Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Fluidization of solids with water in supercritical conditions – Characteristics of pressure fluctuations

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ARTICLE INFO

Article history:
Received 27 October 2015
Received in revised form 5 March 2016
Accepted 9 March 2016
Available online 16 March 2016

Keywords:
Supercritical water
Fluidized bed
Pressure fluctuations
Standard deviation
Frequency domain
Meso-scale energy

ABSTRACT

Three flow pattern evolution processes of fixed-homogeneous, fixed-homogeneous-bubbling and fixed-bubbling have been observed in a water–solid fluidized bed in supercritical conditions. In this paper, pressure fluctuation signals of each fluidization regimes were analyzed by time domain, frequency domain, and time–frequency methods. The characteristics of standard deviation of absolute pressure (AP), power density spectrum (PDS) of differential pressure (DP), multi-resolution decomposed signals and decomposed signals of three scales (macro-scale, meso-scale and micro-scale) were obtained in different flow regimes. The plot of AP standard deviation vs. superficial velocity showed a peak on the transition from fixed bed to homogenous expansion. The dominant frequency of homogenous regime (at ambient, high pressure and sub-critical conditions) was close to zero. In the bubbling regime (some supercritical conditions), a band of frequency between 0 and 1 Hz was observed, which was smaller than the classical gas–solid bubbling fluidized bed. The energy proportion of macro-scale signal component was the highest among the three scales components of signals, which indicated that the macro-scale flow dynamic was dominant.

1. Introduction

Fluidized bed has been applied to gasify biomass and coal for hydrogen production (Matsumura and Minowa, 2004; Lu et al., 2008; Guo and Jin, 2013). In order to optimally operate and control the fluidized bed, the understanding of flow behavior is necessary to achieve a stable fluid-dynamic state for controlling particle–fluid mixing, increasing chemical reaction rate and prolonging residence time. Pressure fluctuation signals are generally used to character the hydrodynamics of different flow regimes within a fluidized bed. The obtaining pressure fluctuation characteristics in each flow regimes will help to determine fluidized quality, identify the transition of flow regimes and monitor operation status online (Bi et al., 1995; Johnsson et al., 2000).

In a classical gas–solid fluidized bed, the characteristics of pressure fluctuations can reflect the complete flow patterns from fixed bed to homogeneous expansion, bubbling, turbulent and dilute transportation. The flow pattern evolutions depend on the superficial velocity, solid flow rate and the properties of solid and fluid. For Geldart Group B particles, transition of fixed-bubbling happens when the superficial velocity exceeds the minimum fluidization velocity. For Geldart Group A particles, there is flow regime

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http://dx.doi.org/10.1016/j.cherd.2016.03.012

Nomenclature

a_k	approximation sub-signal
Ar	Archimedes number
d_i	detail sub-signal
D_n	discrimination number
E	energy of PSD (Pa^2 or $m^2\,s^{-4}$)
E^a	energy of approximation sub-signal (Pa^2 or $m^2\,s^{-4}$)
E^d	energy of detail sub-signal (Pa^2 or $m^2\,s^{-4}$)
Ep	expectation function
f	frequency (Hz)
h	Hurst exponent
m	dilation parameter
N	length of time series
o	translation parameter
P_{xx}	power spectrum
$R(j)$	range function
Re	Reynolds number
R/S	rescaled range function
$S(j)$	standard deviation of $x(j)$
t	time (s)
u	superficial fluid velocity ($m\,s^{-1}$)
u_{mf}	minimum fluidization velocity ($m\,s^{-1}$)
w	window function
$x(n)$	time series
$\bar{x}$	average value

Greek letters

ρ	density ($kg\,m^{-3}$)
σ	standard deviation (Pa)
ζ	mother wavelet function

Subscripts

f	fluid
i	general index
j	general index
k	general index
s	solids
mf	minimum fluidization
mac	macro-scale
meso	meso-scale
mic	micro-scale

Abbreviation

SCW	supercritical water
AP	absolute pressure
DP	differential pressure
PSD	power density spectrum

transition of fixed-homogeneous-bubbling. The minimum fluidization velocity represents the transition velocity of the fixed-homogeneous, and the minimum bubbling velocity determines the boundary of the homogeneous-bubbling. Pressure fluctuation has been widely studied for each regimes of the classical gas–solid fluidized bed in literature (Bi, 2007; Briens and Ellis, 2005). Commonly, time domain, frequency domain and state space methods are applied to analyze the pressure fluctuation signals (van Ommen et al., 2011; Sasic et al., 2007). For the gas–solid fluidized bed, the standard deviation of the signal is taken to identify the regime evolved from fixed bed to bubbling and bubbling to turbulent regime (Jaiboon et al., 2013). The minimum fluidization velocity u_{mf} corresponds to the velocity when the standard deviation starts to rise (Felipe and Rocha, 2007). The maximum value of standard deviation of fluctuations indicates the transition from bubbling to turbulence. The power density spectrum (PSD), as a typical parameter of frequency analysis, puts up significant difference in each flow patterns of bubbling, turbulent, transition between bubbling and turbulent regimes, fast fluidization and pneumatic transport in the classical gas–solid fluidized bed or circulating fluidized bed (Shou and Leu, 2005). Power spectra is greatly affected by the physical properties and the mass flow rates of solid and fluid. Multiple bubble regime always corresponds to a wide bandwidth frequency of 1–4 Hz, and the bandwidth frequency of single bubble or slug flow was narrow (Jaiboon et al., 2013).

Flow pattern evolution processes of fixed-homogenous-turbulence forge a common sense for a classical liquid–solid fluidized bed, such as the water–sand fluidized bed at ambient condition. There are no bubbling in the classical liquid–solid fluidized bed. Homogenous bed fluidization is achieved when the superficial velocity exceeds the minimum fluidization velocity. Pressure fluctuation or vibration signals can be used to characterize the flow behavior in the different flow regimes (Sheikhi et al., 2012, 2013). The plots of standard deviation, skewness and kurtosis of pressure fluctuations vs. superficial velocity are able to determine the minimum fluidization velocity and transition velocity. The first peaks of deviation, skewness and kurtosis of pressure fluctuations are related to the minimum fluidization velocity, and the second peaks of deviation and kurtosis of pressure fluctuations correspond to the transition velocity from homogenous to turbulence (Sheikhi et al., 2012).

Fluidization patterns of Geldart Group B particles in supercritical water (SCW) fluidized bed are different from the classical air–solid system and the ambient water–solid system. Lu and Wei (2015) studied the flow transitions of water–solid fluidized bed in the range of pressure up to 27 MPa and temperature up to 482 °C. When the temperature and pressure were under supercritical conditions, three flow pattern evolution processes of fixed-homogeneous, fixed-homogeneous-bubbling and fixed-bubbling were observed for Geldart Group B and A particles. These transition processes of the SCW fluidized bed were also validated by numerical investigations of CFD-DEM and Eulerian methods (Lu et al., 2014, 2015a,b). However, little investigations about the pressure fluctuations of the different flow regimes within the SCW fluidized bed were reported in the literature. Some researchers concerned another supercritical fluid (CO_2) fluidized bed for the coating application. Marzocchella and Salatino (2000) experimentally found flow patterns including homogeneous, bubbling, transition to turbulent and turbulent in a supercritical CO_2 fluidized with Geldart Group B and A particles with system pressure up to 8 MPa. There was a homogeneous regime between fixed bed and bubbling, even for Geldart Group B particles. They found dimensionless heat-transfer coefficient and variance of differential pressure single can be used to identify the fixed bed, homogenous, bubbling, transition to turbulent and turbulent regime. The flow transition of fixed-homogeneous-bubbling for both Geldart Group B and A particles were observed by Vogt et al. (2005) in a wider range of experimental conditions with pressure up to 30 MPa. They applied analysis of transient capacitance probe signals to determine the bubble occurrence. These studies mainly analyzed the fluctuation signals in time domain. Although