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An investigation into pressure fluctuations for fluidized dense-phase pneumatic transport of fine powders

A. Mittal [a,*], S.S. Mallick [a], P.W. Wypych [b]

[a] Department of Mechanical Engineering, Thapar University, Patiala, Punjab 147004, India
[b] Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong, NSW 2500, Australia

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ABSTRACT

This paper presents results of an ongoing investigation into the flow mechanism for the pneumatic conveying of fine powders conveyed from fluidized dense phase mode to dilute-phase. Three different techniques of signal analysis (i.e. rescaled range analysis, phase space method and technique of Shannon entropy) have been applied to the pressure fluctuations obtained during the solids–gas flow of fly ash (median particle diameter 30 μm; particle density 2300 kg m^{-3}; loose-poured bulk density 700 kg m^{-3}) through a 69 mm I.D. × 168 m long pipeline and also white powder (median particle diameter 55 μm; particle density 1600 kg m^{-3}; loose-poured bulk density 620 kg m^{-3}) through a 69 mm I.D. × 148 m long test rig. Results show that with increasing conveying distance (and conveying velocity in the direction of flow), there is an overall decrease in the values of Hurst exponent, an increase in the area covered by the phase-space diagram and an increase in the Shannon entropy values, indicating an increase in the degree of complexity of flow mechanism (or turbulence) along the length of the conveying pipeline. All the three methods have revealed that the closely coupled bends reverse the trend of change of Hurst exponent, phase-space diagram area and Shannon entropy values. This is due to the slowing down of particles caused by the friction of particles along the bend wall resulting in dampened particle turbulence.

1. Introduction

Pneumatic conveying has emerged as a popular method of material handing for bulk powders and granular products in industries such as power, mining, chemical, agriculture, cement and pharmaceutical. Even though pneumatic conveying is being used extensively in industry, there are still significant challenges involved in designing new systems, primarily due to the difficulties in predicting the flow mechanisms and important design and operating parameters, such as line pressure drop, dense- to dilute-phase transition and blockage or minimum transport conditions. The is due to the complex interaction between solids and gas under actual flow situations, influenced by the various bulk solids characteristics, such as particle shape, size, density, moisture content etc. Previous researchers [1,2] have identified various modes of solid–gas flow inside horizontal pipelines depending upon the nature of product being conveyed (such as deaeration and permeability characteristics) and the superficial flow velocity. For coarse granular particles one popular mode of conveying is dilute-phase, where particles are suspended in the carrier gas throughout the entire cross-section of pipe, while fine powders (such as fly ash, cement etc.) are able to be conveyed in fluidized dense phase, where particles move as dunes along the bottom of pipeline and above this layer some particles travel in suspension. The fluidized dense-phase mode of conveying provides several advantages over conventional dilute-phase, such as high solids loading ratio, smaller sized compressor, reduced gas and particle flow velocity, smaller pipe and support size requirement, etc. However, the flow mechanism is highly complex in dense-phase, since it involves movement of highly turbulent and fluidized dunes at high concentration. As a result, previous investigations carried out by Stegmaier [3], Pan [4], Pan and Wypych [5], Jones and Williams [6] and Williams and Jones [7] have heavily relied on empirical power function based modelling approaches to represent solids friction, minimum transport boundary, etc. However, investigations performed on the scale-up accuracy of these models show that under proper scale-up conditions of pipeline length and/or diameter, these empirical models generally do not provide accurate results [8].These approaches have frequently used steady-state data with very little attention towards understanding the transient nature of pressure fluctuations during solids-gas flows. Pressure fluctuations are produced in pneumatic conveying systems due to the turbulent nature of the gas–solids flow. The inherent fluctuations of flow could be a great source of information in analysing the condition of flow and to provide quantitative interpretation of the flow hydrodynamics inside the pipeline.

Hyun and Young [9] analysed the pressure fluctuations along the height of a riser using deterministic chaos theory to explore the effects

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[*] Corresponding author. Tel.: +91 9996412318.
E-mail address: anumittal_m@yahoo.co.in (A. Mittal).

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of coarse particles and humidity of air on flow. Hoon et al. [10] studied the pressure fluctuations in a fluidized bed of polymer powders by the deterministic chaos analysis. Yong et al. [11] investigated the highly complex and irregular behaviour of multi-phase-flow (gas–solid–liquid) in the riser of a circulating fluidized bed using phase space portraits. Bai et al. [12] carried out research to characterize the fluctuating pressure signals to distinguish between the flow behaviour of different classes of particles in fluidized beds. To examine the chaotic behaviour of six different types of powders and to identify flow regime transitions in reactor, Lijia et al. [13] applied Hurst analysis on pressure fluctuations of the fluidized solids-gas bed. The Hurst exponent represented persistent and anti-persistent behaviour of signal (for $H > 0.5$, implies persistent hydrodynamic behaviour i.e. bubble movement is in ways of chains with local circulation of few small bubbles, while for $H < 0.5$ indicates anti-persistent hydrodynamic behaviour i.e. random movement of medium sized bubbles along with coalescence of small sized bubbles into large bubbles). Ryuji and Atsushi [14] plotted radial distribution of Hurst exponent in the riser for three different values of solids loading ratio and showed that Hurst exponent values increase from the centre of the riser towards the wall. Waheed et al. [15] investigated the pressure fluctuations generated in bubble columns of fluidized beds. The variation in the attractor structure was observed with change in superficial gas velocity with air-water system. Zhong et al. [16] studied the dynamic behaviour of biomass fluidized beds using Shannon entropy. Duan and Cong [17] used the method of Shannon entropy to compare flow behaviour in different regimes and flow pattern of different powders from Geldart [18] Group B and D.

From the above review, it can be seen that a considerable amount of work has been carried out to analyse the pressure fluctuations in the case of fluidized beds. However, only limited research has been reported so far towards analysing pressure fluctuations for horizontal pneumatic transport, especially for fine powders (being conveyed from fluidized dense- to dilute-phase flow).Williams [19] attempted to find the average pulse velocity from pressure fluctuation data using time delay analysis. Dhodapakar and Klinzing [20] observed distinct power spectral density functions for various flow regimes in horizontal pneumatic transport. Cabrejos and Klinzing [2] performed rescaled range analyses on pressure fluctuations to identify different flow regimes for polymer particles, glass beads and alumina. Pahk and Klinzing [21] determined the flow characteristics for horizontal pneumatic conveying of coarse particles by analysing pressure fluctuations using different signals analysis techniques, such as power spectral density, phase space diagram, rescaled range and wavelet analysis. It is apparent that the majority of the research carried out in the area of pressure signal analysis for horizontal pneumatic conveying is for coarse granular products, which involves a comparatively less degree of complexity as compared to the conveying of fine powders under fluidized dense phase conditions. The aim of the present work is to understand the flow mechanisms during the pneumatic transport of fine powders from fluidized dense- to dilute-phase flows by relating the nature of pressure fluctuations to the flow regime inside the pipeline. Shannon entropy, rescaled range analysis (estimation of Hurst exponent) and attractor analysis (construction of phase space diagram) have been used in the present work to analyse the pressure signals.

2. Experimental work

For conveying of fly ash and white powder, two different test rigs were used that are shown in Figs. 1 and 2.

The test setup for conveying fly ash comprised a bottom-discharge blow tank feeding system of capacity 0.9 m^3; mild steel pipeline of 69 mm I.D. and 168 m length including 7 m vertical lift and five 1 m radius 90° bends; 150 mm N.B. (nominal bore) tee-bend, which connects the end of the pipeline to the feed bin; receiver bin of capacity 6 m^3; pressure transducers (P1 to P5) located along the length of pipeline; load cells on feed bin and receiving bin; annubar with DP meter and data acquisition unit for data recording and analysis. Pressure signals were recorded with the help of pressure transducers of Endress and Hauser (model: Cerabar PMC131), having accuracy of 0.05%–0.075%; pressure range of 0–6 and 0–2 bar-gauge (depending on the location of transducer in pipe) and current signal of 4–20 mA. Mass flow rates of solids coming out of blow tank and going into the receiver bin were obtained from the load cell data of the blow tank and receiver bin, respectively. Mass flow rate corresponding to the more accurate receiver bin load cells has been used in the present paper. Air flow rate was measured using an annubar upstream of the blow tank. A flow control valve (needle valve) was used to control the air flow rate. High pressure pinch valves were used in blow tank. Analogue electric output from the pressure transducers (4–20 mA) and load cells (0–5 V) were acquired and digitized at sampling frequency 50 Hz with the help of multi-channel data acquisition system (Datataker 800 or DT800 of Data Electronics) having 16-bit resolution. Sampling frequency selected for acquiring the pressure signals is comparable to the frequency used by other researchers [17,19], who have also performed similar work on analysis of pressure fluctuations obtained during solid–gas flow. For conveying white powder another test rig was used that comprised a bottom-discharge type blow tank feeding system of capacity 0.5 m^3; mild steel pipeline of 69 mm I.D. and 148 m long including a 6.95 m vertical lift and five 1 m radius 90° bends. Locations of the pressure transducers were similar to that of the fly ash test rig except for one new tapping point that was introduced almost at the midpoint of the straight pipe section near the exit of the pipeline. Pressure transducer P6 in the test rig of white powder (Fig. 2) is located at the same position where P5 transducer was located in the fly ash test rig (Fig. 1). The new tapping point in the white powder test rig (P5) was placed almost midway between P4 and P6. P1 transducer was used to record the total pipeline pressure drop, while the static pressures along the pipeline were recorded with the help of pressure transducers P2 to P6. For flow visualization, a sight glass of 1 m length and made up of toughened borosilicate glass was installed just after the P6 location. All other instrumentations used were similar to the test rig used for fly ash shown in Fig. 1. Properties of the fine powders that were pneumatically conveyed are listed in Table 1.

3. Investigation into pressure signal fluctuations

Pressure signal data (pressure fluctuations against time) were obtained from all the pressure transducers (P1 to P5) installed along the 69 mm I.D. and 168 m long pipeline conveying fly ash and from P1 to P6 transducers of the 69 mm I.D. and 148 m long pipeline for white powder. Out of the large number of conveying trials that were performed with a range of mass flow rate of air and solids, pressure fluctuation plots of two experiments for fly ash and two for white powder were typically selected (covering different ranges of mass flow rates of solids and air). Fig. 3 shows the full range (300 s) of pressure signal recorded, while only steady state range (70 s) has been shown in Fig. 4. Similarly for the other conveying trials, steady state range has been selected from the full range and considered for analysis. Figs. 3 and 4 show pressure signals obtained from the high velocity and low solids loading ratio regime (dilute-phase) for fly ash while Fig. 5 shows the pressure fluctuation recorded from the low velocity and high solids loading ratio regime (dense-phase) for fly ash. Similarly for white powder, Fig. 6 shows the high velocity and low solid loading ratio regime, while Fig. 7 shows the low velocity and high solid loading ratio regime.

By comparing the nature of fluctuations of pressure signals obtained from the tapping points P1 to P5 (fly ash) and P1 to P6 (for white powder) of Figs. 3 to 7, it can be inferred that pressure signals obtained at a given location are different with respect to the number of peaks in the signal (i.e. frequency) and the amount of variations of pressure (amplitude of peaks). Thus, signal characteristics appear to be changing depending upon the location of tapping points along the pipelines. Also, comparisons between Figs. 4 and 5 for fly ash and between Figs. 6 and 7