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Statistical and frequency analysis of the pressure fluctuation in a fluidized bed of non-spherical particles

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ABSTRACT

In this paper, the pressure fluctuation in a fluidized bed was measured and processed via standard deviation and power spectrum analysis to investigate the dynamic behavior of the transition from the bubbling to turbulent regime. Two types (Geldart B and D) of non-spherical particles, screened from real bed materials, and their mixture were used as the bed materials. The experiments were conducted in a semi-industrial testing apparatus. The experimental results indicated that the fluidization characteristics of the non-spherical Geldart D particles differed from that of the spherical particles at gas velocities beyond the transition velocity U_c. The standard deviation of the pressure fluctuation measured in the bed increased with the gas velocity, while that measured in the plenum remained constant. Compared to the coarse particles, the fine particles exerted a stronger influence on the dynamic behavior of the fluidized bed and promoted the fluidization regime transition from bubbling toward turbulent. The power spectrum of the pressure fluctuation was calculated using the auto-regressive (AR) model; the hydrodynamics of the fluidized bed were characterized by the major frequency of the power spectrum of the pressure fluctuation. By combining the standard deviation analysis, a new method was proposed to determine the transition velocity U_k via the analysis of the change in the major frequency. The first major frequency was observed to vary within the range of 1.5 to 3 Hz.

1. Introduction

In circulating fluidized bed (CFB) boilers, the diversity of the particle diameter distribution and gas velocity within different parts of the CFB system usually leads to various fluidization states, such as bubbling or turbulent fluidization at the bottom of the furnace, fast fluidization at the upper freeboard, and bubbling fluidization in the loop seal and external heat exchanger (Cen et al., 1998). Different fluidization states may result in different combustion and heat and mass transfer performances. Therefore, a reliable understanding of the flow regime is a necessary and crucial prerequisite for the design and optimization of the combustion and heat exchange performances in the CFB system, especially at the bottom of the bed and in the external heat exchanger.

Many measurement technologies have been developed to investigate the dynamic behaviors of a fluidized bed (Werther, 1999). Among these measurement technologies, pressure-based measurement is one of the most widely used techniques due to its convenience and simplicity. During the data processing, the pressure fluctuation signals are usually analyzed in the time domain, frequency domain, or in the state space to reveal the dynamics of the fluidized bed (Johnsson, Zijerveld, Schouten, van den Bleek, & Leckner, 2000; van Ommen et al., 2011). Svoboda, Cermak, Hartman, Drahos, and Selucky (1983), Hong, Jo, Doh, and Choi (1990), and Wilkinson (1995) used experimental methods to investigate the dependence of pressure fluctuation on the particle parameter, static bed height, gas superficial velocity, and probe position. Bi and Chen (2003) calculated the maximum amplitude and standard deviation of the pressure fluctuation and compared them with the experimental data obtained in a series of fluidized beds with various column diameters to study the effects of the fluidization velocity, static bed height, cross section and position of the pressure probe. Yerushalmi, Cankurt, Geldart, and Liss (1978)

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Nomenclature

a_1	$a_2, a_3 \ldots a_p$ parameter of the AR model
C_D	drag coefficient
d_p	particle diameter, kg/m^3
D_t	column diameter, m
g	acceleration of gravity, 9.81 m/s^2
H_0	static bed height, mm
j	unit of complex
N	number of sampling point
p	order of the AR model
$P_x(\omega)$	power spectrum of the x, dB/Hz
U	gas velocity, m/s
U_c,	U_k transition velocity, m/s
U_{mf}	minimum fluidizing velocity, m/s
U_t	terminal velocity, m/s
w	(n) variance of residual data of AR model
x	(n) pressure fluctuation signal
$\bar{x}$	mean value of pressure, Pa
σ^2	variance of the input sequence
δ_x	standard deviation of pressure fluctuations, Pa
ρ_p	particle density, kg/m^3
ρ_g	air density, kg/m^3
ω	angular frequency, Hz

suggested a definition of U_c, at which the pressure fluctuation reaches its maximum, as the transition velocity from bubbling toward turbulent regime. They also defined the velocity U_k, at which the pressure fluctuation begins to level off, as the onset velocity of the turbulent regime. Chehbouni, Chaouki, Guy, and Klvana (1994) calculated the standard deviations of the absolute and differential pressure fluctuation and stated that U_c characterized the only structural change between the minimum bubbling velocity and the transport velocity. They also concluded that U_k was an artifact due to the use of a differential pressure transducer. Yang and Leu (2008) measured the pressure fluctuation data at different heights along the fluidized bed. Their tests revealed that the U_c, which was determined by the standard deviation of the absolute pressure fluctuation, was almost unaffected by the axial position of the pressure probe but increased as the static bed height increased. They also stated that U_k can be measured based on the absolute pressure measurement.

The power spectrum of the pressure fluctuation can reveal the energy distribution of the pressure fluctuation over the frequency (Zhong & Zhang, 2005). Due to its sensitivity to the flow regime transition, the power spectrum analysis has been proven as an effective tool for accessing the fluid dynamics in a fluidized bed (Jaiboon, Chalermsinsuwan, Mekasut, & Piumsomboon, 2013; Kage, Iwasaki, Yamaguchi, & Matsuno, 1991; Kage, Iwasaki, & Matsumo, 1993; Kage, Agari, Ogura, & Matsuno, 2000; Svensson, Johnsson, & Leckner, 1996a; Svensson, Johnsson, & Leckner, 1996b). Shou and Leu (2005) investigated the major frequency for different flow regimes; they concluded that a wide band spectrum signified an increase in the number of bubbles, while a narrow band with a sharp peak signified either a single bubble or slugging bed behavior. Lin and Wey (2004) calculated the power spectrum of the pressure fluctuation to examine the fluidized quality. They found that the major frequency increased with the gas velocity at low gas velocity and then remained almost constant or declined slightly as the gas velocity was increased further. Guo, Yue, Suda, and Sato (2003) conducted experiments using the Geldart B particles at elevated temperatures. Their results indicated that the major frequency was in the range of 1–4 Hz in the fluidized bed. Employing the power spectrum methodology, Svensson et al. (1996a, 1996b) carried out experiments to investigate the flow regime at the bottom of the CFB furnace and the influence of the pressure drop across the air-distributor.

However, most of the investigations mentioned above focused on the Geldart A and B particles and the fluid cracking catalyst (FCC) particles, whose diameter range was narrow. Although some studies also investigated the dynamic behavior of the Geldart D particles, the results could not meet the operation and design demands of large-scale CFB. Using spherical Al_2O_3 particles (belonging to the Geldart D particle) as the bed material, Brzic, Ahchieva, Piskova, Heinrich, and Grbavcic (2005) reported different successive regimes, namely the single bubble regime, the rapidly growing bubble regime, and the turbulent fluidization regime. Kage et al. (2000) compared the fluid dynamics of Geldart A, B, and D particles of spherical glass beads. Three major frequencies, i.e., the natural frequency of the fluidized bed, the bubble eruption frequency, and the bubble generation frequency, were reported in their work. Furthermore, the latter two frequencies were directly verified using a video camera.

Previous studies mostly used Geldart A and B particles or Geldart D particles with ideal sphericity as the bed material. In addition, traditional methods, usually the fast Fourier transform (FFT), have commonly been used to calculate the power spectrum. Traditional methods suffer from some disadvantages, such as a low discernible level of the spectrum curve (Sasic, Leckner, & Johnsson, 2005; Zhong & Zhang, 2005). In this study, the experiments were conducted on a semi-industrial testing apparatus using non-spherical particles screened from the bed material of a 300 MWe CFB boiler. Moreover, the auto-regressive (AR) model was employed to estimate the power spectrum of pressure fluctuation. The standard deviation of the pressure fluctuation was used as a qualitative means to characterize the flow regime and the bubble behavior. The parameter U_k has frequently been reported in the literature; although it lacks a decisive academic definition or a standard measurement method to date, researchers have obtained different conclusions on U_k in their studies (Bi & Fan, 1992; Chehbouni et al., 1994; Makkawi & Wrigh, 2002). This paper proposed a new method to determine U_k via the power spectrum analysis of the pressure fluctuation. The experimental results may help to elucidate the meaning of U_k.

2. Experimental

The semi-industrial testing apparatus of a fluidized bed is outlined in Fig. 1. The cross section of the furnace has a dimension of 200 mm × 200 mm. The inner height of the furnace is 6000 mm. The air-distributor consists of 22 wind caps in staggered arrangement. The schematic diagram for the air-distributor and the wind cap is shown in Fig. 2. The fluidizing air was supplied by a compressor (12). After being stabilized by a surge tank (11), the compressed air was delivered to a header (10), and two rotameters (8) were used to obtain its volumetric flow rate. Two pressure probes were installed at 100 mm above and below the air-distributor to measure the pressure. Each probe, with an internal diameter of 5 mm, has a length limited to 2 m to avoid interfering measurement (Sasic, Leckner, & Johnsson, 2007). The end tips of the probes were connected to two absolute pressure transducers (5) with a precision of 0.25% and a standard voltage output signal ranging from 1 to 5 V. A microcomputer (7), a USB-4711A type pressure module (Advantech) (6) with 12 bits of resolution, and the pressure transducers (5) constituted the data acquisition system. The data were acquired at a frequency of 50 Hz, and the total number of measured data points exceeded 9000.