other computer-based models or simulations, which have been explored and discussed in forthcoming sections.

It is evident from the literature that there are various aspects which can be incorporated in the modelling of erosion on account of slurry. The behaviour of material during erosion is another aspect which requires attention. The broad classification of mechanism during erosion is categorised as ductile and brittle and subsequently, failure of materials taking place (1). Other authors (5, 11–13, 16, 18–20, 23–28) have focused and considered the ductile materials or ductile mode of erosion wear in modelling for solid particle erosion, solely or slurry erosion. A very few researchers (7, 9, 13) have demonstrated the erosion wear models for brittle materials or the materials, exhibiting brittle mode of erosion mechanism. Majority of the coatings bear non-homogeneous and non-uniform microstructure, similar to brittle materials. A study modelling the slurry erosion for thermal spray coatings with its consideration as brittle mode of behaviour is available in the work of Grewal *et al.* (17).

As this review is intensely concerned about the mathematical modelling for slurry erosion wear for hydroturbine components, there should be apt recommendations of the size and shapes of the slurry erodent particles for wear modelling. Very few authors (3, 6, 23) embodied the influence of shape factors of solid eroding particles in wear modelling. Finnie correlated a parameter with the shape ranging from angular to less angular or spherical, of the abrasive particles (13). Some (28) included both shape factor and aspect ratio in erosion modelling, while some (11, 12) have taken the roundness factor into erosion modelling consideration. Many authors (3–6, 8–12, 16–19, 21, 29) deliberately assumed or considered the spherical shape of eroding particles for simplicity and ease of modelling. In another study (7), angular particles were considered spherically shaped with imaginary radius, for which provision was created in wear expression. All solid particles are not equally effective for creating the mass loss of exposed material. Hydroturbine components generally undergo frequent wear loss due to slurry erosion. Slurry associated to these components comprises finer to coarser sand erodent particles. The morphology of the solid particles does matter towards the extent of erosion. In actual operation of hydropower plants, hydroturbine components face erosion wear due to slurry flow having the sediment sizes, usually up to 300 μm approximately (22, 30–33). Up to this range of erodent sizes, slurry carries the finer (generally ≤150 μm) to coarser (generally >150 μm) sediment particles having spherical or round to angular sharp-edged shapes. Finer sediments which have spherical or round-edged morphology share usually, very less or negligible proportion of quantity in actual slurry flow, faced by hydroturbine components. Very few research studies (34–36) are available associated to wear modelling due to solid particle erosion by angular and irregular shaped particles. In one study (34), Biswas *et al.* commented on the shape of the erodent particles. The authors as a matter of fact suggested to presume the particles of square pyramidal shaped bodies for their actual irregular and sharp edges rather to imagine spherical shapes. Similarly, other study (35) and our earlier investigation (36) also contemplated the square pyramidal shaped erodent particles for establishing the mathematical model for solid particle erosion. Very few authors (5, 13) included the effectiveness of erodent particles. As a general notion, it can be taken as 50% of the total number of particles. In slurry pipelines, all solid particles do not possess necessarily the identical striking velocity. For such conditions of wear modelling, mean velocity of slurry particles (similar to study (6)) can be considered. In many studies, kinetic energy (13, 16, 17, 23, 24, 37) or energy balance (10, 18, 19) of solid eroding particles was taken into consideration for determination of mass loss due to wear. Kinetic energy of striking particles before and after the impact can be one such aspect to be considered in the wear modelling. Cutting by an eroding particle cease when its velocity component parallel to the surface is exhausted before leaving it. Conversely, cutting continues unless the erodent particle leaves the surface. Some authors (5, 18, 19) assumed these two aspects for modelling the erosion. In other studies (29, 34, 35), the authors utilised the erosion efficiency parameter for finding out the actual removed volume from the displaced volume of material due to erosion.

Quantity of slurry erosion relies primarily on seven influential parameters: circularity factor, aspect ratio, impingement angle, impact velocity, particle size, time and solid particle concentration. There are many ways such as rule-based and linear regression of modelling by fuzzy logic, in which models can be constituted associating the variable influential parameters to the slurry erosion in terms of mass loss. Fuzzy rules can be arranged and established on the empirical observations. Some authors exercised the fuzzy logic modelling, employing an authentic, adept and unified system for monitoring and prediction of slurry erosion (28). An approach for prediction of slurry erosion can be the employment of artificial neural network and a few authors (38) implemented this approach in correlation with optimisation by genetic algorithm. Artificial neural network is subject to an accumulation of linked nodes or units; artificial neurons having serviceability identical to human nervous system, while genetic algorithm is a mathematical approach for optimisation, leading to fix worst combinations of operating parameters exhibiting relatively severe erosion. In an another study (39), mathematical modelling based on Monte Carlo technique is followed for fixing the more number of influential values or variables associated to parameters affecting the wear due to slurry. Monte Carlo method or simulation includes computer related algorithms for recurring random sampling. Randomness is employed for problem solution to require desirable numerical outcomes. The method is employed, generally for numerical integration, optimisation and probability distribution. In another method for slurry erosion prediction, the authors (40) developed the finite element models to observe the slurry erosion wear behaviours without the experimentation. Finite element method is usually employed for the solution of the partial differential equations.

Several authors found the computational fluid dynamics (CFD) modelling suitable for erosion prediction. Few other authors practiced CFD approach for modelling the slurry erosion (21, 40–42). The general procedure of modelling by CFD approach for erosion prediction was demonstrated by Edward *et al.* (43). CFD simulation can be used to predict the shape of slurry flow pattern and particle impact profile on the target material. Erosion modelling by CFD approach includes the steps, sequentially: hydrodynamic flow modelling, tracing of slurry particle in the constituted field of flow and mechanistic erosion modelling (21). Hydrodynamic simulation of slurry flow through CFD embodying the basic theories of fluid mechanics is an attempt to ascertain the real and original flow conditions in modelling. These flow conditions decide the motion of slurry particles and consequently their trajectories. Succeeding the paths usually decided by flow conditions, slurry particles strike the target material at distinct and peculiar parameters, which are associated to the manner of their interaction with target material and can vary from one particle to another, depending on flow conditions of slurry. The parameters related to the speeds and directions, include the impact load, velocity, impingement angle of slurry particles, at which they strike the target material and some other parameters such as size, shape factors and relative hardness of slurry particles associated with erosion wear and can be aggregated to generate wear model. Mechanistic erosion modelling is the study of the effect of these parameters on the allied forces during interaction and originates from corresponding wear equations comprising these parameters for prediction of erosion wear.

3. Mathematical Modelling

3.1 Statistical Mathematical Modelling

This section encompasses the mathematical wear correlations or exponent values of distinct related parameters which were established by fully utilising the experimental outcomes for erosion wear estimation.

Erosion wear due to slurry particles functionally depends upon the several parameters discussed previously and can be estimated and forecasted by empirical modelling for wear. Similar to Elkholy (44) for employing a curve fitting technique for analytical wear modelling, many authors (45, 46) have tried to establish correlations for erosive wear rates predicted on the data obtained from experimental studies. These correlations were of the prevalent and popular form, which can be specified as: $E_w = k.\ D^a\ .V^b\ .C^c$, where E_w, D, V and C are designated as erosive wear rate, particle size, velocity and slurry concentration respectively. The exponents a, b and c along with constant (k) are to be computed for different combination of target and solid eroding materials (45):

$$E_w = \begin{cases} 0.178\,D^{0.291}\,V^{2.4882}\,C^{0.516}\,(\text{for brass}) \\ 0.223\,D^{0.344}\,V^{2.148}\,C^{0.556}\,(\text{for mild steel}) \end{cases} \qquad \text{(i)}$$

Similarly, Gandhi *et al.* established the influence of parameters on erosion wear for parallel slurry flow in pot tester and developed the correlations as (46):

$$E_w = 2.57\,D^{0.85}\,V^{2.56}\,C^{0.83}\,(\text{for brass}) \qquad \text{(ii)}$$

Applying the similar approach, Ramachandran *et al.* unfolded mathematical models to assess the abrasive slurry wear rate of the AISI 1040 substrate and three plasma transfer arc hard-faced surfaces which include iron-based alloy (SS316L), cobalt-based alloy (stellite-6) and nickel-based alloy (colmonoy-5). This model integrated the foremost and bilateral effects of four process variables such as abrasive particle size (D), slurry concentration (C), speed of rotation (S) and slurry bath temperature (T). For the four variables, the selected second order polynomial (regression) equation used to represent the response surface (Y) revealing the abrasive slurry wear (ASW) rate (ASW = f(D,C,S,T)) and could be conveyed as:

$$\begin{aligned} Y=&b_0+b_1(D)+b_2(C)+b_3(S)+b_4(T)+b_{11}(D^2) \\ &+b_{22}(C^2)+b_{33}(S^2)+b_{44}(T^2)+b_{12}(DC)+b_{13} \\ &(DS)+b_{14}(DT)+b_{23}(CS)+b_{24}(CT)+b_{34}(ST) \end{aligned} \qquad \text{(iii)}$$

After ascertaining the considerable coefficients (b_0, b_1, b_2, b_3, b_4, b_{11}, b_{22}, b_{33}, b_{44}, b_{12}, b_{13}, b_{14}, b_{23}, b_{24}, b_{34}) at a 90% confidence level by employing the student's t-test to the IBM® SPSS® statistical software package, the final mathematical models were developed and their suitability were checked by using the analysis of variance (ANOVA) technique. Appreciable correlations were established between trial and foretold values of wear rates (47). Similar to the approach of regression analysis, Desale, Gandhi and Jain investigated the slurry erosion wear behaviour of seven types of ductile materials: aluminium alloy (AA6063), mild steel, brass, copper, TBS, AISI304L and 316L and using the experimental outcomes, they developed a correlation for slurry pot tester using least square method for erosion rate prediction having the influence on the hardness ratio (H_P/H_T), impact velocity (V), slurry concentration (C) and erodent size (D). The developed empirical correlation for normal impact erosion rate (E_{W90}) was designated as:

$$E_{w90} = 6.62 \times 10^{-14} \times \alpha_{\left\{\frac{H_P}{H_T}\right\}} V^{2.02}\,D^{1.62}\,C^{-0.285} \qquad \text{(iv)}$$

where, $\alpha_{\left\{\frac{H_P}{H_T}\right\}}$ is a constant, depending upon hardness ratio (25).

Continuing the investigation on the same seven types of ductile materials, the authors developed the correlations for prediction of slurry erosive wear for variation in impact angles. Because of considerable deviation of the cutting wear behaviour with impact angles for different conjunction of target materials and erodent, normalised cutting wear index (ratio of cutting wear to maximum cutting wear) was quantified for developing the correlations for erosive wear with regression analysis. Correlation was developed with dependence of erosion rate on investigated operating parameters; target material hardness (H_T) and shape factor (MSF). The absolute erosion wear (E_W) was considered as the benefaction of the cutting (E_C) and deformation wear rates (E_D) and can be stated as:

$$E_w = E_C + E_D \tag{v}$$

where, deformation wear, $E_D = E_{D90}$ (sin $\varphi)^3$ is the deformation wear due to normal component of impacting velocity to the target material at any angle of impact and E_{D90} is deformation wear under normal impact. Cutting wear rate (E_C) was modelled, empirically as:

$$E_C = 6.20 \times 10^{-12} f(\varphi)(MSF)^{-0.80} V^{2.35} D^{1.55} C^{-0.11} H_T^{-0.72} \tag{vi}$$

where,

$$f(\varphi) = \begin{cases} 0.99\left\{\sin\left(\frac{\pi}{2}\right)\left(\frac{\varphi}{\varphi_o}\right)\right\}^{0.58} & \text{for } 0° \leq \varphi \leq \varphi_o \\ 0.92\left\{\sin\left[\left(\frac{\pi}{2}\right)-\left(\frac{\pi}{2}\right)\frac{(\varphi-\varphi_o)}{90-\varphi_o}\right]\right\}^{4.30} & \text{for } \varphi_o \leq \varphi \leq 90° \end{cases} \tag{vii}$$

The authors also found the relationship [$\varphi_0 = 0.55(H_T)^{0.69}$] between orientation angle (φ_0) for maximum cutting wear rate (E_{Cmax}) and the target material hardness (H_T) for ductile materials (26).

Similarly, Tarodiya and Gandhi recommended the same approach for all the three investigated materials: AISI304L, HCCI and grey cast iron. They gave the empirical correlations and correlated the erosion wear with the experimental outcomes (48). Authors recommended the total wear, combination of cutting and deformation wears (26, 48). Similarly, Patil *et al.* developed the following correlation for erosion wear (E_W) of aluminium as a prime representative of ductile material, exhibiting its parametric dependence on slurry erosion (for aluminium):

$$E_w = 0.075\,\varphi^{0.12} C^{1.09} V^{3.55} D^{1.37} \tag{viii}$$

where, E_W is the erosion wear rate in terms of thickness dropping and φ is impact angle in degree. This empirical parametric relationship was obtained using regression analysis (27). Abouel-Kasem elaborated the erosive wear rate with the power-law relationship of particle size. Exponents to the particle size were different for different values of impact angles and for particle sizes above or below the critical particle size. Exponent with kinetic energies lower than threshold kinetic energy was found more than 1 (1.8 for 30° impact angle and 1.6 for 90° impact angle) and less than 1 (0.66 for 30° impact angle and 0.59 for 90° impact angle) for higher values of kinetic energies (49). Similarly, Padhy and Saini developed the correlation as a function of silt and operating parameters {silt size, silt concentration, jet velocity, operating hours} forecasting the efficiency loss of turbine brass buckets for its manufacturing industries. SigmaPlot® (version 10.0) software was engrossed for regression analysis (50). Grewal, Singh *et al.* developed the regression model implying the operating parameters of velocity, impingement angle and slurry concentration with their interactive terms also using the experimental data for erosion of CA6NM steel (31). Similarly, using the multiple linear regression models developed by Minitab® R14, regression equations were obtained forecasting the response of erosion wear of glass or epoxy composites filled with alumina filler materials. The parameters such as slurry concentration, contact angle and speed were considered for developed regression equations with their individual and interactive effects. The developed model was validated using the experimental data (51). Similarly, Khurana *et al.* obtained the correlations for efficiency loss of Turgo turbine having brass blades for its prediction with the function of silt and operating parameters through regression analysis on the Microsoft Excel software connecting to data received of experiments (52). Similarly, using the least square method with consideration of logarithmic of investigated parameters, experimental results were analysed for erosion wear of brass with high concentration slurries and empirical correlation for the same having the dependence on concentration and velocity was developed and validated (53). Regression mathematical models were developed in the form of equations for the output response as slurry erosive mass loss due to slurry erosion of single matrix fibre composite and hybrid matrix flexible composite made of jute fibre and natural rubber sheets. The parameters considered were packing sequence and slurry speed as well as concentration and the same was validated through experimental data (54). Anova and regression model including all the considered factors like building orientation, layer thickness and impact angles with their interaction effects too were developed for weight gain for fused deposition modelling processed polylactic acid (55).

Nguyen *et al.* developed the correlation for erosion rate with impact velocity using experimental outcomes. 'W' profile shape erosion mechanism was correlated and discussed with the back pressure imposed on SUS304 sample that was the highest at the centre and gradually decreased moving towards outer side. The same was simulated with particle trajectory on the sample (56).

3.1.1 Exponent Values

Exponent values confer more or less impression on the degree of dependence of any function on the related parameter(s). In this direction, numerous authors aligned their work in consonance of slurry erosion for different coated or uncoated materials instead of evolving intact correlations. Goyal *et al.* found the values of exponents of three operating parameters (velocity, particle size, slurry concentration) for power law linear regressions for bare and high-velocity oxy-fuel (HVOF) sprayed ceramic (chromia) coated CA6NM and CF8M turbine steels (57). The authors did similar work on HVOF deposited cermet (WC–10Co-4Cr) and ceramic (Al_2O_3-13TiO_2) coatings on CF8M (58). The authors also obtained and studied these values of exponents for the detonation-gun sprayed coatings of ceramics (Al_2O_3, Al_2O_3-13TiO_2) and cermets (WC-10Co-4Cr) on CF8M and correlated with their experimental outcomes (59, 60). Some authors also obtained and investigated these values of exponents for cermets (Cr_3C_2-NiCr, WC-Co-Cr) and cobalt-nickel-chromium-aluminium-yttrium coatings on CA6NM deposited by HVOF (61, 62). Similarly, Grewal, Agrawal and Singh computed the velocity exponents using the experimental data and investigated its dependence on slurry erosion. They found that composite coatings with 40% and 60% alumina content exhibit the least and highest influence of velocity respectively (22). The other authors, Kumar *et al.* also obtained the exponent values of nickel-based high velocity flame spray (HVFS) coatings namely Ni-20Al_2O_3 and Ni-10Al_2O_3-10TiO_2 on CA6NM for different operating parameters related to slurry erosion to check the extent of their influence (63). Similarly, Sharma, Kaur *et al.* also carried out erosion investigation of nickel-titania and nickel-titania-alumina HVFS deposited CA6NM steels with its bare counterpart and correlated the values of exponent for erosion parameters of velocity, slurry concentration and sand particle size with the experimental data (64). Rai, Kumar and Staubli correlated the normalised erosion by finding the values of constant and exponent of relative flow velocity, suspended sediment concentration, mean sediment size and time duration for all the six chosen materials (bronze, 16Cr-5Ni, 16Cr-4Ni, 13Cr-4Ni, plasma sprayed ceramic (chromia) coating on 13Cr-4Ni, HVOF applied cermet (WC-Co-Cr) coating on 13Cr-4Ni) and investigated the deviations of perceived erosion with predictable data. They also, investigated and studied the variations in evaluation of erosion and sediment parameter (65). Sharma, Kaushal *et al.* also obtained the values of exponent of erosion parameters for cermet (Cr_3C_2-25NiCr, WC-10Co-4Cr) coatings on AISI304 turbine steel and correlated with the experimental outcomes (66). Multiple linear regression equation was developed using Minitab® statistical software while investigating the slurry erosion performance of nickel-based cladding on AISI304 steel and correlated the erosion wear with distinct and selected operating parameters (67). For erosion wear, mathematical models of second order polynomial with regression analysis for carbon steel substrate and its hardfaced surface were developed. SPSS® statistical software package was applied to check the different coefficients of developed regression equations to 90% confidence level. Principal and interaction effect of parameters of rotational speed, erodent size, slurry concentrations and its temperature on the erosion wear interpreted and correlated with the experiments. Suitability of developed mathematical models was checked using the ANOVA technique (68). Similarly, during the investigation of polymeric spray paint film coated on AISI 5117 steel, linear regression model using Minitab® was obtained in the terms of slurry erosion input parameters for prediction of the response value as mass loss of the coated material and the same was validated and correlated with experimental outcomes (69). Similarly, Naveena, Sekhar *et al.* developed a linear regression mathematical model using R-squared method having parametric dependence of slurry concentration, rotational speed and particle size for the erosion wear of aluminium alloy Al6061 either uncoated substrate or plasma sprayed fly ash-alumina. The same was correlated with the experimental data and validated (70). Malfatti *et al.* developed the linear equations for the erosive wear rates of the HVOF deposited WC-10Co-4Cr coatings having different porosities on SS410 exhibiting different wear regimes with respect to testing period (71). Along these lines, we can say that rather to develop statistical equations for erosion wear due to slurry, exponent values of associated parameter(s) communicate an approximate notion about the severity of slurry erosion.

3.2 Mechanistic Mathematical Modelling

Numerous research studies have been carried out in the domain of mathematical analytical wear models based on theoretical analysis for erosion wear estimation. The mechanistic models in the form of erosion wear equations were developed analysing the mechanics of forces, pressures and other related things between the erodent particles and target materials. In some instances, experimental outcomes were also utilised partly for computing some constants in established wear equations related to target material properties and other factors. The significant mathematical wear models included in this article are enlisted in **Table I**.

The work will continue in Part II (72).

Acknowledgments

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Table I Mathematical Analytical Wear Models

Ref.	Author(s)	Year(s)	Parameter(s)	Remark(s)
			Erodent particles, target materials and other(s)	**Erodent shapes and other(s)**
(13)	Finnie	1960	M, V, φ, σ_p, ε, K_s, ω	Abrasive angular particles, a parameter which alters with the shape of erodents, not valid at or nearer to normal impact for ductile materials, equation of motions confers the expressions for stresses to find the initial fracture in brittle materials
(18, 19)	Bitter	1963	M, V, φ, V_{th} (σ_y, ρ_p, v_p, v_t, E_p, E_t), ϵ_D, ϵ_C	Spherical particles, deformation and cutting wear, integration of threshold velocities
(7)	Sheldon and Finnie	1966	V, R, ρ_p, X, l, V_B, v, E	Spherical particles as well as irregular and uneven shaped angular eroding particles assumed as spherical with fictitious radius, erosion behaviour of brittle materials based on Weibull flaw parameter
(20)	Neilson and Gilchrist	1968	M, V, φ, V_{th}, ϵ_D, ϵ_C	Integration of threshold velocity, total Erosion as ductile and brittle benefaction
(8)	Sheldon and Kanhere	1972	V, ρ_p, D, $H_{T\nu}$	Spherical particles
(5)	Finnie	1972	M, m, V, R, φ, I_p, p_H, ε, K_s	Spherical particles, particle rotation
(16)	Tilly	1973	D, D_{th}, V, D_{th}	Spherical particles, integration of threshold velocity and threshold particle size, total erosion as metal removal on indentation plus wear on fragmentation of particles
(24)	Grant and Tabakoff	1973	V, φ, R_T	Inclusion of tangential restitution ratio, erosion dependence on low and high impact angles as the two ways of erosion mechanism
(9)	Evans *et al.*	1978	V, R, ρ_p, H_T, K_C	Spherical particles, erosion behaviour of brittle materials
(10)	Hutchings	1981	V, ρ_p, ρ_t, H_T, ϵ_{DT}	Spherical particles at normal impact, integration of erosion ductility for instance of material removal

(*Continued*)

Table I Mathematical Analytical Wear Models

Ref.	Author(s)	Year(s)	Parameter(s)	Remark(s)
			Erodent particles, target materials and other(s)	Erodent shapes and other(s)
(14, 15)	Bergevin and Nesic	1984, 1991	M, V, φ, V_{cr}, P	Reworked on the Finnie model (13) for no erosion at normal impact, included the critical velocity
(11)	Hashish	1988	$V, R, \varphi, C_V (\sigma_y, \rho_p, R_f)$	Non-spherical particles, inclusion of roundness factor
(12)	Forder *et al.*	1998	$M, V, \varphi, R, C_V (\sigma_{tr}, \rho_p, R_f), D_V (\sigma_{tr}, \rho_t, R_f, v_p, v_t, E_p, E_t), \in_D$	Non-spherical (sub-angular) particles, deformation and cutting wear, inclusion of roundness factor
(29)	Patnaik *et al.*	2008	$V, \varphi, H_T, \rho_t, \eta_A$	Spherical particles, introducing the actual erosion efficiency for normal and oblique impact
(3)	Huang *et al.*	2008	$m, V, \varphi, \rho_p, D, n, \varepsilon_c, \in_{DT}, P_t, P_n$	Abrasive spherical particles, integration of critical plastic strain and erosion ductility, shape factor included for particle's abrasiveness (line and area cutting), deformation and cutting wear
(21)	Wang *et al.*	2009	$m, V, \varphi, H_T, D, \in_{DT}, E_P, E_T, R_s (E_P, E_T)$	Spherical particles, line and area cutting for abrasive particles, total erosion as benefaction of cutting wear and deformation plus fatigue
(34)	Biswas *et al.*	2009	$V, \varphi, H_T, \rho_t, \eta_A$	Square pyramidal particles (height and base equal to average grit size), introducing the actual erosion efficiency for normal and oblique impact
(6)	Huang *et al.*	2010	$V_m, C, D, \rho_p, \rho_l, n, R_{ed} (\rho_l, V_m, d, \mu), R_{ep}, \in_{DT}, P_t, P_n$	Abrasive spherical particles, line and area cutting for abrasive particles, deformation wear neglected for slurry pipeline due to low impact angle, integration of liquid viscosity and Reynolds numbers
(23)	Grewal *et al.*	2012	$V, n, E, G, e, N, \sigma_y$	Integration of strain hardening coefficient and shape factor, normal impact
(35)	Siddhartha *et al.*	2013	$V, \varphi, H_T, \rho_t, \eta_N$	Square pyramidal particles with variation in physical dimensions, not valid for impact angles less than 90°
(17)	Grewal *et al.*	2014	$K_E (m, V), R, H_T, X, r, a, v, K_C, P_{max}, Z, \sigma_y, \sigma_R, E_{eq} (v_p, v_t, E_p, E_t)$	Spherical particles, normal impact, computation based on contact-fracture theory

CRediT Authorship Contribution Statement

Yadav Yogesh Kumar: conceptualisation, formal analysis, investigation, methodology, writing – original draft. Patnaik Amar: visualisation, writing – review and editing. Singh Akant Kumar: visualisation, methodology, writing – review and editing. Sehgal Rakesh: visualisation, writing – review and editing. Sharma Siddhartha: supervision, visualisation, writing – review and editing.

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