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Effect of particle degradation on electrostatic sensor measurements and flow characteristics in dilute pneumatic conveying

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ABSTRACT

Vigorous particle collisions and mechanical processes occurring during high-velocity pneumatic conveying often lead to particle degradation. The resulting particle size reduction and particle number increase will impact on the flow characteristics, and subsequently affect the electrostatic type of flow measurements. This study investigates this phenomenon using both experimental and numerical methods. Particle degradation was induced experimentally by recursively conveying the fillite material within a pneumatic pipeline. The associated particle size reduction was monitored. Three electrostatic sensors were embedded along the pipeline to monitor the flow. The results indicated a decreasing trend in the electrostatic sensor outputs with decreasing particle size, which suggested the attenuation of the flow velocity fluctuation. This trend was more apparent at higher conveying velocities, which suggested that more severe particle degradation occurred under these conditions. Coupled computational fluid dynamics and discrete element methods (CFD–DEM) analysis was used to qualitatively validate these experimental results. The numerical results suggested that smaller particles exhibited lower flow velocity fluctuations, which was consistent with the observed experimental results. These findings provide important information for the accurate application of electrostatic measurement devices in pneumatic conveyors.

Introduction

In pneumatic conveying, the flow rates of solid materials often need to be monitored or controlled. Accurate measurements of the flow velocity, concentration, and flow rate are critical. Electrostatic, electrical capacitance, and microwave measurements are three common non-invasive measurement techniques used for these purposes (Arko et al., 1999; Beck, Green, & Thorn, 1987; Xu, Zhou, & Wang, 2010; Yan, 1996; Yan, Byrne, & Coulthard, 1995). The electrostatic method measures the flow rate by detecting induced charges carried by solid particles (Saleh & Aghili, 2012; Zhang & Coulthard, 2005; Zhang, Coulthard, Cheng, & Keech, 2009). The primary sources of this electrification are frictional contact charging between particles or between particles and the conducting facility, charge transfer or sharing from one particle to another, and charge induction (Farmer, 1992; Zhou, Zhang, Xu, & Wang, 2011).

In reality, particles can be positively and negatively charged during pneumatic transport. Fig. 1(a) schematically demonstrates the principle of this technique. Charge induction occurs at the inner surface of the earthed metal pipe wall and the insulated floating metal electrode. The conditioning circuit is used to detect charge induction on the electrode only. The output of the conditioning circuit can be used to indirectly indicate the solids flow rate (Gajewski & Szaynok, 1981; Masuda, Komatsu, Mitsui, & Iinoya, 1977). In industrial environments, electrostatic sensors are susceptible to low frequency noise. Hence, dynamic measurements are usually used, which measure the fluctuation of the charge or voltage induced in the electrode. The fluctuation of the signal (root mean square value is often used) has been used to indicate the solids flow velocity/flow rate. The signal level and its frequency band largely depend on the dynamic flow velocity fluctuation (Cole, Baum, & Mobbs, 1969; Gajewski, 1997; King, 1973). This is demonstrated in Fig. 1(b), in which higher flow velocity fluctuations lead to an increase in the intensity and frequency of the signal.

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Nomenclature

C_D	Drag coefficient
d_{50}	Mean particle size (μm)
d_p	Particle diameter (m)
$\mathbf{F}_b$	Buoyance force (N)
$\mathbf{F}_c$	Contact force (N)
$\mathbf{F}_d$	Drag force (N)
$\mathbf{F}_f$	Air–particle interphase momentum transfer force (N)
$\mathbf{F}_g$	Gravitational force (N)
g	Gravitational acceleration (m/s^2)
I	Particle inertia ($kg\,m^2$)
$\mathbf{M}$	Contact torque (N m)
m	Particle mass (kg)
P	Air pressure (Pa)
Re	Reynolds number
$\mathbf{U}_f$	Fluid velocity (m/s)
$\mathbf{U}_p$	Particle translational velocity (m/s)
$\hat{U}_{rms}$	Root mean square value of the signal
ε	Void fraction
μ_a	Air viscosity (Pa s)
ρ_a	Air density (kg/m^3)
$\boldsymbol{\omega}$	Particle angular velocity (m/s)
$\Delta\bar{U}$	Signal variation

In dilute gas–solid two-phase flows, the high conveying velocity means that particle degradation/attrition often occurs from recursive particle–particle and particle–wall collisions. This results in: (1) a particle size reduction as the conveying process progresses. Therefore, the total number and total surface area of particles continuously increase for a given mass of material (Chapelle et al., 2004; Kalman, 2000; Mills, Jones, & Agarwal, 2004; Salman, Attila, & Mills, 1992); (2) a decrease in the flow velocity fluctuation. The increasing number of particles enhances the momentum dissipation, which leads to less chaotic velocity variations (Crowe, 2000; Hetsroni, 1989; Yarin & Hetsroni, 1994).

The above two phenomena have opposite effects on the output of electrostatic dynamic sensors. Specifically, an increase in the particle surface area leads to a higher total charge carried by the particles, which will enhance the signal. Conversely, the decreasing flow velocity fluctuation will result in a weaker signal. The overall signal trend (rise or fall) depends on the balance between these two effects. This paper presents experimental results and qualitative simulations on the change in flow characteristics resulting from particle degradation. The experimental and simulated results are consistent with each other.

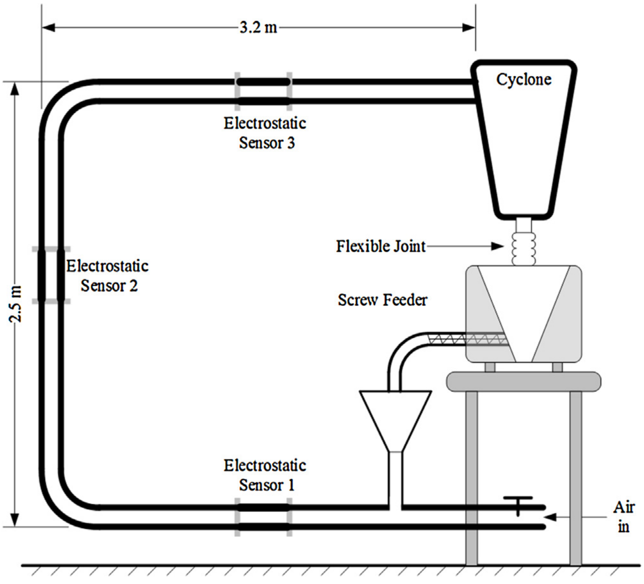

Fig. 2. Schematic of the pneumatic conveying experimental setup.

Experimental scheme

The experimental pneumatic conveying system used in this study is shown schematically in Fig. 2. The 40 mm (internal diameter) pipeline system consisted of one vertical and two horizontal sections. Three electrostatic meters with a same internal bore were installed along the pipe. A draft fan and an air drier were used to provide air to transport the solids fed from the screw feeder. Underneath the screw feeder, a weighing platform measured the mass of the solids, from which the solids mass flow rate was derived. After completing each conveying loop, the solids and air were separated in the cyclone.

During conveying, three electrostatic sensors constantly monitored the flow. The resulting signals were subsequently acquired and transmitted to a computer. The mean solids flow velocity at each of the three measurement locations was produced based on the cross-correlation method (Beck & Plaskowski, 1967; Coulthard, 1973). The mean solids flow rate was indicated by the signal fluctuation level, as previously discussed. The airflow rate was also measured concurrently.

Fillite material was selected for the conveying test. Its material properties are shown in Table 1. Four different air velocities (12, 16, 22, and 26 m/s) at the inlet position were configured, by adjusting the inlet air mass flow rate. A screw feeder was used to feed 3 kg of the fillite material into the pipeline. Under the four air veloci-

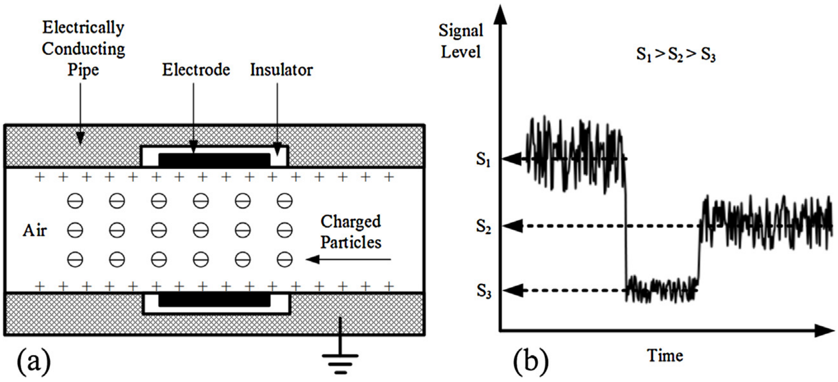

Fig. 1. Electrostatic flow sensor: (a) schematic of the measurement principle and (b) typical sensor output.

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