Current Situation and Prospect of Erosion Wear

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Abstract. The material loss and equipment failure caused by erosion wear is a serious problem in solid-liquid mixture flow in the mechanical, metallurgy, energy, building materials, transportation, aviation, aerospace, military and other industrial departments. Therefore, understanding the erosion wear mechanism, the influencing factors, and how to set up mathematical model are very important. Since the 1950s, the research on the erosion wear made great development. The purpose of this paper is to give a comprehensive review about previous research work of erosion wear. Firstly, the mechanism and influencing factors of erosion wear are introduced. Secondly, the forces of particle caused by fluid are analysed and several erosion models which tested by experimental with good results are introduced. Thirdly, the method of erosion numerical simulation combining computer software and CFD theory is introduced. Finally, based on the conclusion, some useful conclusions are drawn and the future research direction is prospected.

1. Introduction

Erosion is a kind of wear and failure phenomenon that occurs when material is impacted by small and loose flowing particles. Among them, solid particle erosion can be divided into gas-solid erosion and liquid-solid erosion been seen everywhere in engineering. According to statistics, when an aircraft flies in dusty areas, the engine life can be reduced to 1/10 of the normal life. About 1/3 of the boiler piping accidents are caused by erosion wear. For a compressor, as long as the leading edge of the blade has a very small amount of material erosion, local stall can be cause because of a very small gap. The erosion at the position of elbow and reducing diameter in pipeline for air or oil transport can result in significant reduction of the pipeline life. The erosion wear at the valve orifice can affect the static and dynamic characteristic of the valve and result in the decrease of reliability about the system. For the pump the erosion wear of gear and blade leads to the increase of leakage and the decrease of volume efficiency. Especially, because of the particularity of the transport medium, the erosion of the components which washed by the flow is very serious for the mud pump in the construction industry, oil drilling, coal mining and thermal power station. Solid particle erosion wear is widely found in many industrial sectors such as machinery, metallurgy, energy, building materials, transportation, aviation, aerospace and military industry, becoming an important cause of equipment failure or material damage [1-5].

The erosion wear mechanism of particle is quite complex, involving the comprehensive theory of material mechanics, elastic mechanics, fluid mechanics, multiphase flow and so on. Erosion wear is not
only affected by the particle velocity, particle size, hardness, impact Angle and shape, but also the target material hardness, surface roughness, strength, toughness, the influence of the microstructure and chemical composition. Even for the same kind of materials of components, the erosion resistance of large change may occur because the environmental parameters are slightly changed.

Since Finnie [6] put forward the first erosion theory (micro-cutting theory) in 1958, the scholars have been devoted to the research of the erosion wear theory, proposing a large number of analysis methods and prediction models which are based on the experiments in an attempt to explain or predict the erosion behavior of materials. This paper reviews the research work of various erosion theories from the aspects of erosion mechanism, factors affecting erosion, the forces of particle caused by fluid, erosion models tested by experiments with good results and the development simulation method for erosion based CFD. Finally, the future erosion research work is prospected.

2. Erosion wear mechanism

At present, it is generally accepted that the erosion wear of solid particles has two main mechanisms, which depend on the ductility of the surface. For ductile materials, the main mechanisms are micro-cutting and surface hardening. For brittle materials, it is generally believed that erosion is caused by the formation of cracks. The understanding on the mechanism of erosion wear is mainly developed from the following theories.

2.1. Erosion theory of ductile materials

2.1.1. Micro-cutting theory. Finnie [6] proposed the microscopic geometric model of ductile materials. He believed that the erosion of ductile materials was the result of micro-cutting. A crater was formed when a particle hit the surface with a low impact angle. Then the impacts from other particles made the crater larger and larger to form deposited materials around the crater, which were eventually cleared away by constant particle collisions.

2.1.2. Deformation and wear theory. With the view of energy balance, Bitter [8] proposed the deformation wear theory through the energy analysis of the two stages that the particles were being rushed in and being squeezed out during the process of corrosion wear. The erosion wear can be divided into deformation wear and cutting wear. He considered that it may produce elastic deformation or plastic deformation depending on whether the impact stress reached the yield strength of the material, when the particle impacted the surface. Repeated impact would produce work hardening and increased the elastic limit of the material until the stress exceeded the strength of the material to form cracks.

2.1.3. Forging extrusion theory. Levy et al. [9] studied the erosion of plastic materials under high impact angle and researched the dynamic process of erosion wear with step erosion test method and single particle tracing method. No matter at large angle or small angle, due to the constant impact of abrasive particles, the target surface material was constantly squeezed, thus resulted in small, thin, highly deformed lip pieces. The large strain forming a lip, occurs in where a very thin surface layer which is heated to the annealing temperature of the metal due to adiabatic shear deformation. There is a work hardening zone under the material due to plastic deformation. Once this hard subsurface is formed, it will facilitate the formation of the surface lip. Under the repeated impact and extrusion deformation, the lip will peel off from the surface of the material.

2.2. Erosion theory of brittle materials

Different from the mechanism of ductile materials, it is generally believed that erosion is caused by the formation of cracks in brittle materials. When particles hit the surface of brittle materials, transverse and radial cracks will occur, and then the cracks will continue to become bigger and divide the surface into smaller pieces, which will be removed by the hitting from other particles [10-11].
3. Influencing factors of erosion

The erosion resistance of a material is inversely proportional to the weight or volume loss (commonly referred to as erosion rate) caused by particles per unit weight which impact the surface of the material under certain operating conditions. The erosion rate of a material is a system parameter affected by the working environment. It is not only affected by the velocity, particle size, hardness and shape of the incident particle, but also affected by the physical and mechanical properties of the target materials. The erosion resistance of parts made of the same material may change greatly if the environmental parameters are slightly changed. A material with good erosion resistance in one condition may not be erosion resistant in another condition. Therefore, it is necessary to have a comprehensive understanding of the erosion factors which affect the material and master the laws in order to give full play to the material potential. From the perspective of erosion mechanism, these influencing factors should be studied from the aspects of environment, particle performance and material performance [12 -15]. Environmental parameters include incident angle, particle velocity and concentration, environmental temperature, etc. Particle performance parameters include particle size, shape, hardness, density, etc. The properties of target material include hardness, surface roughness, strength, toughness, microstructure and chemical composition.

3.1. Influence of environmental parameters

Impact incidence angle is the angle between the target surface and the impact velocity direction of solid particles. It is show that the greatest erosion usually occurs at a 20 o- 30o impact angle for ductile materials due to the fact that the cut lip is more granular at a lower impact Angle. However, for brittle materials, the greatest erosion occurs at a normal angle (90o), and the main reason for the erosion of brittle materials is the formation of cracks [12, 16]. Therefore, researchers propose a variety of angle functions, most of which are empirical and only valid under limited conditions. In addition, Yoganandh et al. [17] conducted tests on influencing factors of erosion wear by using L9 orthogonal array. It showed that for the contribution rate of erosion, velocity was up to 60%, the impact angle was up to 21%, and the particle concentration and pH distribution were up to 10%.

Particle velocity is mainly affected by fluid velocity and the effect on erosion is very great. This is due to high impact velocity, high kinetic energy and high collision frequency between particles and the wall surface. Particle velocity follows a latent relationship with erosion, which is commonly represented in erosion models by the velocity index n, whose value can vary from 0.3 to 4.5. Moreover, some scholars believe that whether this index is constant depends on the hardness of the eroded material [18, 19], and the typical value of n is between 1.6 and 2.6.

Particle concentration is generally expressed by particle mass flow rate or volume. Most studies show that the erosion rate increases with the increase of particle concentration. Particle concentration increase refers to the increase in the number of solid particles which hit the surface of the target material. So, at a higher concentration, the mass loss on the surface of the target material is greater [20].

The influence of temperature on material erosion is related to the properties of target material, which is hard to describe by simple laws. Some experimental results show that the erosion rate increases with the increase of temperature. However due to the surface oxidation of the target material, the appearance of oxidized abdomen increases the erosion resistance of the material. Therefore, some researchers suggest to use the semi-melting temperature of the material as a criterion for determining whether the erosion wear has increased.

3.2. Influence of particle performance

For particles size, generally larger particles have higher mass than smaller particles, and have greater kinetic energy under the same speed, density, hardness and other conditions, that will lead to higher erosion. In contrast, smaller particles are more susceptible to turbulence, more responsive to fluctuations in the fluid and more efficient in momentum exchange between the fluid and the particles is more efficient. Many scholars have studied the effect of erosion wear for the same material with different particle sizes, the main conclusion is that the larger the particle size is, the higher the erosion rate will
be, and the two are directly proportional to each other [20,21]. However, when the particle size increases to a certain critical value $D_C$, the erosion wear rate of the material almost does not increase with the increase of the size, which is known as the "size effect". The $D_C$ value changes with the different target material and erosion conditions [22].

Particle shape is one of the significant factors affecting the degree of erosion. Finnie [7] believed that the particle shape was also a main factor affecting erosion, and the influence of particles with different shapes on erosion wear was more than 10 times. Particles can be simply divided into angular particles and circular particles. But because of the irregular shape of three-dimensional particles to quantify them is extremely difficult. One such method uses the roundness factor $F$, that is the ratio of the perimeter to the projected area. Levy and Chik [23] used two different particle shapes to do experiments and erosion results show that angular particles were four times larger than circular particles. Subsequently, some successful correlation experiments of the roundness factor erosion rate described by Hutchings [24] appeared. Walker et al. [25] measured the impact of particles with different shapes on the erosion rate of white cast iron by a large Coriolis force tester and studied the difference between two methods to measure the roundness factor of particle shape.

3.3. Influence of target material properties

The characteristics of target material mainly depending on its hardness, surface roughness, strength, toughness, microstructure and chemical composition play a decisive role in the erosion rate of material. It is generally believed that erosion wear decreases with the increase of surface hardness of the target material [15, 26-27]. Gadhikar et al. did some experiments with both heat-treated and unheat-treated 23-8N steel. The results of heat treatment showed that the ductility and impact toughness increased with the increase of hardness, and the yield strength decreased, which led to the increase of anti-erosion wear ability. It was pointed out that the microstructure was one of the most important parameters to affect the erosion behavior of materials.

4. The forces on particle and erosion model

4.1. The forces on the particle

Particles moving together with the fluid will be subjected to the fluid forces and the main forces can be divided into the fluid drag force, pressure gradient force, virtual mass force and gravity. In addition, for sub-microscale particles it is necessary to consider the Brownian forces [28] and Saffman lift which is also named lateral lift [29]. Saffman lift is a shear lift in the direction of relatively high velocity on the surface of the particle due to unbalanced pressure distribution caused by high velocity gradient. The particle rotation has an important effect on its trajectory in the fluid, especially for large and heavy particles with a high moment of inertia. In this case, if the particle rotation is ignored in the simulation, the particle trajectory obtained may be significantly different from the actual trajectory. Therefore, it is necessary to consider the Magnus force which is also named rotational lift, generated by particle rotation [30].

Based on Newton second law, the main force models of particles is as follows. It is worth noting that the following mechanical equation is based on force per unit mass.

$$\frac{d\vec{v}_p}{dt} = \vec{F}_D + \vec{F}_P + \vec{F}_{VM} + \vec{F}_G + \vec{F}_O$$

(1)

Where, $\vec{v}_p$ is particle velocity, $F_D$ is drag force of fluid on particle, $F_P$ is pressure gradient force, $F_{VM}$ is virtual mass force, $F_G$ is gravity and $F_O$ is other forces.

Drag force ($F_D$): The drag force of a fluid on a particle is the most important force on the motion of a particle. The calculation formula is as follows:

$$\vec{F}_D = \frac{\vec{v} - \vec{v}_p}{\tau_r} = 18 \frac{C_p \mu}{24 \rho_p d_p \rho_r} \frac{Re}{d_p} (\vec{v} - \vec{v}_p)$$

(2)
Where \( v \) is the fluid speed, \( v_P \) is particle speed, \( \tau_r \) is the particle relaxation time [31], \( C_D \) is the resistance factor, \( \mu \) is the molecular viscosity of the continuous phase, \( \rho_P \) is the particle density, \( d_P \) is phase diameter, \( \rho_f \) is the fluid density and \( Re \) is the relative Reynolds number.

\[
\text{particle relaxation time: } \tau_r = \frac{\rho_P d_P^2}{18 \mu} \frac{24}{C_D Re}
\]

\[
\text{relative Reynolds number: } Re = \frac{\rho_P d_P |v - v_P|}{\mu}
\]

Pressure gradient force (\( F_P \)) is generated by the pressure distribution of the fluid around the particle in the following form:

\[
\vec{F}_P = \frac{\rho_f}{\rho_P} \vec{v}_P \nabla \vec{v}
\]

Virtual Force (\( F_{VM} \)) refers to the additional Force acting on the particles when the fluid around the particles accelerates the movement.

\[
\vec{F}_{VM} = \frac{1}{2} \frac{\rho_f}{\rho_P} \frac{d}{dt} (\vec{v} - \vec{v}_P)
\]

When the density of the fluid is much lower than the density of the particles, the virtual mass and pressure gradient forces can be neglected. When the ratio of fluid density to particle density is close to 1, the virtual mass force and pressure gradient force cannot be ignored. It is suggested that virtual mass force and pressure gradient force should be considered when the density ratio is greater than 0.1.

Gravity (\( F_G \)) and buoyancy can affect the motion of a particle, as defined by the following equation:

\[
\vec{F}_G = \frac{\rho_f - \rho_P}{\rho_P} \vec{g}
\]

Unlike pressure gradient force and virtual mass force, density difference is important for gravity.

Other forces (\( F_O \)), including shear lift (\( F_{SL} \)), Brownian force (\( F_B \)), Muggle force (\( F_M \)), etc., are selected for mathematical modeling according to specific conditions.

The velocity can be computed by integrating the acceleration and the displacement be computed by integrating the velocity, so that the trajectory of the particle can be determine.

### 4.2. Rebound model of particle wall collision

With every hitting on the wall, the particles will lose some momentum. The recovery coefficient is a measure of momentum loss, which is defined as the ratio of the velocity component after the particle impact to the velocity component before the impact. The model of particle rebound is defined as a function of the impact angle and is usually established by experimenting with different materials.

Grant et al. [32] first introduced an experimental collision model based on the collision between silica sand and target material-Aluminum 2024. The particle diameter was 200μm, and the impact process of the particle was photographed and recorded at high speed.

\[
e_n = \frac{v_n}{v_n} = 0.993 - 1.76\theta + 1.56\theta^2 - 0.49\theta^3
\]

\[
e_t = \frac{v_t}{v_t} = 0.998 - 1.66\theta + 2.11\theta^2 - 0.67\theta^3
\]

Where \( e_n \) is the normal rebound coefficient, \( e_t \) is the tangential rebound coefficient, \( v_n \) is the normal velocity component before the collision between particles and the wall, \( v_n \) is the normal velocity component after the collision between particles and the wall, \( v_t \) is the tangential velocity component before the collision between particles and the wall, \( v_t \) is the tangential velocity component after the collision between particles and the wall, and \( \theta \) is the angle between particle trajectory and the wall before the collision.
Forder et al. [33] introduced an experimental collision mode based on the collision between AISI4130 carbon steel and sand particles with diameters of 150-300\(\mu m\)

\[
e_n = \frac{v_n}{v_{ni}} = 0.988 - 0.78\theta + 0.19\theta^2 - 0.024\theta^3 + 0.027\theta^4
\]

(10)

\[
e_i = \frac{v_i}{v_{ri}} = 1 - 0.78\theta + 0.84\theta^2 - 0.21\theta^3 + 0.028\theta^4 - 0.022\theta^5
\]

(11)

The tangential and normal components of the velocity after collision can be calculated by the tangential and normal rebound coefficients above. These two models are often used in recent research of the erosion wear.

4.3. Research on theoretical model of erosion

Since Finnie [6] put forward the first erosion theory (micro-cutting theory) in 1958, the scholars have been devoted to the research of the erosion wear theory, proposing a large number of analysis methods and prediction models which are based on the experiments in an attempt to explain or predict the erosion behavior of materials. Meng et al. [34, 35] reviewed the erosion calculation models before 1995 analyzing the origin, content and applicability of most of the wear models and equations in the literature. So far, there is no general calculation model that can fully and comprehensively reveal material erosion.

Zhang [36] et al. compared Finnie and other four erosion calculation models by combining experiments and CFD simulation with direct impact experiments in both liquid-solid and air-solid flows. The results showed that the E/CRC model of the Erosion Corrosion Research Center and the model developed by Oka et al. had the least error. Darihaki et al. [37] simulated the erosion behavior of mud flow in throttling geometry by combining experiments and simulations. They compared the simulation results of 5 erosion calculation models with experiments’ results and found that the model developed by Mansouri et al. was more accurate in calculating mud erosion rate of throttling geometry. These erosion models are described below.

Most erosion equations introduce erosion rate (ER) in the form of erosion, that is, the ratio of the mass of the material removed from the surface to the mass of the particle hitting the wall. Erosion rate can be converted into other forms of erosion in different units.

Ahlert [38] conducted impact tests on AISI 1018 steel to study the influence of particle collision angle and surface humidity on erosion and derived the erosion model (E/CRC).

\[
ER = C(HB)^{a_{39}} F_s v_i f(\theta)
\]

(12)

\[
f(\theta) = a_1\theta + a_2\theta^2 + a_3\theta^3 + a_4\theta^4 + a_5\theta^5
\]

(13)

Where \(C\) is the wall material constant. \(HB\) is the Brinell Hardness value of the wall material. \(F_s\) is the particle shape constant and the values of full circle, semi-circle and sharp particles are 0.2, 0.53 and 1 respectively. \(v_i\) is the collision velocity. \(f(\theta)\) is the collision angle function. \(n\) is the collision velocity index is an empirical constant.

Oka et al. [18, 19] proposed an erosion equation including more parameters after conducting experiments under a large number of test conditions.

\[
ER = 10^{-8} \rho_w f(\theta) E_{w0}
\]

(14)

\[
E_{w0} = K(Hv)^{k_1} \rho_v^{k_2} \left(\frac{D'}{D}\right)^{k_3}
\]

(15)

\[
f(\theta) = (\sin \theta)^{k_4} (1 + Hv (1 - \sin \theta))^{k_5}
\]

(16)

\(E_{w0}\) is the volume erosion rate under the normal impact angle, taking mm\(^3\)/kg as the unit. \(Hv\) represents the Vickers hardness of the wall material in GPa as the unit. \(k_1\) and \(k_2\) depend on the particle and wall material properties, while \(K, k_3, \nu'\) (reference collision velocity) and \(D'\) (reference particle diameter) only depend on the particle properties.

Mansouri et al. [39] developed the following erosion equation based on direct impact tests of liquid-carried particles on stainless steel (SS316).
\( ER = C(HB)^{a_{00}} f(\theta)w_p^a \)  

(17)

\( f(\theta) = A(\sin \theta)^{a_1}(1 + Hv^a_2(1 - \sin \theta))^{a_2} \)  

(18)

Combining the empirical method with mechanical method, Arabnejad2015 et al. [40] established a semi-mechanical erosion model considering shear and deformation, which was consistent with the experimental data.

\[
ER = ER_C + ER_D
\]

(19)

\[
ER_C = \begin{cases} 
C_sF_3v_p^{a_1}\sin(\theta)[2K\cos(\theta) - \sin(\theta)]/2K^2 & ; \theta \leq \tan^{-1}(K) \\
C_sF_3v_p^{a_1}\cos^2(\theta)/2 & ; \theta > \tan^{-1}(K) 
\end{cases}
\]

(20)

\[
ER_D = C_sF_3(v_p\sin(\theta) - V_{th})^2
\]

(21)

Where \( ER_C \) and \( ER_D \) are respectively the cutting and deformation erosion rates. \( F_s \) is the particle shape constant and the values of full circle, semi-circle and sharp particles are 0.2, 0.53 and 1 respectively. \( V_{th} \) is the threshold velocity of deformation erosion.

5. Progress of erosion numerical simulation

The erosion simulation calculation based on CFD is mainly divided into three parts, which are internal flow field calculation, particle trajectory tracking and erosion calculation using erosion equation [41]. Navier-Stokes equation and turbulence model are generally used to solve the pressure, velocity, component and turbulent kinetic energy of the flow field. Secondly, the discrete phase model based on Lagrange-Euler method is used for particle track tracking calculation, and relevant information such as collision velocity, collision angle and collision position are recorded. Finally, the appropriate erosion model is used to calculate the erosion of particles with the relevant parameters obtained by previous simulation.

The erosion simulation researches based on CFD theory are initially under the assumption of sparse flow with low particle concentration, ignoring the interaction between particles and the effect of particles on the flow field and usually use discrete phase (DPM) to conduct particle motion and erosion rate calculation. Based on CFD erosion simulation, Mazumder [42] adopted discrete phase model (DPM) for particle motion modeling, ignoring the interaction and rebound between particles to study the influence of the velocity of fluid and gas on the maximum erosion position in a U-bend. Njobuenwu et al. [43] used CFD erosion model, combining Lagrange particle tracking program with erosion model and considering the interaction between particles to predict the erosion of low-concentration particle flow in a 90° square cross-section bend, and the wall surface and the model ran well. Chen et al. [44] proposed a comprehensive method to estimate the erosion of elbow of gas, liquid and sand multiphase flow. The method combined the mechanical analysis of multiphase flow with the erosion prediction method based on single-phase CFD to simplify the erosion problem of multiphase flow, and the simulation results were basically consistent with the literature data. Zhang et al. [36] adopted the particle-wall rebound model based on CFD and ignoring the interaction between particles. They compared the particle velocity and erosion obtained by simulation calculation in water and air with the measured data. The results show that the calculated results were in good agreement with the numerical results. Y. Zhang [45], considering the turbulence velocity distribution in the near-wall area to the influence of particle collision velocity, proposed a near-wall correction method for interaction with turbulent particles, and improved the CFD computational model based on particle erosion. However, the model was still suitable for sparse flows with low particle concentration.

In recent years, with the progress of particle simulation technology, discrete element method (DEM), as one of the mainstream discrete modeling technologies, can provide the dynamic information of a single particle and simulate the liquid-solid two-phase flow from dense to sparse, which has great potential in particle erosion research. Zhang et al. [46] described the particle motion trajectory using DEM, calculated the interaction between solid and liquid based on the buoyancy model of fluid density,
and characterized the erosion severity by the particle-wall interaction. M. Varga et al. [47] used CFD-DEM method to simulate the particle flow in the feed pipeline, and also conducted long-term wear measurement. The simulation prediction results were consistent with the high wear rate of erosion test. Chu and Yu [48-51] combining DEM code with CFD software, successfully applied it to particle fluid flow simulation in complex three-dimensional systems. By combining DEM with CFD, Jukai et al. [52] proposed a two-phase flow erosion prediction model for elbow pipeline based on CFD, considering the interaction between liquid and particle, particle and particle, and particle and wall. The standard wall function was adopted for the near-wall area, and the Hertz Mindlin (no slip) model was adopted for the particle-to-particle and particle-to-wall areas [53]. Avi Uzi [54] et al. proposed a new concept of one-dimensional erosion model (ODEM). ODEM is a statistical distribution function that combines one-dimensional flow model with the description of particle-wall collision characteristics, including collision frequency, circumference Angle, impact Angle and impact velocity. Gianandrea Vittorio Messa [55] et al. proposed an innovative method for erosion prediction based on CFD and combining Euler-Euler and Euler-Lagrange. Compared with the standard method, the advantage of this method lies in its numerical efficiency, because the Lagrange description of solid phase is limited to the specific subdomain of the most vulnerable surface. S. Lain et al. [56], combining the appropriate turbulence model with fully two-way coupling model, considering the rotation of the particle movement and force, and considering the surface roughness and the collision between particles, carried out the calculation of four-direction coupled erosion wear.

In general, through user programming correction algorithm to consider the influence of particle collision, particle motion on fluid, near-wall turbulence model, wall roughness and other factors, the simulation calculation based on CFD develops towards a faster and more accurate direction.

6. Conclusion
Published research on erosion mainly focuses on the impact of particle size, angle, velocity and concentration on the erosion. The erosion model established is an empirical formula combining theory and experiment under certain assumptions and with specific material objects.

There are few researches on the influence of the surface condition of the target material against corrosion wear. Therefore, it is necessary to study the influence of different surface conditions against corrosion wear, such as surface roughness, toughness, strength, microstructure and chemical composition.

The preconditions about whether to consider the force of particles on the liquid, the force between particles and the secondary collision between particles, need to be further studied.

The influence of the temperature and viscosity of the liquid on the trajectory of particles is seldom studied.

The trend is to combine CFD theory with ODE or other theories and to implement simulation with user-defined function modification models.

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