Powder Technology 320 (2017) 726–738

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Analysis of particle dynamics in a horizontal pneumatic conveying of the minimum pressure drop based on POD and wavelet transform

Yan Zheng [a], Akira Rinoshika [b,c,*]

[a] School of Automotive and Traffic Engineering, Jiangsu University of Technology, Changzhou, Jiangsu 213001, China
[b] School of Aeronautic Science and Engineering, Beihang University, 37#, Xueyuan, Haidian District, Beijing 100191, China
[c] Department of Mechanical Systems Engineering, Graduate School of Science and Engineering, Yamagata University, 4-3-16 Jonan, Yonezawa-shi, Yamagata 992-8510, Japan

ARTICLE INFO

Article history:
Received 11 January 2017
Received in revised form 9 June 2017
Accepted 31 July 2017
Available online 04 August 2017

Keywords:
Particle fluctuation velocity
PIV
Pneumatic conveying
POD
Wavelet transform

ABSTRACT

In order to study the characters of particle fluctuation velocity at the minimum pressure drop (MPD) velocity in the acceleration and fully developed regimes of a horizontal pneumatic conveying, the particle fluctuation velocities measured by the high-speed particle image velocimetry (PIV) are first analyzed by time-averaged particle velocity, fluctuating energy, power spectrum and autocorrelation. Then the proper orthogonal decomposition (POD) and continuous wavelet transform are developed to reveal the particle fluctuation velocities in terms of the contributions to the particle fluctuation energy, time-frequency distribution, as well as probability density function from POD modes. The energy distributions of POD modes suggest that the first two POD modes are most energetic and dominate the particle motion, and the dominance increases from the acceleration regime to fully-developed regime. The time-frequency characteristics of POD modes reveal that small-scale particle fluctuations are suppressed in the fully-developed regime. It implies that the suppression of small-scale particle fluctuations may result in lower pressure drop at MPD velocity. The PDF distributions of POD modes exhibit that the particle fluctuation of first two POD modes follows the Gaussian distribution in the acceleration and fully developed regimes. However, the PDF distributions of POD modes gradually deviate from Gaussian distribution as increasing mode number.

1. Introduction

In a significant number of industrial processes, pneumatic conveying has been widely applied to transport the granular materials. Depending on the conveying purposes, different conveying regimes, such as dilute- and dense-phase conveying, are used. In the case of dilute-phase conveying, a high conveying velocity is often operated and results in additional energy consumption, pipe erosion and particle degradation. However, the dense-phase conveying of low conveying velocity usually leads to unstable flow, and causes blockage and pipe vibration. Therefore a primary key of efficient design and safe operation of pneumatic conveying system is to keep the minimum conveying velocity necessary to minimize the energy consumption with the steady and continuous transport [1–3]. To realize the purpose, it is of fundamental significance to study the mechanism of gas-particle two-phase flows, especially the dynamics of solid particles in the range of low air velocity, thus motivating the present work.

Among previous experimental studies on particle dynamics, LDA (Laser Doppler anemometry) or PIV (particle image velocimetry) is one of the popular techniques for measuring the fluctuation velocity of air and solid particles. Morsi et al. [4] investigated the characteristics of turbulent gas-particulate flow in the vicinity of a single tube by LDA. Lu et al. [5] developed an extended LDA technique to measure the distributions of particle velocities and particle number rates over a whole pipe cross-section in a dilute pneumatic conveying system. Juray et al. [6] applied LDA to investigate gas–solid mixing in the inlet zone of a dilute circulating fluidized bed. However, these investigations focused on the interaction between particles and turbulence in full-developed regime of dilute phase suspension pipe flow. To measure particle velocity fluctuations in dense-phase two-phase flows, PIV [7,8] is applied to sedimentation and granular bed in a hopper. The applicability and validity of PIV on the gas-solid two-phase flows has been proved [7–11]. Recently Yan and Rinoshika [11] applied PIV to measure the time-averaged particle velocity and concentration in a horizontal pneumatic conveying system.

Due to the complicated characters of particle motion and the complex phase interactions, the multiphase flow appears as an unsteady dynamic system. In order to reveal the unsteady features of gas-solid two-phase flow, several mathematical methods, such as power spectrum analysis [12,13], wavelet analysis [14,15], and correlation analysis,

* Corresponding author at: Department of Mechanical Systems Engineering, Graduate School of Science and Engineering, Yamagata University, 4-3-16 Jonan, Yonezawa-shi, Yamagata 992-8510, Japan.
E-mail address: rinosika@yz.yamagata-u.ac.jp (A. Rinoshika).

http://dx.doi.org/10.1016/j.powtec.2017.07.092

have been applied to the analysis of the flow structures of gas-solid two-phase flow. These mathematical tools have provided the understanding of the features of two-phase flow in both Fourier and physical spaces. However, little research focus dynamics of solid particles at the low air velocity in the view of energy distribution, which will provide fundamental information on the particle motion of time-frequency distribution in the relatively dense-phase, thus motivating the present work. The proper orthogonal decomposition technique (POD) may provide thus effective tool to analyze the particle fluctuation velocity in an energetic view.

Since the pioneering work of Lumley [16], POD analysis has been widely used to elucidate turbulent structure [17–19]. In the field of the two-phase flow, Tu et al. [20] applied POD to study the fluctuation energy created by the introduction of gas bubbles in a two-phase bubble flow. They concluded that the energy spectrum was higher for the gas phase than for the liquid phase in the first 26 modes. Munir et al. [21–22] applied POD analysis to velocity fields of both liquid-gas two phase flow. The POD analysis for a turbulence channel laden flow dispersed with small bubbles showed that the bubble injection influenced the large-scale turbulent structures [23]. However, little work deals with the POD analysis of particle fluctuation velocity in the gas-solid two-phase pipe flows, thus attracting our interest.

This study aims at revealing particle dynamics in the acceleration and fully developed regimes of a horizontal pneumatic conveying by combining the POD decomposition and continuous wavelet transform. Particle velocities measured by high speed PIV is first analyzed by time-averaged particle velocity, fluctuating energy, power spectrum and autocorrelation. Then the POD decomposition and continuous wavelet transform are employed to reveal the particle fluctuation velocities in terms of the contributions from POD modes to the particle fluctuation energy, time-frequency distribution, as well as probability density function.

2. Experimental setup and procedure

2.1. Experimental setup

Fig. 1 shows the experimental setup of the positive pressure pneumatic conveying system used in the present study. Air from a blower flows through the orifice meter, and picks up the solid materials fed by gravity from the feed tank at the inlet of the pipe. Then, the gas-particle mixture enters a conveying smooth acrylic pipeline with an inside diameter of D = 80 ± 5 mm and the particles are separated by the separator at the pipeline exit. The test pipe consists of a transparent smooth acrylic tube with a total length of about 5 m. The airflow rate and the solids mass flow rate are respectively measured by the orifice meter and load cell. The pressures loss of the conveying pipeline was measured by two differential pressure transducers (Toyoda, PMS-5M-1H) between two pressure gauge positions in Fig. 1. The precision of pressure transducer is ±0.02%. Pressure signals are amplified and then digitized using an A/D board and a personal computer at a sampling frequency of 500 kHz. In this study, air from the blower flows through a pipe with the length of 10 m before entering into the test pipe, so the velocity and pressure fluctuation caused by blower may be eliminated.

Fig. 2. Conveying solid particles.

The polyethylene non-spherical particles with a volume equivalent diameter of $d_p = 3.3 \pm 0.15$ mm, aspect ratio of 2.06 and solid density of 952 kg/m^3, as shown in Fig. 2, are used as conveying particles. Here the terminal velocity of the particle is 8.6 m/s, which is the air velocity required for a particle to suspend in a vertical air stream. The superficial mean air velocity U_a is varied from 11 to 16 m/s, and the mass flow rate of solids G_s is fixed at 0.40 kg/s. The statistical uncertainty of the superficial mean air velocity, the solids mass flow rate and the gauge pressure are ±3.86%, ±1.4% and ±1.43% at the 95% confidence level, respectively.

2.2. PIV measurement of particle velocity

The PIV measurements, as presented in Fig. 1, were carried out at three different locations: x = 0.3 m (x/D = 4, Location A), 2 m (x/D = 25, Location B) and 3.5 m (x/D = 44, Location C) from the inlet of the conveying pipeline, here x represents the distance from the inlet of particles. A light sheet of thickness b = 5 mm produced by a high-intensity continuous light source (Metal Halide 250, Moritex), as shown in Fig. 3, is used to illuminate the objective particulate flow on the center plane of the pipeline. A high-speed camera (Photron FASTCAM SA3) with a resolution of 1024 × 1024 pixels was used to

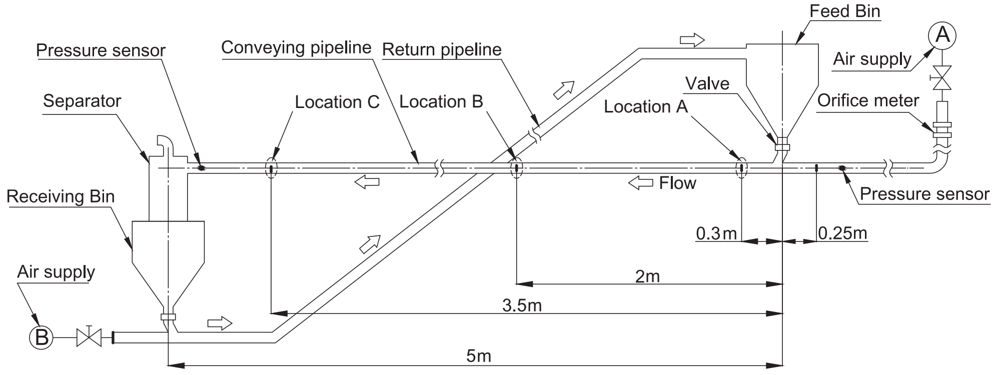

Fig. 1. Schematic of the experimental setup.