Applied Thermal Engineering 108 (2016) 502–507

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Experimental research and HHT analysis on the flow characteristics of pneumatic conveying under high pressure

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HIGHLIGHTS

- Mechanism affecting the flow characteristics of pneumatic conveying was revealed.
- Hilbert-Huang transform and experiments were conducted on the influence factors.
- Energy distribution of pressure signal reflects the flow regime & characteristics.
- Some of the results have also been verified by numerical simulation.

ARTICLE INFO

Article history:
Received 29 April 2016
Accepted 23 July 2016
Available online 25 July 2016

Keywords:
Pneumatic conveying
High pressure
Flow characteristics
Flow regime
Hilbert-Huang transform (HHT)

ABSTRACT

Pneumatic conveying under high pressure plays an important role in coal gasification. Reveal of the underlying mechanism affecting the conveying characteristics, especially the flow regime, is of great significance. Due to strong adhesion to the pipe wall of coal powder with particle size smaller than 120 μm, direct optical observation is very difficult. By combining HHT analysis and experiments, investigation on the flow regime of pulverized coal with 300 μm was proved feasible. Then this method was applied to pulverized coal with smaller size, focusing on the influences of superficial gas velocity, particle size, and conveying pressure, respectively. The results indicate that as superficial gas velocity reduces, the coal particles gradually deposit onto the bottom of the pipeline, with lower moving speed and lower-frequency collisions. Coal powder with smaller particle size is relatively easy to be carried by conveying gas flow to form suspended flow, whereas pulverized coal with larger size tends to fall down onto the bottom and form a settled layer. In addition, pneumatic conveying under higher pressure will lead to lower superficial gas velocity and higher solid-gas ratio, which consequently causes the particles to slow down and drop onto the bottom, with the collisions less intense and frequent.

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1. Introduction

Pneumatic conveying under high pressure is a key technology in the field of pressurized coal gasification. In order to produce high-quality coal gas, understanding the flow characteristics of pneumatic conveying under high pressure is of great importance [1–3]. Among the flow characteristics, flow regime research helps to analyze the phase fraction, solid-phase flow rate, and more importantly, to acquire the stability and reliability of the entire pneumatic conveying system [4,5]. In a long term, pneumatic conveying applications rely mainly on empirical methods because of insufficient information for predicting flow regimes and the parameters involved. Revealing the influences of various parameters on the flow characteristics, especially on the flow regimes, has become major concern [6].

Pressure fluctuation signal from the pneumatic conveying process can reflect flow characteristics to a large extent, because it includes various important information such as particle(s) movement, agglomeration, collapse, collisions inside particles and between particles and wall, the geometric construction of conveying system, properties of conveyed materials and most importantly, flow regime [7–9]. That is to say, the pressure signal contains abundant multi-scale information and traditional statistical analysis cannot fully uncover the multi-scale flow characteristics of pneumatic conveying.

Recently, multi-scale analysis method has been employed in investigating multiphase flow dynamics, and valuable findings

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http://dx.doi.org/10.1016/j.applthermaleng.2016.07.160
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Nomenclature

V_g	superficial gas velocity, $m \cdot s^{-1}$
μ	solid-gas ratio, $kg \cdot m^{-3}$
d_p	average particle size, µm
f	frequency
t	time
P	conveying pressure, MPa

have been obtained. For instance, Wavelet Transform has been applied to conduct multi-resolution analysis of pressure or differential pressure series acquired from multiphase flow system, in order to investigate the multi-scale characteristics of multiphase flow dynamics [10,11]. However, essentially Wavelet is a kind of window-adjustable Fourier transform and is a linear analysis method [12], which generally has low resolution due to the limited size of basic wavelet.

With the advantage of solving harmonic distortion problem usually encountered by Fourier transform when processing non-linear and non-stationary data, a relatively new multi-scale approach named Hilbert-Huang Transform (HHT) arose and has been successfully applied in some multi-phase applications recently, such as detecting particles agglomeration in gas-solid fluidized bed [13], flow regime identification of gas-liquid flow [14–16], etc. In the previous article, the authors have conducted HHT analysis on the pressurized pneumatic conveying of quartz powder with average diameter of 400 µm, which built a relationship between flow pattern and HHT characteristics [17].

In this paper, experimental research was carried out on a pilot-scale pneumatic conveying system operated under high pressure. Firstly, two different flow regimes were observed at different superficial gas velocity for coal powder with average diameter of 300 µm. Then HHT analysis was performed on the pressure fluctuation signal for each flow regime, which helped to find out the underlying mechanism affecting the flow characteristics and proved the feasibility of HHT analysis on the pneumatic conveying of pulverized coal at high pressure. Further research by HHT analysis, combined with numerical simulation and experiments, was conducted on the pressurized pneumatic conveying of 52 µm pulverized coal, focusing on the influences of superficial gas velocity, particle size and conveying pressure, respectively.

2. Experimental setup & Hilbert-Huang transform (HHT)

The pilot-scale experimental setup of pneumatic conveying at high pressure is schematically depicted in Fig. 1. High-pressure carrying gas from buffer tank is divided into fluidizing gas, pressurizing gas and complementary gas. The conveyed material in sending hopper is fluidized from the bottom with fluidizing gas and is discharged from the top of the hopper. Complementary gas is infused at the outlet of sending hopper to boost conveying capacity, and to adjust superficial gas velocity and solid-gas ratio. Pressuring gas is inflated into the sending hopper to keep the pressure constant. The pressure of receiving hopper is controlled by a motorized valve. The two hoppers both have a volume of 0.648 m^3. The conveying pipeline of total length of 53.4 m is made of stainless steel pipe with inner diameter of 10 mm. The volume flow rate of gas is measured by rotor flow meter, and the mass of pulverized coal in hopper is measured with weight cells. Pressure fluctuation signal is acquired by a piezoresistive pressure transmitter with frequency of 1 kHz and precision of 0.2%. Physical properties of conveyed materials are outlined in Table 1. Particle size was measured by a laser particle-diameter analyzer (LS200, Beckman Coulter Inc., USA). The main procedures of HHT analysis can be referred to references [12–17].

3. Results and discussion

3.1. Feasibility of HHT analysis on the flow regimes of pneumatic conveying of pulverized coal

Due to strong adhesion and electrostatic attraction of pulverized coal with mean diameter of smaller than 120 µm to the pipe wall, coal powder of 300 µm was selected as the conveyed material in order to exhibit the flow regimes more clearly. High-speed digital video camera was employed to photograph the flow regimes. Length of the visualization section was 0.16 m and inner diameter was 10 mm.

Figs. 2 and 3 show two different flow regimes under different superficial gas velocity while keeping conveying pressure and total differential pressure constant. At relatively high gas velocity (V_g = 9.2 $m \cdot s^{-1}$), the solid concentration was low and particles were uniformly distributed on the cross-section of the pipeline, which formed the dilute and suspended flow regime (Fig. 2). When the superficial gas velocity reduced to 3.8 $m \cdot s^{-1}$, dune flow was observed with the moving speed of about 1.7 $m \cdot s^{-1}$, shown in Fig. 3. At further lower gas velocity less than 2.5 $m \cdot s^{-1}$, the pneumatic conveying process was rather instable and blockage usually took place.

In addition, Hilbert-Huang spectrum produces an understandable visual two-dimension contour of the fluctuation, which illustrates the time and frequency dependent energy of the pressure fluctuation. The color bars beside each Hilbert spectrum ranging from dark blue[1] to dark red indicate the energy changes from the minimum to the maximum value. Besides, the Hilbert-Huang spectrum shows the time-dependent instantaneous frequencies of the IMFs and the color-bar denoting the amplitude of the pressure fluctuation shows that the fluctuation is non-stationary, which reflects that the non-stationary signal resulted from particles with different velocities, radial and axial velocity change of the particles in the sensing zone of the pressure sensor, particle-to-particle and particle-to-wall collisions with different speed and frequency. Thus the Hilbert-Huang transform can explain the characteristics of pneumatic conveying from a more detailed and novel perspective.

It is notable from Hilbert spectrums of the pressure fluctuations shown in Figs. 2b and 3b that the energy of the signals moves towards lower frequency, with decreasing superficial gas velocity and with flow regime transforming from suspended flow to dune flow. Hilbert-Huang spectrum depicts the variation of the energy and instantaneous frequency of the signals with time, which can reflect the flow characteristics at different gas-solid flow conditions.

In order to find out the quantitative relation between the energy distribution of the pressure fluctuation and flow regime of pneumatic conveying, the IMF components are divided into

[1] For interpretation of color in Figs. 2, 4 and 5, the reader is referred to the web version of this article.

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