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An integrated multi-channel electrostatic sensing and digital imaging system for the on-line measurement of biomass–coal particles in fuel injection pipelines

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HIGHLIGHTS

- A system integrating electrostatic sensing and imaging techniques is reported.
- Averaged and local particle velocities are measured from electrostatic sensor arrays.
- Particle size distribution is obtained through digital imaging.
- Experiments were conducted on a 150 mm bore pipeline with coal and biomass–coal mixtures.

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ABSTRACT

The measurement of key parameters of biomass–coal particles in a pneumatic conveying pipeline at a power plant presents a significant challenge due to the inherent complexity of the dilute particle flow and differences in physical properties between the different kinds of fuels. This paper presents the latest development in on-line continuous measurement of mean particle velocity, concentration and particle size distribution of pulverised fuel using multi-channel electrostatic sensing and digital imaging techniques. An integrated instrumentation system has been implemented to achieve the intended measurement of pulverised fuel particles. Comprehensive tests were conducted on a 150 mm bore horizontal pipe section of a large scale test facility using pulverised coal and biomass–coal blends. The results suggest that the characteristics of the pulverized fuel flow depend on the flow velocity and biomass proportion in the mixture and, to a large extent, on the biomass properties. It is found that coal particles travel faster and carry more electrostatic charge than biomass–coal blends. As more biomass particles (up to 20% by weight) are added to the flow, the particle velocity reduces, the electrostatic charge level decreases, and the flow becomes less stable in comparison with coal flow.

1. Introduction

Pulverised fuel (PF) transportation in pneumatically conveying pipelines has been an area of concern as biomass–coal co-firing is widely adopted as an important technology for reducing greenhouse gas emissions in the power generation industry. As biomass comes from different sources in a wide variety of forms [1] and textural characteristics, biomass particles are commonly irregular in shape. Biomass particles range in size from hundreds of micrometres to a few millimeters while the average diameter of coal particles is around 60 μm. Biomass particles may also contain significant amount of moisture when the storage and transportation conditions vary. Thus, the movement behaviors of a biomass–coal mixture in a pneumatic conveying pipeline become even more complex than that of the coal flow due to the differences between the physical properties of different kinds of biomass and coal [2]. This will affect the balanced fuel delivery between the PF distribution lines, the final compositions of the fuel flows to the burners through bifurcations and trifurcations and, eventually, the combustion performance of the power plant.

A number of techniques have been applied to the field of gas–solid flow measurement [3,4], but still very little is known about the dynamic nature of biomass–coal flow in PF lines as most of the techniques are unsuitable for the online continuous measurement of pneumatically conveyed particles in a harsh industrial

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environment. The method based on a laser transmission fluctuation spectrometer is expected to achieve on-line measurement of pulverised coal flow [5], however the sensing volume is very small and an intrusive probe has to be used to support the optical elements. Among optical methods, digital imaging provides a means of achieving on-line continuous particle sizing as well as solid concentration measurement [2,6]. Ultrasound method works by introducing acoustic waves into the pipe and measuring the echo waves from both upstream and downstream directions [5]. The mean particle velocity is deduced from the air velocity which is calculated by the difference between upstream and downstream acoustic propagation velocities [7], but it is very sensitive to external vibration noise and variations in particle size. The capacitive method measures the relative permittivity fluctuations of the solid phase in the cross-section of the pipeline using a pair of sensors [8]. However, experiment results have shown that measurements are highly sensitive to moisture content of particles and it is suitable for dense-phase flow measurement. Due to its advantages of simple structure, robustness and low cost, electrostatic sensing techniques have been used by many researchers [9–12]. Electrostatic sensing along with cross-correlation [11–14] and spatial filtering [15,16] signal processing methods have been successfully tested under both laboratory and power plant conditions for the measurement of gas–solid flow and encouraging results have been obtained.

This paper presents the latest development of an integrated multi-channel electrostatic sensing and digital imaging system that is capable of measuring key parameters of dilute biomass–coal flow in real time. The electrostatic sensing part is based on multi-channel electrostatic sensing and cross-correlation signal processing techniques for the measurement of particle velocity and electrostatic charge level of moving particles. The other area of advancement arising from the system is the digital imaging method for on-line particle sizing that has revolved around novel image processing algorithms and cost effective hardware. A 150 mm bore integrated system was constructed and tested on a large scale test facility circulating pulverized coal and sawdust-coal blends. The dynamic behaviors of the pneumatically conveyed fuel particles in a pipeline are studied through a series of experimental tests.

2. Measurement principles and system implementation

2.1. Measurement principles

2.1.1. Electrostatic sensor based velocity, concentration and flow stability measurement

PF particles in a pneumatic pipeline carry certain electrostatic charge due to the friction between particles and conveying air, collision between particles themselves and impact between particles and pipe wall. The fluctuation of the electrostatic field caused by the moving particles can be detected by insulated metal electrodes in conjunction with dedicated electronic circuits. Electrostatic sensing along with correlation signal processing algorithms is an effective way to determine the velocity of the particles [9]. A pair of identical electrostatic sensors, which are perpendicular to the direction of the flow, are used to measure the particle velocity. Fig. 1(a) shows typical random signals from the sensors and their resulting cross correlation function. The transit time (τ) taken by the particles to move from the upstream sensor to the downstream sensor can be determined from the location of the dominant peak in the correlation function [9], as shown in Fig. 1(b). As a result, the particle velocity is derived from

$$v_c = \frac{L}{\tau} \tag{1}$$

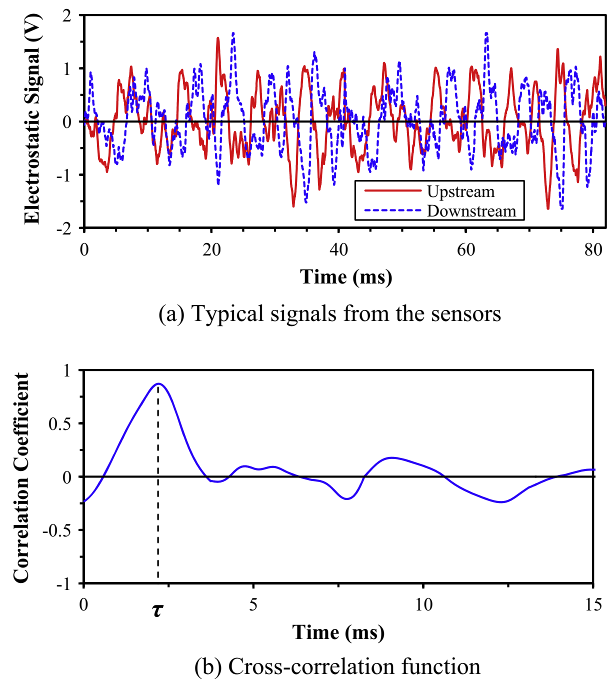

Fig. 1. Typical random signals from the electrostatic sensors and resulting cross-correlation function.

where L is the spacing between upstream and downstream sensors. It should be pointed out that the correlation velocity measured from Eq. (1) is not necessarily the expected "mean particle velocity", depending up the sensitivity profile of the sensor, particle velocity profile, particle distribution in the sensing volume and algorithm of correlation computation [9].

Since the particle flow in a PF line is mostly dilute, we can assume, from a statistical point of view, each particle has the same chance of charging and travels at a similar velocity when the flow is stable. Thus, the root-mean-square (RMS) magnitude of the sensor signal can be regarded as relative volumetric concentration [9]. The relative volumetric concentration of particles indicates the non-quantitative variation in the cross-sectional area occupied by the moving particles. As the correlation method only measures the similarity between the upstream and downstream signals by calculating their correlation coefficient, the velocity measurement is little dependent upon the signal amplitude. For a given spacing between the upstream and downstream sensors, the peak value of the correlation function derived from the measured signals is an indicator of the flow stability, as the more stable the flow, the greater the correlation coefficient.

2.1.2. Digital imaging based particle sizing

The general arrangement of a particle imaging system is illustrated schematically in Fig. 2.

The front illumination scheme is used as it provides practical benefits – the light source and camera can exist as a single unit, thus complex illumination optics is not required [2]. In a pixel based digital image, the number of pixels making up each particle can be counted and then used to calculate its equivalent diameter, which is the diameter of a perfect circle of the same area:

$$D_{eq} = 2\sqrt{\frac{n_p \cdot A_{px}}{\pi}} \tag{2}$$

where n_p is the number of pixels making up the particle and A_{px} is the area of each pixel. The volumetric concentration of particles