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Monitoring acoustic emission (AE) energy in slurry impingement using a new model for particle impact

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ABSTRACT

A series of systematic impact tests have been carried out to investigate the influence of particle size, free stream velocity, particle impact angle, and nominal particle concentration on the amount of energy dissipated in a carbon steel target using a slurry impingement erosion test rig, as indicated by the acoustic emission (AE) recorded by a sensor mounted on the back of the target. Silica sand particles of mean particle size 152.5, 231, and 362.5 μm were used for impingement on the target at angles varying between 30° and 90° while the free stream velocity was changed between 4.2 and 12.7 m/s.

In previous work by the authors, it was demonstrated that the AE time series associated with particle-laden air striking a carbon steel target could be described as the cumulation of individual particle arrival events each drawn from a statistical distribution model. The high arrival rate involved in a slurry jet poses challenges in resolving individual particle impact signatures in the AE record, and so the model has been extended in this paper to account for different particle carrier-fluids and to situations where arrivals cannot necessarily be resolved.

1. Introduction

Slurry erosion is caused by the interaction between solid particles suspended in a liquid and a surface which experiences a loss of mass due to successive impacts of hard particles travelling at substantial velocities. Slurry erosion has been recognized as a serious problem in many industrial applications such as slurry transport pipelines, slurry handling systems and hydraulic components, causing thinning of components, surface roughening and degradation, and reduction in functional life. A number of studies (e.g. [2–4]) have shown a correlation between the rate of dissipation of the kinetic energy of impact and the rate of material removal. Also, there is a general agreement that the AE energy associated with particle impingement is proportional to the incident kinetic energy $1/2mv^2$ [1,5–8]. Therefore, the measurement of AE energy associated with particle-laden liquid impingement seems likely to offer a means of monitoring slurry erosion.

There is ample experimental evidence of the effect of particle impingement parameters on erosion, and, whereas this has been reviewed in detail by the authors elsewhere [7], those studies that emphasise effects peculiar to erosion where the carrier fluid is liquid are selected here. Turenne et al. [9] have investigated the effect of particle concentration in a slurry on the erosion rate of aluminium samples using a narrow slurry jet of (200–300 μm) sand particles in water at normal incidence angle at a fixed velocity of 17 m/s, whilst varying the slurry concentration between 1 and 20% by weight. They

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characterised the so-called "blanketing effect" in dense slurries by identifying an erosion efficiency, η_e, (ratio of mass lost by erosion to mass of erodent used) which decreased with the inverse cube root of the volume fraction of sand in the stream, f:

$$\eta_e = \frac{K}{f^{0.33}}$$

where K is a constant which will depend on the erodent, the target, the jet size and the fluid velocity. On examination of the eroded surfaces, Turenne et al. also noted that they expected that different impingement angles could result in very different effects of slurry concentration even to the extent that efficiency could increase with concentration at low angles of incidence. Fang et al. [10] directed a jet of silica sand (particle size 600–850 μm) suspended in water at samples of four different ceramics and found that the erosion rate did not change in a consistent way in the concentration range 3 to 7.5 wt %, although the maximum erosion rate for all the materials investigated was at an impact angle of 90°. Iwai et al. [11] investigated the slurry wear rate of 13 materials and found that the effect of changing one of the experimental conditions such as jet velocity V_j, particle size d, and particle concentration C on the erosion rate of the target E_r was characterised typically by exponents whose values were chosen to fit the experimental data as follows:

$$E_r \propto V_j^{1.3-3.2} D^3 C^{0.5}$$

Particularly when the carrier fluid is a liquid, fluid–particle–surface interactions can have a significant effect on particle trajectories and velocities near the target, and hence on the AE energy transferred to the target. Laitone [12] was one of the first to comment that particles approaching a surface always impinge with angles of less than 90° indicating that there is always a difference between the true incidence angle and the angle of the approaching flow. Benchaita et al. [13] have noted that the form and dimensions of the erosion crater in a copper target subject to a 20 mm square section jet consisting of a 0.3 wt% suspension of silica sand in water were consistent with a spread in particle trajectories from normal to more inclined angles. They identified three regions in a jet with normal incidence; a uniform flow at the nozzle exit, a streamlined flow near the target and a uniform exit flow parallel to the surface. In the streamlined region, the components of the flow are given by:

$$v_x = M_x \quad \text{and} \quad v_y = M_y,$$

where x and y are measured from the stagnation point and M is a flow parameter which depends on the jet velocity, the nozzle width and the stand-off distance. These authors also noted that the boundary layer thickness, given by $\delta = 2.4\sqrt{\nu/M}$ (where ν is the kinematic viscosity of the fluid), relative to the particle size is important in assessing the extent to which the boundary layer will slow the impinging particles.

Clark and Burmeister [14] have identified the role of a "squeeze film" as a cushion between an approaching particle and a surface, irrespective of particle size and initial velocity of approach. They suggested that the extrusion of the intervening layer may even prevent impact entirely at low Reynolds numbers, a suggestion which was confirmed later by Wong and Clark [15] who showed that, for 50 μm glass beads in a flow at 6 m/s, impact is prevented altogether. More recently, Clark [16] has noted that knowledge of the flow conditions close to the surface in erosion testers, such as the slurry pot, is "not very sound", but that the impact velocity of particles, deduced from individual crater dimensions, can be 50% or less of the free stream velocity of the fluid. Much of this difference can be explained by potential flow taking into account the distribution of impact angles and consequent components of the velocity normal to the target, and the rest was attributed to the retardation effect of the squeeze film, with small ($<$ 100 μm) particles in dense slurries being most susceptible. Not only may particles approaching the target surface at low Reynolds number be unable to penetrate the squeeze film on rebound or approach, but also, in more concentrated slurries, a layer of particles can become trapped at the surface offering the target some protection from the effect of impact by further approaching particles.

Turenne and Fiset [17] solved numerically the differential equations for particle movement in the flow field near the surface for a slurry jet impinging a surface with normal incidence. By curve-fitting their numerical results, they produced parametric equations for particle trajectories in terms of the final radial position of the particle on the surface, r, the incident speed V, and the impact angle θ as a function of initial location of the particle in the jet, r_i, the initial velocity (jet exit velocity) V_j, and the particle size d:

$$\begin{aligned} r &= 0.192d^{\left(-0.775-0.587r_i+0.018V_j\right)} + r_i \\ V &= -1.14 + 0.004\frac{r_i V_j^{0.5}}{d^2} + 0.762dV_j \\ \theta &= \tan^{-1}\left(64.136d^{\left(11.094-7.293/r_i^{0.1}-0.089V_j\right)}\right) \end{aligned} \tag{1}$$

Turenne and Fiset noted that the predominant variable affecting the impact parameters is the particle size. Due to their higher inertia, the trajectories of larger particles are deflected less, resulting in an impact angle closer to the original jet direction, and the impact velocity is also a higher proportion of the original jet velocity.

Monitoring of particle impact using acoustic emission (AE) relies upon a fraction of the incident kinetic energy of each impacting particle dissipating as elastic waves, which propagate through the target material before being detected by a suitably placed AE sensor. Some of the investigators in this area have concentrated on monitoring the erosion variables [18,19], and