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Transient parameter analysis of pneumatic conveying of fine particles for predicting the change of mode of flow

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ABSTRACT

During the process of pneumatic conveying of fine particles, the flow mode may change from dense to dilute. In studying this mode change, we evaluate three parameters (Hurst exponent, Shannon entropy, and phase-space attractor size) used in signal analysis. Experimental data of pneumatic conveying of fly ash at three locations along a 173-m-long pipeline were used for this analysis. Variations in magnitude of the Hurst exponent, Shannon entropy, and size of the phase space attractor exhibit different trends in their variations for dense and dilute mode of flow. From these trends it is possible to predict the change from dense to dilute mode and the location along the length of the pipeline of this change in mode of flow.

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Introduction

Fine particles or powders can be conveyed by fluidized dense phase conveying in which the material flows in two distinct layers, an upper dilute flow and a lower dense flow. Compared with the dilute mode of flow, the dense mode of flow has many advantages such as low power consumption, low pipe wear, and low particle degradation. During conveying, the material which is in the dense mode at the inlet of a long pipeline may change to the dilute mode at a certain location along the length of the pipeline. This arises from a gradual expansion of gas from the inlet to the outlet of the pipeline. This change in mode of flow from dense to dilute depends upon many factors such as length and diameter of the pipeline, inlet pressure, and solids loading ratio. Solids loading ratio (m^*) is defined as the ratio of solids mass flow rate to air mass flow rate. When the flow becomes dilute, the power consumption increases, particles degrade, and pipes are subject to erosive wear. For dilute flow, erosive wear is more significant at bends in the pipeline. Operating in dilute mode for any extended period in time may require replacing pipes in these bends or even straight sections. If the particle is abrasive (for example, alumina or silica sand) then the erosive wear may be significant. Hence it is necessary to trace the location of flow mode transition for a given flow condition or pipeline configuration.

Few researchers have investigated the tracing of the location of transition in mode of flow. Williams, Jones, and Cenna (2008) applied the wavelet technique to analyze variations in pulse amplitude of the pressure signal along a length of pipeline and concluded that pulse amplitude increases because gas expands along the pipeline. Behera, Agarwal, Jones, and Williams (2012) analyzed the variation of transient parameters in pressure data such as pulse amplitude, pulse slope ratio, and pulse time ratio. The variation of the pulse slope ratio at three locations along the pipeline provided an approximate location of the flow mode transition. Mittal, Mallick, and Wypych (2014) studied the variation of parameters such as standard deviation and Shannon entropy for analyzing the flow in bends. They observed that both values tend to decrease after a bend. Mittal, Mallick, and Wypych (2015) used signal analysis parameters and a technique (Shannon entropy, Hurst exponent, and phase space diagram) to study flow behavior of conveyors with bend sections of pipeline. Pahk and Klinzing (2008) used pressure fluctuations in pneumatic conveyors transferring polymer pellets to observe the flow regimes. They used four different analyses—power spectral density analysis, phase space diagram analysis, rescaled range analysis, and wavelet analysis. Few investigations have been performed for pneumatic conveying of fine particles to determine the transition location from dense to dilute flow. In this paper, three signal parameters (Hurst exponent, Shannon entropy, and phase space diagram) are used to analyze their variation along the length of the pipeline.

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For the analysis of fluidized bed of sand particles, Ahuja, Agarwal, Sethi, and Raj (2005) used the Hurst exponent, which they found to rise, peak and then fall with increasing superficial gas velocity. Azizpour, Mostoufi, Zarghami, and Sotudeh-Gharebagh (2011) used the Hurst exponent as a parameter for analyzing fluidized bed hydrodynamics near the transition point from bubbling to turbulent fluidization regime. They observed a similar trend in the Hurst exponent of macro structures. This trend in the Hurst exponent has been correlated with a regime transition in the fluidized bed. Sheikhi, Sotudeh-Gharebagh, Mostoufi, and Zargham (2013) divided signals into three levels of micro-, meso-, and macro-scales. They observed micro-scale signals with all Hurst exponents smaller than 0.5, meso-scale signals with some Hurst exponents larger than 0.5 and some smaller than 0.5, and macro-scale signal with Hurst exponent greater than 0.5. Sedighikamala and Zarghami (2013) studied the behavior of a gas solid fluidized bed and found that the behavior of macrostructures (bubbles) did not change notably with increasing gas velocity because the change in Hurst exponent is small.

Kang, Woo, Ko, Cho, and Kim (1999) analyzed pressure fluctuation signals from three-phase fluidized bed. They observed in pressure fluctuation data that the Shannon entropy of pressure fluctuation data attained a local minimum by varying the liquid flow rate. A flow transition in the fluidized solid particles was detected quite conveniently using the variation in Shannon entropy. Zhong et al. (2009) studied the transitions of flow patterns (under-fluidization, steady fluidization, and turbulent fluidization) in a biomass fluidized bed from variations in Shannon entropy. Zhong and Zhang (2005) observed that for a spout fluid bed at high spouting velocity the Shannon entropy at all bed locations increased sharply accompanied by an asymmetric unstable flow. The Shannon entropies of different flow regimes are distinct, so they were used to identify the flow regimes. Duan and Cong (2013) analyzed pressure fluctuations resulting from the non-uniform flow behavior of solid particles (particles classed as Geldart groups B and D) in a fluidized bed using an analysis of Shannon entropy. Based on its variation, they were able to observe transitions between bubbling fluidization, turbulent fluidization, and fast fluidization.

Kim and Han (1999) studied the effects of coarse particles and relative humidity of air on the flow behavior of polymer powders–air suspension in the riser. They observed that the size of the phase-space attractor increased with increasing solid circulation rate. Similarly, Briongos and Soler (2005) used the attractor size to characterize fluidization dynamics in slugging flow regime. Here the increased number of particles may have increased the interactions between particle–particle and particle–wall. Zhao, Jin, Gao, Du, and Wang (2014) also used the phase space attractor to analyze different flow patterns in a vertical upward three-phase flow of oil–gas–water.

Experimental

Pneumatic conveying experiments were conducted over a 173-m-long test pipeline conveying fly ash. Fly ash has a particle density of 2096 kg/m^3 and mean particle diameter 14.91 μm. The calculated terminal velocity of fly-ash particles is 0.013 m/s. Based on Geldart's fluidization diagram (a plot between particle–gas density ratio and mean particle diameter), the fly ash used in this experiment was classified as Group A. Group A materials have higher air retention capability and hence are suitable for fluidized dense phase flow. The particle size distribution for this fly ash material has been presented in Fig. 1. The experiments were performed by pre-pressurizing the conveying material in a 1-m^3 top discharge blow tank or feeder with the help of supplied air from a controlled bank of sonic nozzles before feeding into the pipeline (53-mm pipe diameter, 173-m length, see Fig. 2 for a schematic diagram of the pipeline). One pressure transmitter was located near to the supply point of air at the bottom of the blow tank (primary air) to measure the primary air pressure. Part of the air is supplied near to the feeding point of the blow tank (secondary air) at which the pressure is measured using a pressure transmitter; this pressure is referred to as the secondary air pressure. Twenty-two pressure transmitters were fixed on the top and bottom of the pipeline at different locations along its length to measure the gauge pressure values. A SCXI-1102 data acquisition system (Yokogawa, Japan) was used to record electrical signals from the load cells and pressure transmitters. This system has 32 differential channels. Pressure data were recorded by each of the pressure transmitters at a sampling frequency between 80 and 100 Hz. The solids mass flow rates from the blow tank and into the receiver were measured using a series of load cells. Before conducting the experiment, the pressure transmitters were calibrated using a Barnett deadweight tester and the load cells were calibrated by placing different known weights upon it. The experiments were performed over a 12–50 range in solids loading ratios for fly ash. The inlet gas velocity for fly ash varied between 3–12 m/s.

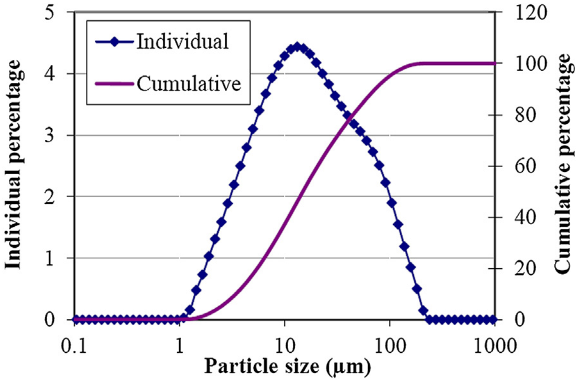

Fig. 1. Particle size distribution of fly ash.

Transient parameter analysis

After a bend, particles are subjected to deceleration that dampens particle turbulence. Nevertheless, after a certain distance, particles are reaccelerated in the flow. Pressure signals near a bend are affected (Mittal et al., 2014). Hence transmitter locations are chosen sufficiently distant (approximately 8 m) from a bend section of pipe. Pressure transmitters T1, T15, and T17 were maintained at distances 27, 100, and 129 m, respectively from the blow tank. The location of transmitter T1 was chosen as the flow there reaches a steady state. The transmitters T15 and T17 were located well apart from each other and also T1 so that different signal data can be captured for each transmitter.

For the purpose of analysis, three distinct flow conditions were chosen as:

Case	ΔP (kPa)	m^*
1	233	26.3
2	235	29.6
3	186	14.2

The Hurst exponent, Shannon entropy, and phase-space attractor size were calculated for the time-varying pressure data registered by the transmitters at the three locations (T1, T15, T17) for each of the flow conditions. Pressure signals for the three flow conditions at T1 are presented in Fig. 3. Variations of the calculated parameters were also analyzed and given below. For the present analysis, the flow is considered as dense if the superficial gas velocity is below 15 m/s and dilute if this velocity is above 15 m/s.

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