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Flow patterns of pulverized coal pneumatic conveying and time-series analysis of pressure fluctuations

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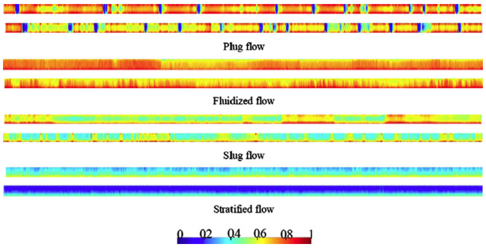
HIGHLIGHTS

- Obtained flow patterns in three conveying systems at high solid–gas ratio;
- Proposed effective empirical formulas to predict transition of flow patterns;
- Analyzed pressure fluctuations to reveal flow stability and flow characteristics of flow patterns.

GRAPHICAL ABSTRACT

There are multiple air gaps appearing in plug flow. The particles are full of pipe with higher solid concentration in fluidized flow without gas gaps. There is a settled layer between solid slugs with higher solid concentrations for slug flow. The flow pattern is characterizes by dilute-phase flow at the top of pipe and dense-phase flow in the bottom for stratified flow.



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ABSTRACT

Flow instability is a key question which needs to be solved for the development of dense-phase pneumatic conveying. Flow patterns are closely related with flow instability. There is a gap in our knowledge of gas–solid flow patterns in the dense-phase pneumatic conveying due to the lack of advanced measure technology and analysis methods. Electrical Capacitance Tomography (ECT) is an effective and advanced measure method which was used to research flow patterns in pulverized coal dense-phase pneumatic conveying with solid–gas ration of 60–560 kg/kg. With stack of ECT images in order of time, different flow patterns were defined and classified in the horizontal and vertical pneumatic conveying systems. Plug flow, fluidized flow, slug flow and stratified flow were observed in the horizontal pneumatic conveying; there were plug flow, fluidized flow, slug flow and annular flow in the vertical pneumatic conveying. The relationship between Reynolds number and Archimedes number was used to predict transition of these flow patterns. The prediction is in good agreement with experimental results in the experimental range. In addition, some analysis methods were introduced to research the flow patterns, such as the Standard Deviation (SD), Power Spectrum Density (PSD) and wavelet analysis. We found that flow stability can be represented with SD and PSD. PSD is preferred to SD for its higher resolution ratio and noise immunity. The wavelet analysis can reflect flow characteristics and energy distributions in the different scales for different flow patterns.

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1. Introduction

Pulverized coal dense-phase pneumatic conveying has applied successfully in dry coal powder gasification due to lower gas consumption. However, unsteady flow and blockage in the conveying may affect the combustion characteristics of the gasifier.

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This has attracted more attention from some researchers. Li et al. (2002) found that the unsteady flow and blockage were related with flow patterns in a great extent. Furthermore, the accuracy of measurement of gas–solid flow parameters also depended on flow patterns (Guo et al., 2006). The design of pneumatic conveying systems required us to know flow patterns of gas–solid flow (Rabinovich and Kalman, 2011). Therefore, research on flow patterns of pneumatic conveying has an important significance for industrial application.

Pneumatic conveying was generally divided into two categories, dense-phase and lean-phase conveying (Konrad, 1986). Chen et al. (1998) observed plug flow, slug flow, dune flow, stratified flow and suspension flow in the horizontal conveying. Slug flow was a discontinuous flow and caused large pressure pulses. Further decrease of gas velocity induced the blockage of pipe. The large pressure pulses were a warning signal. The flow regimes included packed bed flow, bubble-free dense-phase flow, slug/bubble flow, fast fluidization or turbulence flow in gas–solid vertical transport (Bi and Grace, 1995). In addition, some scholars attempted to use some empirical formulas to predict the transition of flow patterns (Wypych and Yi, 2003; Bi et al., 1993).

Although pneumatic conveying processes were of great importance for industrial applications, these applications mostly depended on empirical methods due to the lack of sufficient information and data to predict the essential flow patterns and the conveying parameters (Pahk and Klinzing, 2008). Pressure fluctuations contain abundant information of gas–solid flow mode, and can be used to identify flow patterns online. The signals seemed to be random, but in essence were related to flow patterns (Zhou et al., 2007). Tsuji and Morikawa (1982) and Matsumoto and Harakawa (1987) suggested that the identification of flow patterns was feasible through pressure fluctuations.

Pulverized coal is black and apt to adhere to the wall of glass pipe. As a result, it is very difficult for us to visually observe the flow patterns of pulverized coal. Furthermore, visual observations were uncertain and vague (Dhodapkar and Klinzing, 1993). Thus, more and more researchers begin to use Electrical Capacitance Tomography technology to monitor flow patterns. Ostrowski et al. (1999) introduced Electrical Capacitance Tomography (ECT) to monitor dense phase plug flow and demonstrated that ECT was a robust tool in flow pattern detection of dense phase powder conveying. Jaworski and Dyakowski (2002) gave body shape type information, internal structure of the flow instabilities, their propagation velocity and frequency characteristics using a twin-plane ECT in the dense-phase pneumatic conveying. Romanowski et al. (2006) used Bayesian statistics for analysis of ECT data during slug formation in the horizontal pneumatic conveying.

Although ECT has been used successfully in laboratory tests, its application in industry has been limited either by difficulties in practical implementation or simply by cost (Li et al., 2002). However, pressure fluctuations are detected readily by pressure transducers in industrial pneumatic conveying pipelines. These transducers commonly used in process control applications are simple and cost-effective instruments. Furthermore, they have no impact on flow in the pipe. Therefore, the identification of flow patterns through pressure signals has attracted more and more attentions (Liu et al., 2008).

Dhodapkar and Klinzing (1993), studied pressure fluctuations in pneumatic conveying systems and found that the distinguishing power spectral density (PSD) functions were observed for the various flow regimes. Hui (2002) extracted the fluctuating pressure components caused by dispersed suspension and dune flow from the random-like pressure fluctuations through wavelet multi-resolution analysis. Pahk and Klinzing (2008) analyzed time series of the observed pressure signals in order to obtain information about flow regimes based on four different analysis techniques: PSD, phase space diagram, rescaled range analysis and wavelet analysis.

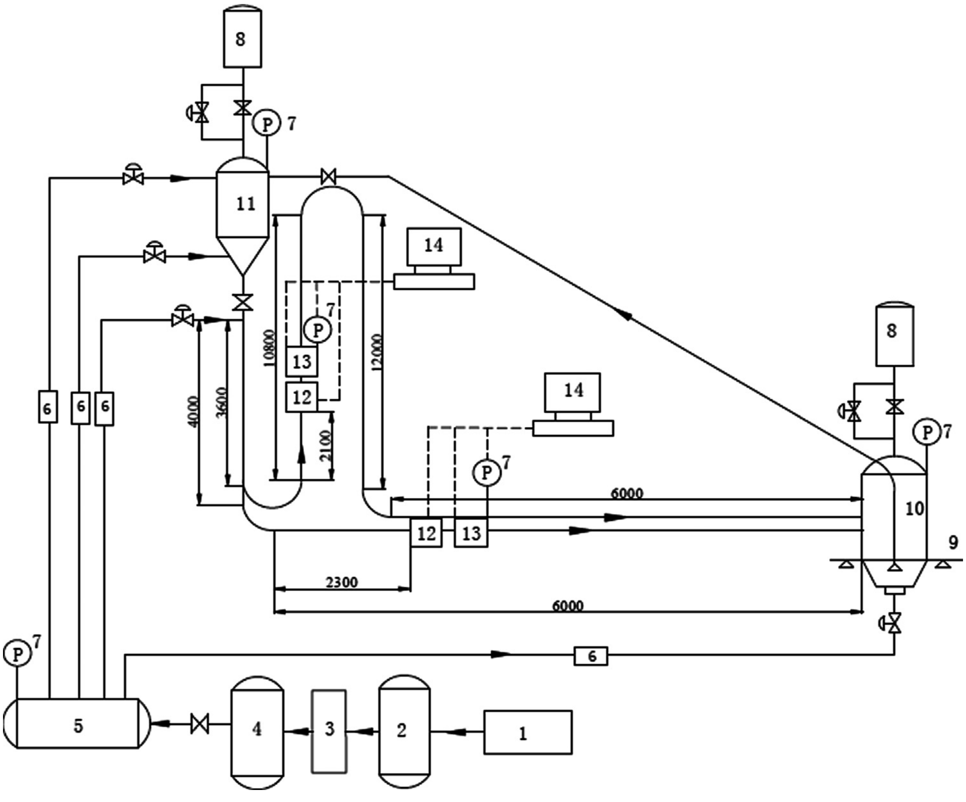

Fig. 1. Schematic for three conveying systems, 1 — air compressor; 2,4,5 — buffer; 3 — drier; 6 — gas mass flow meter; 7 — pressure transducer; 8 — dust; 9 — weigh cell; 10 — receiving vessel; 11 — feeding vessel; 12 — solid mass flow meter; 13 — ECT sensor; 14 — computer.

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