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Original Research Paper

Multi-scale analysis on particle dynamics of a horizontal self-excited pneumatic conveying at the minimum pressure drop

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A B S T R A C T

High-speed PIV is first used to measure the fluctuating particle velocities of a horizontal self-excited pneumatic conveying at low air velocity of minimum pressure drop in the acceleration and fully-developed regimes. Then, an orthogonal wavelet multi-resolution analysis and power spectrum are employed to reveal multi-scale characteristics of particle fluctuation velocity. It is found that the pronounced peaks of the spectra of axial and vertical fluctuation velocities appear in the low frequency range near the bottom of the pipe, and the peaks of the spectra become larger by using fins. In the range of low frequencies (3–25 Hz), the wavelet components of the fluctuating energy of axial particle velocity are the main contributions, accounting for 35% and 91% for non-fin and using fins, respectively, near the bottom of the pipe. However, in the range of relatively high frequencies (50–400 Hz), the wavelet components of using fins, accounting for approximately 57%, become smaller than that of non-fin, accounting for approximately 66%, in the fully-developed regime near the top of the pipe. The auto-correlation with fins displays large quasi-periodical waves in the low frequency regime as τ increases.

1. Introduction

For many decades, pneumatic conveying of particulate materials has been widely used in various industrial applications (including steel making, chemical pharmaceutical, food processing, power generation, agricultural grain processing and commodity conveying processes) since it is convenient due to its special advantages, such as high efficiency, easy automation, flexibility of layout, security, low maintenance, easy installation and environmentally friendly conveying [1]. However, in the past decade, unstable particle fluctuations have occurred due to low conveying velocities in dense-phase conveying, which then result in pipe blockage [2–5]. On the other hand, the high power consumption, particle deposition and pipe erosion and blocking are often generated when particle materials are conveyed, especially in a dilute-phase conveying system of high air velocity. Therefore, as significant design criteria for pneumatic conveying, the pressure drop and conveying velocity should be reduced as low as possible so that materials can be transported stably and continuously [6]. To meet this goal, many new energy-saving techniques have been proposed, including the swirling flow [7–8], spiral tube [9], spiral flow [10], venturi feeder [1] and dune model [11].

It is a well-known fact that a large kinetic energy of air flow is required to accelerate particles in an acceleration region, and less kinetic energy is required to replenish the lost kinetic energy of particles due to impact and friction in a remaining region in the pneumatic conveying system. Although pneumatic conveying has enough kinetic energy of air flow to accelerate particles, the suspended force acting on particles is very small so that the particles are easily deposit on the bottom of the pipeline through the force of gravity. In order to efficiently accelerate particles, it is very important for suspend particles in an acceleration region as easy as possible [12]. Recently, by vertically mounting soft fins in front of the particle inlet to stimulate air flow oscillation, Yan and Rinoshika [12] found that the conveying velocity and power consumption were decreased effectively, it is because that the vibration of soft fins causes the oscillation of air flow as the air flows over soft fins, so that the particles were easily dispersed and suspended, and then the deposition of particles on the bottom of the pipeline may be avoided. Based on our experimental observation of particle motions, the vertical mounting soft fins are more

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efficient than any other orientation. And it is verified the particles can be easily accelerated and suspended due to fins by analyzing the profiles of ensemble-averaged particle velocity and time-averaged particle concentration measured by high-speed PIV [13].

However, the fundamental mechanism behind the observation that the oscillation of soft fins is able to decrease the conveying velocity effectively in a steady conveying system is not completely understood. The fluctuation signal of particle velocity is a dynamic reflex of the inter-coupling among the air flow, particles and wall of pipe in the pneumatic conveying system. And the fluctuation signal of particle velocity contains the abundant information of the operation state of gas-solid two phase and flow pattern transition, it is non-stationary and includes the wide frequency range in this study, and then it is essential that the fluctuation signal of particle velocity make the local and microcosmic analyses to study the multi-scale kinetics of particle fluctuation velocity by using wavelet transform in a relatively dense-phase. This is of fundamental significance and thus motivates the present work.

As a forceful multi-scale analysis method, wavelet transform has been applied to extract useful data to analyze the turbulence structures of different scales [14–16]. For example, using an orthogonal wavelet multi-resolution technique, Rinoshika and Zhou [17–20] divided the turbulent structure into a few wavelet components according to their characteristics or center frequencies, which exhibited the turbulent structures of different scales. To investigate the particle flow patterns and multi-scale characteristics of gas–solid two-phase pipe flow, the wall pressure–time signals have also been analyzed by the orthogonal wavelet multi-resolution technique [21–24]. Recently, the method of orthogonal wavelet multi-resolution was first utilized by Rinoshika et al. [25] to process the fluctuating particle velocities of the high-speed PIV, which aimed at extracting quantitative data on the particle fluctuation velocity of different frequencies in a horizontal air–solid two-phase pipe flow.

This study is aimed at revealing the influence of using soft fins on multi-scale particle kinetics at the air conveying velocity of the minimum pressure drop in a horizontal self-excited pneumatic conveying system. For this purpose, high-speed PIV is employed to measure the distributions of the particle fluctuation velocity at a certain pipe section where the regime is totally developed. Then, the orthogonal wavelet multi-resolution technique is first applied to divide the particle fluctuation velocities into different scales. The multi-scale kinetics of particle fluctuation velocity is quantitatively analyzed with respect to the contributions from different scales to the mean-squared particle fluctuation velocity and auto-correlation.

2. Experimental apparatus and procedure

2.1. Experimental setup

The experimental device of the positive pressure conveying system employed in this study is exhibited in Fig. 1. Air from a blast blower threads the orifice meter and takes away the particle fed by gravity from the storage bin at the inlet of the transporting pipeline. Then, the phase of gas-solid enters the experimental pipe, and the particles are separated from the mixture of gas-solid by the separator at the pipe exit. The conveying pipe is composed of a horizontal stable acrylic pipe with an inner diameter of $D = 80$ mm and overall length of $L = 5$ m. The airflow rate and the solids mass flow rate are measured by the orifice meter and load cell (measuring the material reduction of feed bin in unit time), respectively. At the same time, two pressure sensors are set to measure the gage pressure along the pipe.

The polyethylene particles with an average diameter of 2.3 mm and density of 978 kg/m^3 are employed as the experimental conveying material, whose size distribution ranges between 2.03 and 2.56 mm with a standard deviation of 0.25 mm. The terminal velocity of a particle, which is denoted as the air velocity capable of suspending particles in a vertical airflow, is set to 8.6 m/s. The apparent air velocity U_a varies from 10 to 16 m/s, and the mass flow rate of solids G_s is set to 0.45 kg/s.

The statistical uncertainty of the apparent average air velocity, the particle mass flow rate and the gage pressure are ±3.86%, ±1.30% and ±1.45% at the confidence level of 95%, respectively.

2.2. Soft fins

To stimulate airflow oscillation, four pieces of soft fins made of polyethylene, as shown in Fig. 2, are installed in a vertical center plane through the pipe axis in front of the feed inlet. Each piece of soft fin has a width of 19.5 mm and thickness of 0.2 mm with a density of 789 kg/m^3. Two experimental types of soft fins having different lengths of 200 and 300 mm (in accordance with piece masses of 0.63 and 0.95 g) are named SF200 and SF300, respectively. During the process of conveying particles, the oscillating soft fin of SF300 directly touches the particles, which are fed from the feed tank at the inlet of the conveying pipeline. While SF200 is only oscillated from side to side due to turbulent air flow and do not touch particle streams.

2.3. High-speed PIV imaging set-up and procedure

Fig. 3 presents the schematic drawing of the high-speed PIV experimental installation. A high-speed camera (Photron FASTCAM-SA3) with a distinguishability of 1024 × 1024 pixels was employed to catch the 3000 continuous digital particle images at a frame rate of 1000 fps (frame per second), in which the shutter speed of each frame was set to 0.1 ms. The particulate flow in the pipe, captured by the high-speed camera, is highly three-dimensional in this study. The experiment was carried out at the spatial scale of the pipeline with the inside diameter of 80 mm and the length of 5000 mm. And a thin light-sheet of thickness $b = 5$ mm generated by a high-intensity consecutive light source (Fig. 3) was utilized to illuminate the objective particulate flow on the vertical center plane of the pipeline. The measurements were performed 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 particle inlet (Fig. 1).

In this study, the particle group velocities of gas-particle two-phase flow were measured by PIV based on spatial cross-correlation method. The large PIV interrogation areas containing several particles were adopted since the size of the particle was relatively large. The measured flow area is about 80 mm × 111 mm and is divided into 18 × 25 interrogation areas and the size of each interrogation area is about 4.4 mm × 4.4 mm. The high-speed PIV images were analyzed by the PIV view software (Fig. 4). The velocity of each interrogation area or particle group is defined as local particle velocity [13–14], which has two components of u_p (horizontal direction x) and v_p (vertical direction y). Fluctuating velocities of particles, u'_p in the x-direction and v'_p in y-direction, are computed by subtracting the mean.

To prove the PIV measurement results, SigmaScan Pro 5 software was used to manually calculate the particle velocities by analyzing the particle path in the continuous high-speed images, which is also known as PTV. It is found that the particle velocity distribution of PIV is in good agreement with that of PTV, where the mean proportional error is less than 1.19%. This result proves the high accuracy of the PIV measurement. In this study, the

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