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Original Research Paper

Wavelet multi-resolution analysis on particle dynamics in a horizontal pneumatic conveying

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ABSTRACT

The particle velocities are measured by the high-speed particle image velocimetry (PIV) in the acceleration and fully developed regimes of a horizontal pneumatic conveying. Based on the measured particle fluctuation velocities, continuous wavelet transform and one-dimensional orthogonal wavelet decomposition were applied to reveal particle dynamics in terms of time frequency analysis, the contribution from wavelet level to the particle fluctuation energy, spatial correlation and probability distribution of wavelet levels. The time frequency characteristics of particle fluctuation velocity suggest that the small-scale particle motions are suppressed and tend to transfer into large scale particle motions from acceleration regime to fully developed regime. In the near bottom part of pipe, the fluctuation energy of axial particle motion is mainly contributed from the wavelet levels of relatively low frequency, however, in the near top part of pipe, wavelet levels of relatively high frequency make comparable contribution to the axial particle fluctuation energy in the suspension flow regime, and this contribution decreases as particles are accelerated along the pipe. The low frequency wavelet levels exhibit large spatial correlation, and this spatial correlation increases as the particles flow from acceleration regime to fully developed regime. The skewness factor and kurtosis factor of wavelet level suggest that the deviation of Gaussian probability distribution is associated with the central frequency of wavelet level, and the deviation from Gaussian distribution is more evident as increasing central frequency. The higher wavelet levels can be linked to small sale particle motions, which lead to irregular particle fluctuation velocity.

1. Introduction

In a significant number of industrial processes, pneumatic conveying has been widely used to transport the granular materials. For practical purposes, different conveying regimes such as dilute- and dense- phase conveying are used. The dilute phase conveying usually operated at high conveying velocity, leading to high pressure drop, pipe erosion, and particle degradation. For dense phase conveying, low conveying velocity usually results in unstable flow, which causes conveying pipe blockage and vibration. Therefore, a key design criterion of pneumatic conveying system is to keep the conveying velocity as low as possible to minimize the pressure drop without blockage occurs [1–3]. To realize the purpose, it is of great importance to investigate the particle dynamics of pneumatic conveying system, especially the particle dynamics in the range of relatively low conveying velocity.

Among the previous experimental studies on gas-solid two-phase flow, LDA (Laser Doppler Anemometry) or PIV (Particle Image Velocimetry) is one of the popular techniques for measuring the velocity fields of gas or solid particles. Using LDA, Morsi et al. investigated the particle dynamics of gas-solid two-phase flow in the vicinity of a single tube [4]. An extended LDA method was developed to measure the distributions of particle velocities and particle number rates over a whole pipe cross-section in a dilute pneumatic conveying system [5]. 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 fields in relatively dense two-phase flow, PIV is used to investigate particle sedimentation [7] and granular distributions in a hopper

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[8]. Recently Yan and Rinoshika [9] used PIV to measure the time-averaged velocity and concentration of particles in a two-phase pipe flow. However, little attention has been paid to the dynamics of solid particles from fully-developed to acceleration-regime in the relatively dense-phase, which will provide fundamental information on the pneumatic conveying, thus motivating the present work.

During the past decades, wavelet analysis has been extensively applied in the investigation of diverse physical phenomena and found to be particularly useful. Li [10] applied wavelet multi-resolution and cross-correlation analysis in the dispersed suspension swirling flow and dune flow, and the pressure fluctuation were extracted and analyzed in different scales. Ren et al. [11] analyzed dynamic behavior in fluidized beds by examining wavelet spectrum functions of various dynamic signals. They decomposed the signals into three components: micro-scale (particle size), meso-scale (cluster size) and macro-scale (unit size). Nguyen et al. [12] developed a method for the objective discrimination of the two-phase flow pattern by means of the local wavelet energy coefficients map of continuous wavelet transform. Besides, orthogonal wavelet analysis was also applied to investigate the wall pressure–time signal in a two-phase flow [13]. Takei et al. [14] used the three-dimensional wavelet multi-resolution technique to extract the particle concentration distribution of dense flow captured by Computed Tomography (CT), and the time and spatial particle distribution with a specific frequency level was visualized using this technique. However, little attention has been paid to the particle fluctuation velocity fields in both fully-developed and acceleration regimes from multi-scale point of view, which would provide more detailed information on the particle dynamics in the gas–solid two-phase pneumatic conveying system, thus attracting our interest.

This study aims at revealing the multi-scale particle dynamics in the acceleration- and fully-developed regimes based on continuous and one-dimensional orthogonal wavelet analyses. Firstly, the time frequency characteristics of axial particle fluctuation velocities are investigated by continuous wavelet transform. Secondly, the particle fluctuation velocities are decomposed into different wavelet levels based on their central frequencies. Finally, the fluctuation velocities of different wavelet levels are analyzed in terms of particle fluctuation energy, two-point correlation and probability distribution.

2. Experimental setup

2.1. Test rig configuration

Fig. 1 shows the test rig configuration of the positive pneumatic conveying adopted in the present study. The horizontal test pipe is made up of transparent resin material, having an inner diameter of D_{in} = 80 ± 5 mm, and the length of it is 5 ± 0.02 m. Before entering into the test pipe, the air from the blower flows through a pipe with a length of 10 m. Solid particles supplied from the feed bin are picked up by the air flows from the blower. At the end of test pipe, solid particles are separated through a separator. The solid mass flow rate and airflow rate were measured by the load cell and orifice meter respectively. The pressure loss was detected using differential pressure transducers (Toyoda, PMS-5M-1H) positioned at the entrance and outlet of test pipe. In present study, the cylindrical polyethylene particles having a volume equivalent diameter of d_p = 2.3 ± 0.12 mm, aspect ratio of 2.24 and solid density of 978 kg/m^3 are used as conveying particles. Here the terminal velocity of this particle is 7.5 m/s. The experiments were performed at the superficial mean air velocity U_a = 14.13 m/s, and the mass flow rate of solids Gs is fixed at 0.45 kg/s. The statistical uncertainty of the superficial mean air velocity, the solids mass flow rate and the gauge pressure are respectively ±3.46%, ±1.38% and ±1.43% at the 95% confidence level.

2.2. Particle velocity measurement

Fig. 2 presents the schematic of the PIV measurement adopted in present study. A light sheet with a thickness of 5 mm was generated by a high-intensity continuous light source (Metal Halide 250, Moritex), which is used to light up the moving particles on the central axial plane of the test pipe. 2000 successive digital images with a resolution of 1024 × 768 pixels were captured by a high-speed camera (Photron FASTCAM SA3) at a frame rate of 1000 fps (frame per second), and the corresponding sampling rate of particle velocity is 1 ms. The PIV measurements, as shown in Fig. 1, were carried out at three different locations: x = 0.3 m (x/D_{in} = 4, Location A), 2 m (x/D_{in} = 25, Location B) and 3.5 m (x/D_{in} = 44, Location C), here x is the horizontal distance from particle inlet.

Since the size of conveying particle is relatively large, the measurement domain of particulate flow is divided into many interrogation areas. Each interrogation area should be large enough to contain several particles as a group to obtain reliable measurement [7]. In this study, the measurement domain with the size of 80 mm × 111 mm was divided into 18 × 25 interrogation areas. The pixel size is about 0.11 mm/pixel, and the spatial resolution of particle velocity vectors is about 4.4 mm. The velocity of each interrogation area was calculated using FFT based cross correlation technique between two successive particle images at a known time interval. The statistical uncertainty of the measured particle velocity was estimated at ±3.86% at the 95% confidence level.

To identify the flow regimes of abovementioned three locations, the variation of the time-averaged axial particle velocity along

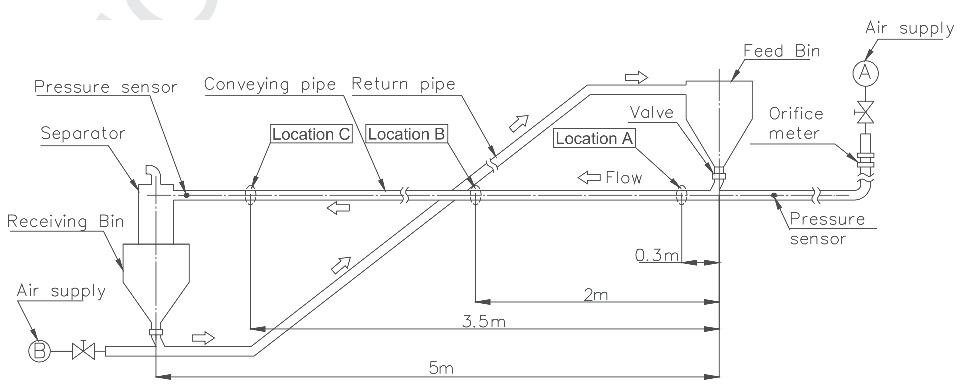

Fig. 1. Test rig configuration of positive pneumatic conveying.

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