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Online continuous measurement of the size distribution of pneumatically conveyed particles by acoustic emission methods

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ABSTRACT

The particle size distribution of pulverized fuel in pneumatic conveying pipelines is an important physical characteristic closely related to mill energy economy, fuel flow property, combustion efficiency and pollutant emissions. In order to determine the size distribution of pneumatically conveyed fuel particles on an online continuous basis, an instrumentation system based on acoustic emission (AE) method is developed. This method extracts information about particle size distribution from the impulsive AE signals generated by the impacts of particles with a metallic waveguide introduced into the particle flow. Analytical modeling of the particle impact is performed in order to establish the relationship between the particle size and the peak AE voltage. With the particle velocity obtained from an electrostatic velocimetry system and the pulse magnitude determined using a peak detection algorithm, the particle size is computed directly using the developed model. Experimental results obtained with glass beads on a laboratory-scale particle flow test rig demonstrate that the system is capable of discriminating particles of different sizes from the AE signals. The system has several appealing features such as online continuous measurement, high sensitivity, simple sensor structure and low cost, which make it well suited for industrial applications.

1. Introduction

The pneumatic conveying of pulverized fuel (coal or biomass) through enclosed pipelines is an important technique widely used in the power generation, steel and cement industries. One of the key parameters in such gas–solid two-phase flow systems is the size distribution of pulverized coal or biomass particles. Many aspects of the combustion process, such as fuel flow property, pipe erosion, flame stability, combustion efficiency and pollutant emissions, are heavily affected by the size of fuel particles [1–4]. Online continuous measurement of particle size distribution could help realize optimized mill operation settings, balanced coal flow to burners and improved combustion performance.

The strong demand for online sizing of fuel particles in pneumatic conveying pipelines has let, over the years, to the development of a variety of techniques and instruments. Most of the proposed particle sizing techniques are based on well known physical principles, such as laser diffraction [5], digital imaging [6], ultrasound attenuation [7], mechanical vibration [8] and electrostatic sensing [9]. The particle size distribution can either be constructed by measurement of individual particles and counts of particles of similar size, or be extracted from a combined signal for all particles. Although the feasibility of these techniques has been verified in laboratory conditions, their deployments in the field remain problematic due to the hostile environmental conditions, high implementation and maintenance costs, or requirements on sensor accuracy, reliability and durability. For instance, digital imaging is deemed a promising technique for on-line continuous measurement of particle size, but the contamination of optical access windows due to fine dust deposition even coupled with air purging mechanism makes the technique unsuitable for long-term, routine operation in an industrial environment. In power plants, a common technique for the measurement of fuel fineness has long been isokinetic sampling and sieving method. Because the method is both cumbersome and costly, inspections of fuel fineness are conducted only periodically or when anomalous operating conditions are detected. The long time delay between particle sampling and the results analysis also precludes the possibility of real-time feedback control and optimization. Therefore, it is desirable to develop a new practical technique that is accurate, reliable, simple and cost-effective for online particle sizing.

This paper is concerned with online particle sizing using acoustic emission (AE) method. AE refers to the generation of transient elastic stress waves due to the rapid release of energy from localized sources within a material. There have been some

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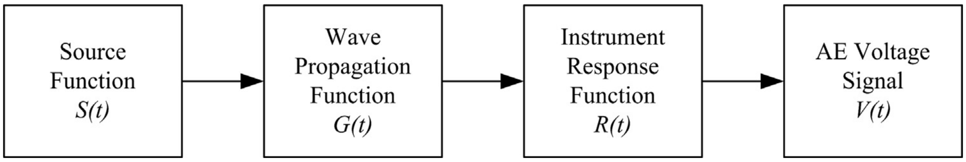

Fig. 1. Signal shaping chain.

preliminary studies of the AE method for particle size analysis. The seminal work conducted by Buttle et al. [10] demonstrated that the peak amplitude and rise time of the AE signal arising from particle impact upon an aluminum target plate could be used to recover particle size information under certain conditions. Due to the complexity of the instruments used, elaborate theoretical analysis and precisely controlled laboratory conditions are required and their technique is thus impractical for industrial applications. Bastari et al. [11] proposed a system identification technique to establish the relations between the acquired AE signals and the size distribution of impacting coal powder. A multi-step procedure, consisting of wavelet packet decomposition, multivariate data analysis and neural network mapping, is employed for particle sizing under limited operating conditions. Uher and Benes [12] validated experimentally the applicability of Hertz theory of contact in the measurement of particle size distribution in solid particle flow. The agreement between the theoretical and experimental data in spectral characteristics suggests possibility of distinguishing particle mixtures by means of spectral analysis of the AE signal. Boschetto and Quadrini [13] used AE signals to recognize different size distributions of metallic and inorganic powder. A simple threshold-based time-counting technique is used to derive approximate particle sizing results. It can be concluded from the review of all existing literature that the AE-based particle sizing technique is still at an early stage of development. There exist many scientific and technical issues to be examined, such as AE generation and propagation mechanisms in particle flow, optimal probing design, quantitative characterization of AE signals and efficient algorithms for online particle sizing. Moreover, a cost-effective instrument operating on this principle in a real industrial environment remains to be developed.

This paper presents for the first time the design, implementation and experimental assessment of an AE-based online particle sizing instrument. The developed instrument allows the solid particles to strike a metallic waveguide protruding into the particle flow for generation of impulsive AE signals. The impact signals are then detected by a piezoelectric AE sensor and analyzed in an online continuous manner to infer the particle size during each impact event. The effectiveness of the prototype instrument is experimentally validated under laboratory conditions. The instrument enjoys several advantages such as online continuous measurement, high sensitivity, simple sensor structure and low cost and is thus well suited for industrial applications.

2. Methodology

2.1. Theoretical model

The impacts of solid particles upon a metallic plate generate transient elastic stress waves that propagate away from the impact points. The stress wave signatures are closely related to the impulsive forces that the particles impose on the plate. One of the key parameters affecting the impact force is the size of the impinging particle. The minute surface displacements caused by stress waves can be detected by a piezoelectric transducer, located some distance away from the AE source. Through physical modeling and digital signal processing, it is possible to quantitatively characterize the particle size distribution from individual or successive impact events.

The AE signal from the transducer is dependent not only upon the particle and impact dynamics but also upon the physics of wave propagation and the instrument response to surface vibrations. As illustrated in Fig. 1, the original motion at the source is shaped by a chain of distinct processes. Assuming that the wave propagation medium and the instrument can be modeled as linear, time invariant systems, the AE signal can be expressed as [10]

$$V(t) = S(t)^{*}G(t)^{*}R(t) \tag{1}$$

where $V(t)$ denotes the measured AE voltage signal and $S(t)$, $G(t)$ and $R(t)$ are the acoustic source, wave propagation and instrument response functions, respectively. The symbol * represents convolution.

If the wave propagation and the instrument response functions are known, their effects can be decoupled from the measured AE signal through de-convolution. Information about the particle size is then extracted from the derived source function. The above technique, known as quantitative AE, can achieve quantitative characterization of the particle size. However, determination of the wave propagation and instrument response functions require precise modeling of the physical process and accurate calibration of the data acquisition system, both of which are challenging tasks. It is also doubtful that such a technique could be utilized in practical situations, where the particles are irregular in shape, the signals are contaminated by noise and the pulses are overlapped due to simultaneous impacts of multiple particles. For these reasons, an inferential particle sizing approach based on the peak voltages of individual impact events is employed in the present study.

The source function (Fig. 1) representing the time history of the impact force can be determined by Hertz theory of contact [14]. The formulation of the theory assumes that the impact is normal and elastic, the particle is spherical and the plate is perfectly flat. The impulsive force that the particle imparts to the plate can be approximated by [15]

$$S(t) = \begin{cases} f_{max}(\sin(\pi t/t_c))^{3/2} & \text{for } 0 < t < t_c \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where $t_c = 4.53(4\rho_1\pi(\delta_1+\delta_2)/3)^{2/5} r_1 v_0^{-1/5}$ is the time the particle spends in contact with the plate, and $f_{max} = 1.917\rho_1^{3/5}(\delta_1+\delta_2)^{-2/5} r_1^2 v_0^{6/5}$ is the peak compression force. In above equations, $\delta_i = (1-\mu_i^2)/(\pi E_i)$, E and μ are Young's modulus and Poisson's ratio, respectively, and subscripts 1 and 2 refer to the materials of the particle and the plate, respectively. ρ_1, r_1 and v_0 represent the mass density, mass equivalent radius and approach velocity of the particle, respectively. Given particle velocity and properties of both materials, the particle size can be theoretically derived from the source function.

With the assumption that the wave propagation medium and the instrument are linear, time invariant systems, the maximum voltage of an AE pulse corresponds to the maximum compression and is proportional to the peak compression force. Therefore, the relationship between the maximum voltage of an AE pulse, the