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Monitoring acoustic emission (AE) energy of abrasive particle impacts in a slurry flow loop using a statistical distribution model

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ABSTRACT

Slurry erosion has been recognized as a serious problem in many industrial applications. In slurry flows, the estimation of the amount of incident kinetic energy that transmits from particles suspended in the fluid to the containment structures is a key aspect in evaluating its abrasive potential. This work represents a systematic investigation of particle impact energy measurement using acoustic emission (AE), as indicated by a sensor mounted on the outer surface of a sharp bend, in an arrangement that had been pre-calibrated using controlled single and multiple impacts. Particle size, free stream velocity, and nominal particle concentration were varied, and the amount of energy dissipated in the carbon steel bend was assessed using a slurry impingement flow loop test rig. Silica sand particles of mean particle size 225–650 μm were used for impingement on the bend with particle nominal concentrations between 1 and 5% while the free stream velocity was changed between 4.2 and 14 ms^{-1}.

The measured AE energy was found, in general, to scale with the incident kinetic energy of the particles, although the high arrival rate involved in the slurry impingement flow loop poses challenges in resolving individual particle impact signatures in the AE record. The results have been reconciled with earlier work by the authors on sparse streams where there are few particle overlaps and good control over particle kinetic energies, by extending their model to account for different particle carrier-fluids and to situations where arrivals cannot necessarily be resolved. The outcome is a traceable methodology whereby a quantitative assessment of particle impingement rate can be made in practical situations.

1. Introduction

Due to the continual need to enhance petroleum production using different reservoir fracturing techniques, loss of pressure in the reservoir and well ageing, there is a consequent increasing likelihood of abrasive particles, such as sand, being present in the hydrocarbon flow at the primary stages of production [1]. This poses serious challenges to the integrity of the production assets, causing thinning of components, surface roughening and degradation, and reduction in functional life, and there is a consequent need to be able to monitor the erosive effect of particle-laden streams on the containment structures (usually pipes). Slurry erosion occurs as a result of interaction between a particle-laden liquid and the containment structure which experiences a material loss due to successive impacts of solid particles travelling at substantial velocities. A number of studies [2–4] have shown a correlation between the rate of dissipated incident kinetic energy due to particle impact and the rate of material removal. Also, amongst researchers in applications of Acoustic Emission (AE) monitoring, there is a general agreement that the AE energy associated with particle impingement is proportional to the incident kinetic energy $\frac{1}{2}mv_i^2$ [1,5–8], where the relevant mass, m, and velocity, v_i, may be for an individual particle or, more often, an assemblage of particles. Therefore, the measurement of AE energy associated with particle-laden liquid impingement seems likely to offer a quantitative means of monitoring sand particle impacts and hence slurry erosion.

Studies of the effect of particle impingement parameters on erosion and the effects peculiar to erosion where the carrier fluid is liquid (reviewed in detail elsewhere [7,9]), have lent impetus to the application of AE as a tool to monitor erosion damage caused by solid particle impacts. Monitoring particle impact using AE is based upon a fraction of the incident kinetic energy of each impacting particle dissipating as elastic waves through the target medium (whose shape and elastic properties affect the propagation characteristics of the signal) before being detected by a suitable AE sensor. Despite the theoretical observation that a relatively low

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Nomenclature

List of symbols and abbreviations

AE	acoustic emission
C	solids concentration in flow loop (expressed as weight percentage)
d	diameter of impacting particle
E_c	AE energy calculated from statistical distribution function model
E_{mean}	mean of the calibration lognormal pdf of AE energy per particle impact over a fixed time (normally one second) for a specific sensor amplification, V^2 s
E_{meas}	measured AE energy over a fixed time (normally one second) for a specific sensor amplification, V^2 s
E'_{meas}	measured AE energy over one second associated with particle impacts, V^2 s
E_w	measured AE energy over one second associated with particle-free water impingement, V^2 s
m	mass of impinging particle
n	curve fit power index, as in $y = Ax^n + B$
n_i	curve fit power index for a particular independent variable (e.g., particle diameter n_d)
$\dot{n}_p$	expected particle arrival rate at target (per second)
r_i	radial position of a particle in a roughly circular impingement area
rms AE	root-mean-square of the acoustic emission time series, often used as a time-series itself, of lower effective sampling rate)
t	time (variable)
v	fluid speed in flow loop
v_i	incident velocity of impinging particle
v_p	particle speed in an impinging flow (function of r_i)
$\overline{v_p}$	average particle speed in an impinging flow
$V(t)$	time series amplified AE voltage
wt%	percentage, by weight (for example mass of particles as a percentage of total mass of particles plus carrier fluid)

percentage of the incident KE is dissipated in the target as elastic waves (AE), AE has attracted many researchers to examine its potential in monitoring particle impact and slurry erosion. The generated AE signal can be characterised not only on the basis of the particle impact dynamics (which affect the generation of elastic waves in the target medium), but also upon the propagation path of waves through the target and the type and location of the sensors. Therefore, whereas it is a relatively simple matter to establish a correlation between AE and cumulative impact energy in the laboratory, there is a significant calibration problem when it comes to practical application.

One of the seminal studies of hard particle impact on surfaces using acoustic emission was by Buttle and Scruby [6] in which individual glass and bronze particles were dropped freely in a vacuum onto a specimen on whose opposite face an AE sensor was mounted. They concluded that, AE can be used to distinguish particle size provided that the time between individual impacts is at least 1 ms. Using a different approach, Boschetto and Quadrini [10] have dropped a predefined weight of powder samples onto a metal plate whilst recording the AE. Different particle materials and size distributions were used, and a normalised number of associated AE counts were measured. Boschetto and Quadrini obtained a simple relationship between AE counts and the mean particle diameter. In an attempt to use AE to estimate the mass flow rates of particles in abrasive jets (controlled to be between 1 and 11 g min^{-1}), Ivantsiv et al. [11] used glass beads and aluminium oxide powder, in the range of 25–60 μm, and velocities of around 150 ms^{-1}, giving particle impacts separated by around 30–100 μs. Two approaches were used to estimate the mass flow rate, the first using a dynamic threshold to quantify individual impacts and the second using the power spectral density (PSD) of the AE signal. Also working with high particle arrival rate, but in the quite distinct application of thermal spraying, Faisal et al. [12] concluded that the measured AE energy can be well correlated with expected kinetic energy.

A few researchers have already assessed AE for its potential for on-line monitoring, carrying out experiments in flow loops and slurry impingement rigs. Duclos et al. [13] used AE to monitor the impacts of various sizes and concentrations of sand particles borne by water in a flow loop. They observed a general third power correlation between the measured AE energy and the particle diameter, but the energy was lower than expected for higher particle sizes, which was attributed to particle drop-out according to Stokes' Law. Hou et al. [14] measured the "acoustic noise" produced by a high concentration slurry of fine silica sand particles (13 μm) flowing in a small diameter flow loop by mounting an AE sensor on the external wall of the pipe. Using both AE signature and stepwise regression analysis, they obtained correlations between the AE and the physical properties of the flow, such as solid concentration, mass flow rate and volume flow rate. Ferrer et al. [15,16] have attempted to characterise the mechanical damage due to single and multiple particle impacts by monitoring impingement in a slurry jet rig with an AE sensor coupled onto the back face of a 304L stainless steel target varying the fluid flow rate (1–16 ms^{-1}), particle concentration (1–8 wt%), and angle of impact (30–90°). They observed a linear correlation between AE energy and particle impact KE, and also showed that the measured cumulative AE energy is proportional to the material weight loss. On this basis, they claimed that acoustic energy may be used to measure a loss of mass due to particle impacts in slurry transport pipelines, although clearly some kind of calibration would be required. Similarly, Oltra et al. [17] showed that the mechanical wear (measured as a mass loss after the 1 h erosion test) was proportional to the mean value of rms AE signal for the duration of the test. Burstein and Sasaki [5], as well as concurring with the observation [17], further indicated that using either the maximum amplitude of individual AE events or the rms AE value was an acceptable measure of the magnitude of the (wear inducing) impacts in a slurry jet impingement rig.

An essential aspect of AE monitoring is to be able to establish the physical phenomena which generate the AE. In the case of particle-laden flows, the phenomenon of interest is particle impact with the containment walls, although there may well be other sources (such as that caused by turbulent flow) which constitute noise. Ferrer et al. [15] demonstrated a relationship between particle launch kinetic energy and AE energy by making measurements on single particle impacts prior to their slurry impingement studies [16], and have published an AE record which purports to show single particle impacts, although it is not clear what impingement conditions were represented. Ukpai et al. [18] have also published raw AE records showing what they claim to be single impact events in slurry flows, although they stop short of determining the yield (particle launch rate to impact event rate). Given that both Ukpai et al. and Ferrer et al. used hit-based AE systems with a threshold, it is possible that many events are lost in the dead time or under the threshold and so calibration would depend somewhat