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.

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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 led, 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
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 required and their technique is thus impractical for industrial applications. Due to 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]

\[ V(t) = S(t)^* G(t)^* R(t) \]

(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 impulse force that the particle imparts to the plate can be approximated by [15]

\[ S(t) = \begin{cases} 
\frac{f_{\text{max}}}{\pi} & 0 < t < t_c \\
0 & \text{otherwise}
\end{cases} 
\]

(2)

where \( t_c = 4.53(4\rho_1\pi(\delta_1 + \delta_2))^{2/5}r_1v_0^{1/5} \) is the time the particle spends in contact with the plate, and \( f_{\text{max}} = 1.917\rho_1^{2/5}(\delta_1 + \delta_2)^{-2/5}r_1v_0^{1/5} \) is the peak compression force. In above equations, \( \delta_i = (1 - \mu_i^2)(\pi E_i) \), \( E \) and \( \mu \) 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. \( \rho_1, r_1 \) 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
particle velocity and the particle size can be expressed as [16]

\[ V_{\text{max}} = K r_1 \sqrt{v_0^2 v_0^6} \]  

(3)

where \( V_{\text{max}} \) is the maximum voltage of the AE pulse and \( K \) is a proportionality constant. Calibration of \( K \) can be performed using isometric particles of known size distributions. Once the particle velocity and the constant are determined, the particle size can be directly computed from the peak pulse voltage using Eq. (3).

2.2. Instrument design

The measurement of particles in pneumatic conveying pipelines can be implemented by detecting the AE signals generated by impacts of particles either with a natural bend in the pipeline wall or with an artificial obstacle introduced into the flow. In order to isolate structural noises from the pipeline and obtain a reasonable impact frequency, an intruded waveguide is employed as the target for particle impacts. After propagating through the waveguide, the AE signals are detected by an AE sensor attached to the outer end of the waveguide. Fig. 2 shows the sensing arrangement for on-line particle size measurement.

A prototype instrument for online particle sizing was designed and constructed. 3-D drawings and installation of the prototype sensing head are shown in Fig. 3. The main body of the sensing head is a 100 mm bore spool piece, which can be connected to the pipeline through the flanges at both ends. The waveguide rod, made of durable metal–ceramic composites, penetrates into the particle flow through the wall of the spool piece. The middle section of the waveguide is cylindrical for sealing with rubber bushings. The inside section is semi-cylindrical with the flat surface facing the flow, which enables normal particle impact. The outside section is also semi-cylindrical but with opposite direction of the flat surface, onto which the AE sensor is attached. The diameter of the waveguide is 10 mm and the penetration distance is 50 mm, so that the area for particle impact is 500 mm². The instrument permits adjustment of the penetration distance in order to change the number of particle impacts per unit time. The acoustic emission signal due to particle impact covers a broad frequency range, from the audible to the ultrasonic frequencies [17]. In order to avoid the influence of audible environmental noise and to reduce the computational overhead due to high speed sampling, a low-frequency ultrasonic piezoelectric AE sensor (type SR40M, SOUNDWEL) is used. The sensor operates in the bandwidth of 15–70 kHz, with 40 kHz as the resonance frequency. Moreover, three circular electrostatic electrodes positioned upstream of the waveguide (Fig. 3) are used to measure the velocity of particles [18,19].

The signals from the sensing head are fed to a signal processing system that performs signal conditioning, data acquisition and computation. The AE signal is amplified with a voltage gain of 40 dB and then filtered through a band-pass filter with a frequency range of 20–100 kHz. The current signals from the electrostatic sensors are converted into voltage signals and then amplified and filtered. An analog-to-digital converter digitizes the four signals simultaneously at a sampling rate of 1.25 MHz for each channel. The particle sizing algorithm is implemented on a high-performance floating point digital signal processor running at 300 MHz. The particle sizing
results are transmitted to a host computer through a RS232 interface for display and storage. Fig. 4 shows the block diagram of the signal processing system.

2.3. Particle sizing algorithm

Fig. 5 shows a typical AE signal due to two successive impact events. The test particles are glass beads with an approximate diameter of 180 μm. The impact velocity is about 8.0 m/s. As illustrated in Fig. 5, the impulsive signal arising from a particle impact event is followed by a sequence of damped oscillations. In order to achieve particle sizing, the primary peak during each impact event should be detected. Here we propose a search algorithm for peak detection. The procedure of the peak detection algorithm is as follows:

Step 1. Detection of all possible peak candidates: all the local maxima between two consecutive local minima are regarded as peak candidates.
Step 2. Localization of the primary peak candidates: for three consecutive peak candidates, the one located in the middle and greater than the other two is regarded as the primary peak candidate.
Step 3. Removal of false peak candidates by thresholding: all the primary peak candidates smaller than a certain threshold are deemed as pseudo peaks due to noise and are thus removed.

3. Results and discussion

3.1. Experimental set-up

Experiments with the prototype particle sizing system were carried out on a 100 mm bore particle flow test rig. Fig. 6 shows the layout of the test rig. The sensing head was installed in a vertical section of the polymethyl methacrylate pipeline. An industrial suction system was connected to the pipeline to generate a steady air flow. Glass beads ranging from 20 μm to 250 μm in diameter were fed into the rig via a feeding hopper. The particle velocity was varied by adjusting the power of the suction system, while the impact frequency was tuned by regulating the particle discharge rate of the feeding hopper. Table 1 summarizes the physical properties of the test particles and the experimental conditions.

3.2. Experimental results

The first experiment was to investigate AE signals generated by particles of different sizes. For this purpose, the glass beads were sieved into three size ranges using a mechanical sieve shaker. The particle velocity before collision was around 8.0 m/s and the mass flow rate was 2.0 g/s. Fig. 7 shows the AE signals generated by particles below 90 μm, between 90 μm and 180 μm and above 180 μm, respectively. It is apparent that, under the above conditions, signals from individual impacts could be resolved in time and larger particles generated higher signal peaks. Therefore, the theory based on which the particle sizing algorithm was derived could be partially validated. The burst AE signals generated by small particles were so weak that they were almost immersed in
the background noise, which was mainly caused by the strong airborne sound from the suction system.

To determine a reference particle size distribution of the off-the-shelf glass beads is not straightforward. For ease of operation, glass beads in different size ranges were mixed with known mass ratio. The measured particle size was used to compute the mass of the particle, and the total mass of particles within a size range was obtained through simple summation. The measured mass ratio was compared with the prescribed mass ratio, which could indicate the effectiveness of the system. Table 2 and Fig. 8 show the measured total mass and the mass ratio for particles in different size ranges, respectively. The prescribed mass ratio for particles below 90 μm, between 90 μm and 180 μm and above 180 μm was 50%:30%:20%. The results suggest that higher particle velocity leads to increased accuracy of the measurements. At all velocities, the mass for particles above 180 μm remained almost fixed because all the impacts were detected. At low velocity, the pulsed signals generated by small particles were comparable to the noise and can hardly be detected, which led to large errors in the measured mass ratio. As the velocity increased, more smaller particles were detected and the results became more accurate.

**Table 2**

<table>
<thead>
<tr>
<th>Mass Ratio (%)</th>
<th>&lt; 90 μm</th>
<th>90–180 μm</th>
<th>&gt; 180 μm</th>
<th>Total mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 m/s</td>
<td>2.18 g</td>
<td>2.98 g</td>
<td>5.62 g</td>
<td>10.78 g</td>
</tr>
<tr>
<td>9 m/s</td>
<td>6.95 g</td>
<td>5.40 g</td>
<td>5.76 g</td>
<td>18.11 g</td>
</tr>
<tr>
<td>12 m/s</td>
<td>11.46 g</td>
<td>8.11 g</td>
<td>5.68 g</td>
<td>25.24 g</td>
</tr>
</tbody>
</table>

**Fig. 8.** Measured mass ratio of particles in different size ranges.

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**Fig. 7.** AE signals generated by particles in different size ranges. (a) Particles below 90 μm. (b) Particles between 90 μm and 180 μm. (c) Particles above 180 μm.

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**Conclusions**

This paper presented a prototype AE-based instrumentation system for the online measurement of particle size distribution in gas–solid two-phase flows. The relationship between the particle size and the peak AE voltage was theoretically established. A particle sizing algorithm was developed using peak detection techniques. Experimental results obtained with poly-dispersed glass beads have verified the possibility of online particle size measurement from burst AE signals generated by individual impact events.

Significant further work is required to advance the technique. Firstly, the dynamics of particle collision and wave propagation should be investigated through numerical simulation. A deeper understanding of the physical process will shed light on the optimized design of the sensing head. Secondly, the theoretic model based on which the particle sizing algorithm is developed should be refined for a wide range of flow conditions. The accuracy of the results is expected to be improved by making more realistic assumptions. Thirdly, effective denoising techniques and precision signal conditioning electronics will be employed in order to extend the lower limit of the measurable particle size. Finally, the performance of the instrument under a wider range of conditions, such as variations in test material, particle concentration and installation location on the pipeline, should be investigated.
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References