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Research Letter

Erosion-Oxidation Response of Boiler Grade Steels: A Mathematical Investigation

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A ductile erosion model embodying the mechanisms of erosion involving cutting wear and repeated plastic deformation has been developed to predict erosion rates of boiler grade steels. The issue of erosion-oxidation interaction has also been addressed to further predict the mass loss resulted from this composite mechanism. A deterministic formalism for the kinetics of oxide-scale growth and a probabilistic approach to characterize the material loss are employed to describe simultaneous actions of high-temperature oxidation and mechanical erosion. The model predictions are in good agreement with the published data.

1. INTRODUCTION

Erosion is a process by which material is removed from the layers of a surface impacted by a stream of abrasive particles. The magnitude of the wear is quantified by the volume or mass of the material that is removed by the action of the impacting particles. In coal-fired boilers, ash particles collide with the surface of the boiler steel components (air preheater, economizer, and super-heater tubes) resulting in considerable erosion of metallic materials. Such erosion, together with the processes of blocking, fouling, and corrosion, shortens the service life of the boiler components. The resulting penalty is not only the cost of replacing the components but also the cost of stoppage of power production. It is desirable, therefore, to be able to predict the rate of erosion of the boiler components in order to systematically plan the maintenance and/or replacement schedules of these components to avoid forced outages [1–5].

High-temperature erosion, which involves the conjoint action of high-temperature oxidation and damage due to solid particle impact, is a complex process. Material damage occurs through the interaction of both oxidation and erosion, with metal recession rates often enhanced as a result of the synergetic effect of these two processes. In this paper, mathematical investigations have been carried out on the basis of a ductile erosion model to characterize and quantify the wear behavior and mechanism of various boiler grade steels. The erosion-oxidation synergetic impact is also modeled to characterize the material damage in a high-temperature-oxidizing environment based on a composite deterministic-probabilistic modeling framework.

2. MATHEMATICAL SIMULATION

There are three important phenomena by which metal is removed by the impacting particles at elevated temperature:

(i) removal of material due to cutting wear,

(ii) removal of material due to repeated plastic deformation,

(iii) effect of temperature on tensile properties of the material.

The first two phenomena are applicable to erosion at room temperature.

2.1. *Mechanism of cutting wear*

An ash particle, that strikes the surface at an acute angle and at a velocity greater than the critical velocity needed for the penetration of the material's surface, removes some material in a process similar to the cutting action of a machine tool (micromachining action). At the impact location, the particle loses a fraction of its kinetic energy to the target

material in the form of heat and energy for deformation of the surface. When the shear strain exceeds the elastic strain limit of the target material, the particle penetrates the surface of the material and ploughs along the surface, removing material.

In the case of cutting wear, the material's resistance to deformation needs to be overcome by the impacting particles to penetrate the surface of the material. The differential equation of motion for the depth of penetration is given as [1–3]

$$m_p \frac{d^2L}{dt^2} = -\pi \frac{d_p}{2} Lc\sigma_y, \tag{1}$$

where L is the depth of penetration, m_p is the mass of the particle, d_p is the diameter of the particle, t is the time, σ_y is the yield stress of the target material, and c is a particle shape factor. For sphere particles, shape factor is equal to 3.

The erosion rate due to cutting wear ε_c, defined as the ratio of the mass of the material eroded (m), from the target surface to mass of the impacting particle (m_p), is given by the following equation [1–3]:

$$\varepsilon_c = \frac{m}{m_p} = \frac{k_c\,\rho_m \rho_p^{3/2}\, d_p^3\, v^3 \sin^3\beta}{3^3 \sigma_y^{3/2} (\pi \rho_p (d_p^3/6))} = \frac{k_1\,\rho_m \rho_p^{1/2}\, v^3 \sin^3\beta}{\sigma_y^{3/2}}, \tag{2}$$

where V and β are the impacting velocity and angle of the particle, respectively. ρ_m and ρ_p are the densities of the target material, and the particle K_c and K_1 are constants [1–3].

2.2. Mechanism of plastic deformation wear

During particle impact, the loss of material from an eroding surface may occur as a consequence of a composite sequential mechanism similar to a combined process of extrusion-forging mechanism. The extruded platelets from shallow craters made by the impacting particle are further forged into a strained condition. Because of the high-strain rates, adiabatic shear heating occurs in the surface region immediate to the impact site. The kinetic energy of the impacting particles is sufficient to generate considerably greater force being imparted to the metal than is required to create platelets on the surface and as a consequence, a work hardened zone formed, and steady state erosion begins.

Particle kinetic energy, responsible for extrusion-forging process during plastic deformation, is given as [1–3]

$$E_1 = \frac{1}{2}\frac{\pi d_p^3}{6}\rho_p\, V^2 \sin^2\beta = \frac{\pi}{12}\rho_p d_p^3\, V^2 \sin^2\beta, \tag{3}$$

where d_p and ρ_p are the particle diameter and density, respectively, and V and β are the particle incident velocity and angle, respectively. The final expression for the erosion rate, due to plastic deformation, ε_p, is [1–3]

$$\varepsilon_p = \frac{m}{m_p} = \frac{K_p \rho_m \rho_p^{3/2} d_p^3\, V^3 \sin^3\beta}{H_V^{3/2} (\rho_p \pi d_p^3/6)} = \frac{K_2 \rho_m \rho_p^{1/2}\, V^3 \sin^3\beta}{H_V^{3/2}}, \tag{4}$$

where K_2 is a constant [1–3].

2.3. Overall erosion rate

It is difficult to predict accurately the proportions contributed by each of the two mechanisms to the overall material loss. However, the overall erosion rate, combining the cutting and plastic deformation wear mechanisms, may be then given by the following equation [1–3]:

$$\varepsilon = \frac{K_3 \rho_m \rho_p^{1/2}\, V^3 \sin^3\beta}{\sigma_y^{3/2}}, \tag{5}$$

where K_3 is a constant pertaining to erosion modelling of ductile metal surfaces impacted by fly ash.

2.4. Model for erosion-oxidation interaction

Material removal from a brittle oxide surface on a ductile substrate at high temperature is due to a composite mechanism, involving fracture, chipping, oxide spallation at the metal-oxide interface, cutting wear, and plastic deformation of metal substrate. Following the general oxidation law, the thickness of the oxide layer "δ" formed during time "θ" is given as [6, 7]

$$\delta = K\theta^n, \tag{6}$$

where K and n are mechanism dependent kinetic parameters. K generally being related to temperature, through Arrhenius relationship:

$$K = Ae^{(-Q/RT)}, \tag{7}$$

where A is an experimentally determined Arrhenius constant (preexponential factor), Q is the activation energy, R is the universal gas constant, and T is the absolute temperature.

Erosion can be described as a stochastic phenomenon. In the spatial domain, individual erosion events take place in a random manner. It is assumed that the instantaneous number of events on the entire surface can increase deterministically as a linear function of time. The average oxide-scale thickness, $\langle\delta\rangle$, under the influence of erosion, is given by the following dimensionless equation [6, 7]:

$$\langle\delta\rangle = \frac{nK}{(F\pi\sigma^2)^n}\gamma(n, F\pi\sigma^2\theta), \tag{8}$$

where $F\pi\sigma^2\theta$ represents dimensionless time, F is the average dimensional flux of impinging erodent, and σ is the radius of erosion footprint. "γ" is the incomplete gamma function and is given by [6, 7]

$$\gamma(\xi, x) = \int_0^x u^{\xi-1}\exp(-u)du. \tag{9}$$

The following mass loss equation is derived from the above equation to quantify the erosion under the influence of oxidation:

$$\Delta M(\theta) = (1 - f_m)\rho_0\langle\delta\rangle - f_m F\pi\sigma^2\rho_0 \int_0^\theta \langle\delta\rangle d\theta, \tag{10}$$

where $\Delta M(\theta)$, f_m, and ρ_0 are total erosion loss, mass fraction of oxide associated with the steel/alloy, and densities of individual oxides (NiO, Fe_2O_3, and Cr_2O_3), respectively.

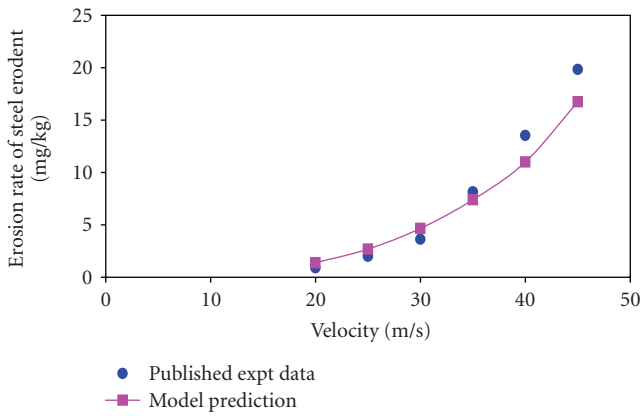

Figure 1: Variation of erosion rate with impingement velocity for 1.25 Cr-1Mo-V Steel (impingement angle = 30° and at room temperature).

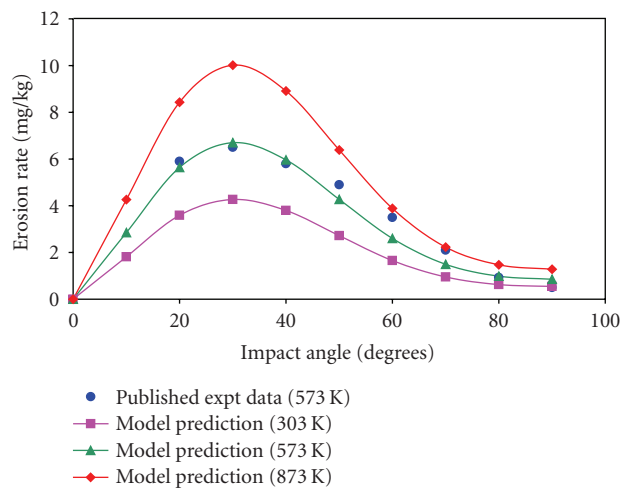

Figure 2: Variation of erosion rate with impingement angle for Carbon steel (room temperature, and elevated temperatures 573 K and 873 K).

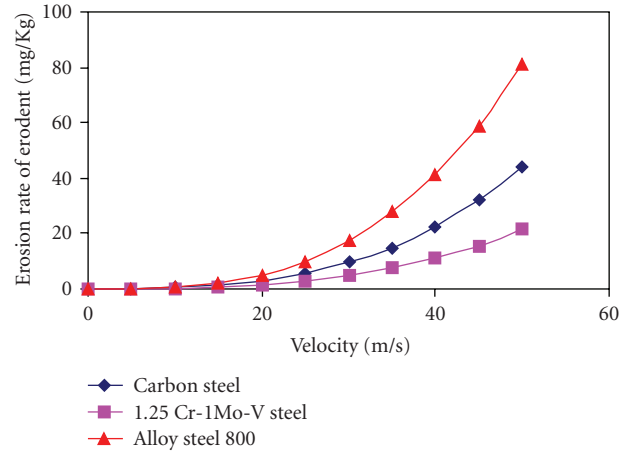

Figure 3: Variation of erosion rate with impingement velocity for different grades of steel (room temperature and impingement angle = 30°).

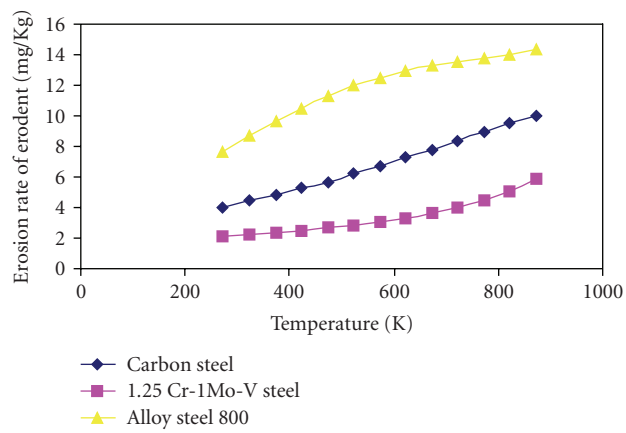

Figure 4: Variation of erosion rate with temperature for different grades of steel (impingement velocity = 20 m/s and impingement angle = 30°).

3. RESULTS

The erosion rates have been computed as function of ash particle impingement velocity, impingement angle, percentage silica in the ash sample, average density of ash particles, density of the steel component, yield stress of the steel component, and temperature of the steel component. The computations have been carried out for three boiler grade steels, namely, carbon steel, 1.25 Cr-1Mo-V steel, and alloy steel 800.

Some typical results of model predictions are discussed here. Figure 1 depicts the erosion rate (mg/kg of erodent) as a function of impact velocity for a given impingement angle of 30° and at room temperature for 1.25Cr-1Mo-V steel. The simulated result is validated with the published literature [1, 2] and is found to be in good agreement. Figure 2 shows the erosion rate as a function of impingement angle for carbon steel at different temperatures of the substrate, that is, 303, 573, and 873 K, respectively. The prediction of temperature dependent erosion is also validated with the published data [1, 2]. It is observed that for low values of impingement angle, the erosion rate increases with an increase in the impingement angle, and the maximum erosion rate occurs with impingement angle between 20°–40°. Thereafter, the erosion rate decreases. This has also been validated with the published data. The erosion rate with variation of impact velocity for the three steels is shown in Figure 3, while Figure 4 shows the change in erosion behavior with change in the temperature of the substrate. It is observed that 1.25 Cr-1Mo-V steel shows least erosion rate (or maximum erosion resistance), whereas the alloy steel 800 has the maximum erosion rate (or least erosion resistance). Figure 5 shows the erosion behavior with respect to silica content of 55% and 70% in the ash. It is seen that an increase of 15% silica in the

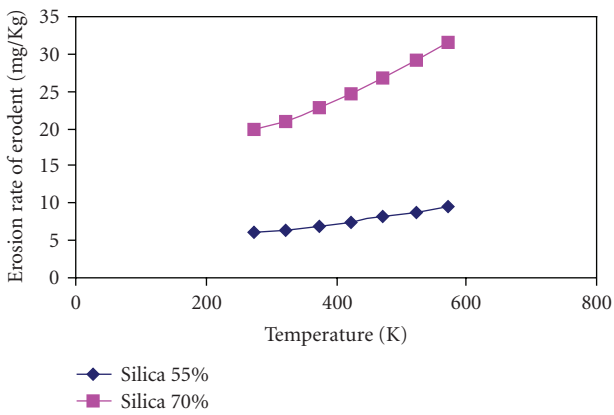

Figure 5: Effect of silica content on the erosion rate for carbon steel (impingement velocity = 30 m/s, impingement angle = 30°).

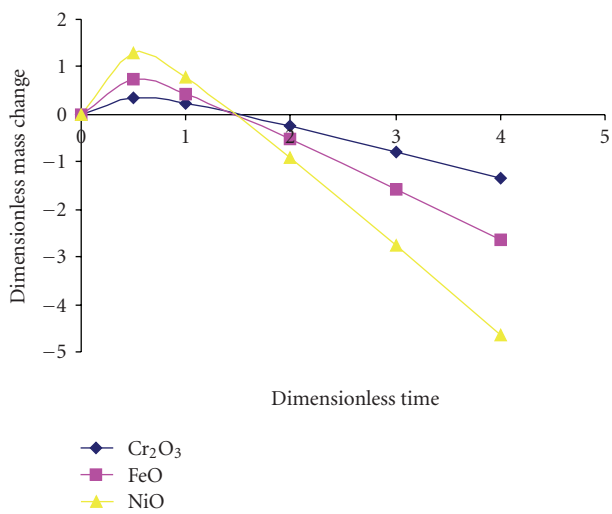

Figure 6: Variation of dimensionless mass change with dimensionless time for alloy 800 steel for different oxides.

ash results in 2–3 times enhancement in the erosion rate. A mass loss graph is shown in Figure 6 depicting dimensionless mass change as a function of dimensionless time. Erosion losses of three different oxides, namely, chromium, iron, and nickel oxides for alloy steel 800 are shown under solid particles impact. The quantitative mass loss prediction is verified with the published data [6, 7].

4. CONCLUSION

A mathematical model has been developed to predict the erosion rate for fly ash particles impingement on typical boiler grade steels. Stochastic approach is employed to model erosion-oxidation interaction phenomena. The following conclusions are drawn:

(i) erosion rate increases monotonically with an increase in impact velocity for a given impingement angle and temperature of the substrate;

(ii) erosion rate is maximum for impact angles in the range of 20°–40° for a given velocity and temperature;

(iii) the erosion rate is significantly enhanced with an increase in silica content of the ash;

(vi) erosion rate of nickel oxide is faster with regard to iron and chromium oxides, which is attributed to the relatively faster growth of nickel oxide with respect to other oxides.

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