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Velocity characterization of dense phase pneumatically conveyed solid particles in horizontal pipeline through an integrated electrostatic sensor

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ABSTRACT

Dense phase pneumatic conveying of pulverized fuel particles under high pressure is one of the key techniques in large scale gasification of coal and petroleum coke. The real time and continuous measurement of dense phase gas–solid flow parameters such as particle velocity, concentration and mass flow rate has great significance for the in-depth understanding of particle flow dynamic behaviors and the optimized design of the conveying system. In this paper, an integrated electrostatic sensor is designed and used to explore the flow characteristics of anthracite and petroleum coke particles on a dense phase pneumatic conveyor. The ring electrodes in the integrated sensor are capable of measuring the "mean" velocity of solid particles over the whole cross-section of the pipeline, while the arc electrodes are employed to determine the local velocity of particles near them. The experimental results on a dense phase pneumatic conveyor under high pressure demonstrate that the flow characteristics depend on the physical properties of solid particles and carrying gas. Petroleum coke particles are much easier to be suspended in the gas flow than the anthracite particles, but its flow stability is worse. The local velocities from the arc electrode pairs mounted on the top of the pipeline are usually higher than those from the arc electrodes on the bottom for a stratified flow. The velocity from the ring electrode pair, indicating the mean velocity of particles over the whole cross-section, is usually higher than the local velocities from the arc electrode pairs for a suspension flow. In addition, the relationship between the mass flow rate and charge level of dense phase pneumatically conveyed solid particles is very complicated due to the complexity of the particle flow and the charge level cannot be used to measure particle concentration or mass flow rate.

Introduction

Coal gasification is one of potential ways to realize the highly efficient and clean utilization of coal resource. At present, the entrained-flow gasifier has been industrialized for the large-scale coal gasification. With the rapid increase of energy demand in China, a great quantity of petroleum coke, a byproduct of oil refining, is produced every year and has replaced the coal as the raw materials partly or entirely in some gasifiers (Liu et al., 2012). For the purpose of meeting the operation demand of the gasification system, saving energy and improving synthesis gas quality, the raw materials should be pneumatically conveyed into the gasifier in dense phase under a high pressure, which is one of the key techniques in large-scale gasification of coal and petroleum coke.

Dense phase pneumatic conveying of pulverized fuel is a typical dense phase gas–solid two phase flow. As the dense phase gas–solid two phase flow in the pneumatic transport pipeline is an unsteady and complex non-linear dynamical system, a detailed understanding of the particle flow behavior is important for the design, optimization and operation of the dense phase pneumatic conveying systems. So it is of great significance to achieve the real time and continuous measurement of solid particle flow parameters (particle velocity, concentration and mass flow rate) for characterizing particle flow behavior. Unfortunately, conventional methods for the exploration of the dense phase pneumatic conveying, such as phase diagram and transient pressure analysis

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(Molerus, 1996; Cong et al., 2011), cannot meet the requirements. Many advanced techniques have been investigated and developed for the flow measurement of pneumatically conveyed solid particles (Zheng and Liu, 2011), such as light scattering, digital imaging, acoustics, radiometric method and electrostatic method. Up to date, light scattering (Cai et al., 2005) and digital imaging (Carter and Yan, 2003) are unsuitable for the measurements of the dense phase particle flow due to the high solid particle concentration. Acoustic technique (Albion et al., 2007) is capable of measuring the mass flow rate of solid particles in dilute-phase and fully developed flow conditions. However, it is not appropriate for the unstable dense phase particle flow measurement. Radiometric method (Barratt et al., 2001) can be used for the dense particle flow measurement. However, it has a risk of radiation leakage and is usually costly due to the complicated sensor structure and radiation shielding. Electrostatic method is based on the particle electrification due to the interactions among particles, gas and pipe wall in a gas–solid flow system. Although particle electrification is risky to cause serious spark discharge and even explosions in bulk solid handling industry, a specially designed electrostatic sensor can be utilized to measure and characterize the gas–solid flow due to its advantages of high sensitivity, simple structure, low cost and strong applicability (Yan et al., 1995a; Shao et al., 2010; Qian and Yan, 2012; Qian et al., 2012; Gajewski, 2008; Xu et al., 2009, 2012a; Zhang and Coulthard, 2005; Zhang et al., 2009; Zheng and Liu, 2011). Both intrusive and non-intrusive electrostatic sensors in combination with cross-correlation method have been developed to measure particle velocity successfully by Yan et al. (1995a) and Shao et al. (2010). A multi-channel electrostatic sensor array was developed to investigate the dynamic behavior of biomass-coal flow under laboratory and industrial scale test facilities (Qian and Yan, 2012, Qian et al., 2012). On the basis of in-depth investigation into the spatial filtering effect and temporal frequency characteristics of a ring electrode and ring-shaped electrode array, Xu et al. (2009 and 2012a) proposed a spatial filtering velocimeter for the particle mean velocity measurement and applied it to a dense phase pneumatic conveying system. At present, electrostatic sensor is mainly used to measure the "mean" particle velocity over the whole cross-section of pipe in dense phase pneumatic conveying. However, the particle velocity distribution measurement of dense phase pneumatically conveyed particles is scarcely reported. In addition, intrusive sensor is not suggested for the dense phase gas–solid flow due to the high probability of pipeline blockage.

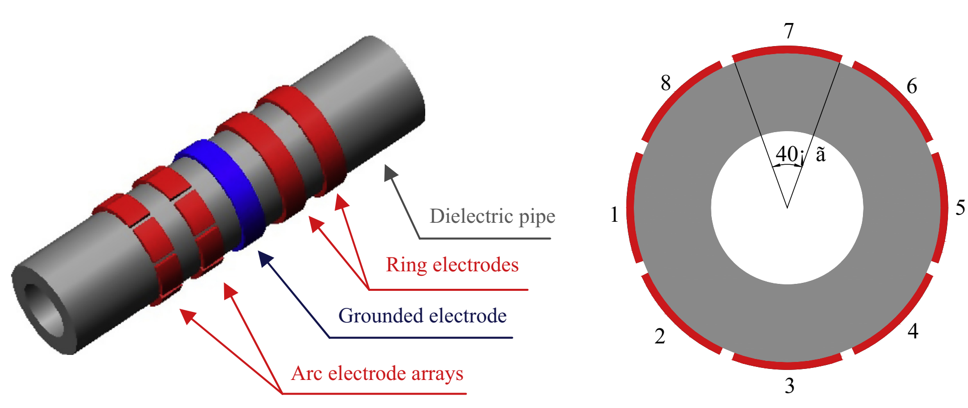
The objective of the present paper is to study the velocity characteristics of dense phase pneumatically conveyed solid particles using an integrated electrostatic sensor. The integrated electrostatic sensor, which is non-intrusive and consists of two ring electrodes and two 8-electrode arrays, is designed and used to measure the cross-sectional mean and local velocities of particles and the charge level. Further the flow characteristics of the anthracite and petroleum coke particles are experimentally investigated in a horizontal dense phase pneumatic conveying pipe with an inner diameter of 10 mm under various operation conditions. The experimental results are finally presented and analyzed.

Measurement principles

Electrostatic sensor combined with cross-correlation technique has been successfully used to measure particle velocity (Yan et al., 1995a; Shao et al., 2010; Qian and Yan, 2012; Qian et al., 2012; Zhang et al., 2010). The sensor includes two electrostatic electrodes called upstream and downstream sensors, which are mounted on a straight conveying pipe with a suitable distance. When the particles move along the axial direction of the pipe, the output signals from the two electrodes are similar with a time delay. Through the cross-correlation processing of the two signals, the transit time (the time delay) can be determined. And the particle velocity is equal to the known axial distance between the upstream and downstream sensors divided by the transit time. The ring electrode pair indicates the solid particle "mean" velocity over the whole cross-section, which is the integral of each streamline velocity weighed by the spatial sensitivity, cross-correlation coefficient and solid concentration at that stream (Yan et al., 1995a). However, the arc electrode has a localized sensing zone and so it is only sensitive to the nearby charged particles (Xu et al., 2012b). As a consequence, the arc electrode can measure the local velocity of the particles near it.

The cross-correlation coefficient of the output signals from the upstream and downstream electrodes represents the reliability of the measured velocity by cross-correlation method and the particle flow stability (Qian and Yan, 2012). The higher cross-correlation coefficient means that the correlation of the two signals is better, and thus the measured velocity is more reliable and the flow is more stable.

The root-mean-square (RMS) value of the output signal from the electrostatic sensor is usually regarded as the charge level of



(a) View of the integrated sensor (b) Cross-section view of the arc electrode arrays

Fig. 1. The configuration of the integrated sensor.