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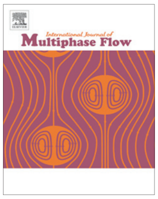

Flow structure and bubble dynamics in supercritical water fluidized bed and gas fluidized bed: A comparative study

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ABSTRACT

Supercritical water (SCW) fluidized bed is a new reactor concept for hydrogen production from biomass or coal gasification. In this paper, a comparative study on flow structure and bubble dynamics in a supercritical water fluidized bed and a gas fluidized bed was carried out using the discrete element method (DEM). The results show that supercritical water condition reduces the incipient fluidization velocity, changes regime transitions, i.e. a homogeneous fluidization was observed when the superficial velocity is in the range of the minimum fluidization velocity and minimum bubbling velocity even the solids behave as Geldart B powders in the gas fluidized bed. Bubbling fluidization in the supercritical water fluidized bed was formed after superficial velocity exceeds the minimum bubbling velocity, as in the gas fluidized bed. Bubble is one of the most important features in fluidized bed, which is also the emphasis in this paper. Bubble growth was effectively suppressed in the supercritical water fluidized bed, which resulted in a more uniform flow structure. By analyzing a large number of bubbles, bubble dynamic characteristics such as diameter distribution, frequency, rising path and so on, were obtained. It is found that bubble dynamic characteristics in the supercritical water fluidized bed differ a lot from that in the gas fluidized bed, and there is a better fluidization quality induced by the bubble dynamics in the supercritical water fluidized bed.

Introduction

Nowadays, on account of the extensive consuming of fossil fuel, the problems of environmental pollution and exhaustion of energy resources are becoming worse and worse. Hydrogen as a clean and renewable alternative fuel is gaining more and more attention. Supercritical water gasification (SCWG) of wet biomass (Matsumura et al., 2005; Lu et al., 2007, 2012) is a promising and clean technology to produce hydrogen. In 2008, we successfully developed a supercritical water (SCW) fluidized bed to gasify wet biomass, for avoiding plugging which often takes place in the tubular reactor (Lu et al., 2008). However, in our previous experiment (Lu et al., 2008), the inhomogeneous distribution of temperature in the SCW fluidized bed, instability of the gaseous product, and particles overflowing from the reactor were usually observed. The reason, we believe, is that the design of SCW fluidized bed is mainly based on the theory of traditional fluidized bed (Lu et al., 2013). Therefore, a comprehensive understanding about the effect of different operating conditions on flow structure and bubble dynamics in the fluidized bed is very necessary.

Although there are a large number of investigations on the fluidized bed under ambient condition, few works have focused on the fluidized bed under supercritical or high-pressure conditions. It has been found by previous researchers that there exists a section of homogeneous fluidization without bubbles when the superficial velocity exceeds the minimum fluidization velocity in a gas fluidized bed under high-pressure conditions, although the solids are categorized as Geldart B particles under ambient conditions (Varadi and Grace, 1978; Rowe et al., 1983; Li and Kuipers, 2002; Vogt et al., 2005). Botterill and Desai (1972) conducted an experimental work in which air or CO_2 up to 1000 kPa was used as fluidization agent. They found that the quality of fluidization increases and heat transfer coefficient doubles for large particles as the pressure increases from 1 to 10 bar. Jacob and Weimer (1987) found particulate bed expansion can be adequately described by Foscolo–Gibilaro theory through experimental work in which the gas is made up of CO and H_2 with the pressure up to 12.4 MPa. Li and Kuipers (2002) carried out a discrete particle simulation to study the effect of pressure on gas–solid flow behavior in dense gas-fluidized beds. They found that there is a more particulate flow structure in the fluidized bed under high-pressure condition, with enhanced particle–fluid interaction and decreased particle–particle interaction.

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When the gas flow in excess of that required to maintain the dense phase at minimum fluidization conditions flows through the bed, bubbles and through flow are formed (Johnsson et al., 1991). Bubble is an important feature in fluidized bed, which has a strong influence on the fluid hydrodynamics. The fluidization quality of a fluidized bed is highly dependent on the distribution of bubbles and their physical properties such as dimension, frequency, velocity, rising path and so on. Generally, big bubbles worsen the homogeneity of flow structure of the bed, while uniformly-distributed small bubbles with lower velocity produce high-quality fluidization. The investigation of bubble properties has received much attention over a considerable span of time by using different experimental techniques (Rowe and Partridg, 1965; Rowe and Everett, 1972; Halow and Nicoletti, 1992; Glicksman et al., 1987; Caicedo et al., 2003; Shen et al., 2004; Busciglio et al., 2008) and numerical methods (Hoomans et al., 1996; Boemer et al., 1997; Gera et al., 1998; Hulme et al., 2005; Olaofe et al., 2011).

Bubble properties are highly dependent on the operating condition, and the bubble dynamics in fluidized bed under high-pressure or supercritical conditions are much different from that under ambient conditions. Elevated pressure or supercritical conditions usually improve the fluidization quality. A smooth fluidization featured by smaller bubbles under elevated pressure was found in the experiments by previous researchers (Knowlton, 1977; Rowe and MacGillivray, 1980; Barreto et al., 1983; Chitester et al., 1984; Cai et al., 1989). However, different behaviors about bubble velocity were observed in previous experiments. Rowe and MacGillivray (1980) and Hoffmann and Yates (1986) observed that bubble velocity increases at air fluidized bed with the pressure up to 400 kPa and N_2 fluidized bed up to 8000 kPa, respectively, while Barreto et al. (1983) found that bubble velocity decreases in N_2 fluidized bed up to 2000 kPa. The stability of bubbles in fluidized bed under elevated pressure condition is decreased (Hoffmann and Yates, 1986), which results in decreased maximum stable bubble size and increased bubble frequency (Subzwari et al., 1978; Barreto et al., 1983; Chan et al., 1987). Furthermore, Vogt et al. (2005) carried out a comprehensive experimental study on the fluidization behavior with supercritical carbon dioxide at pressures up to 30 MPa for various solids which behave as Geldart A and B powders under ambient conditions, respectively. A correlation for homogeneous bed expansion, and minimum bubbling velocity was derived.

SCW is a special kind of fluid, and SCW fluidized bed is a new kind of technology which has been rarely investigated. Potic et al. (2005) introduced the concept of a micro-fluidized bed, which was a cylindrical quartz reactor with an internal diameter of 1 mm used for process conditions up to 773 K and 244 bar. In their experiment, homogeneous fluidization and slugging fluidization were found. In our previous work (Lu et al., 2013), the hydrodynamics of a SCW fluidized bed with internal diameter 35 mm and length 600 mm was investigated. Experimental condition was set within the range of 633–693 K and 23–27 MPa and an experimental correlation of the minimum fluidization velocity (u_{mf}) was obtained. In 2014, we (Lu et al., 2014) conducted a comprehensive numerical study on fluid hydrodynamics in SCW fluidized bed. Uniform fluidization was found even the particles are categorized as Geldart B powders under ambient condition, and it is found that bed expansion cannot be described by the empirical correlations of Richardson and Zaki (1954) or Vogt et al. (2005). However, bubble dynamics such as bubble diameter distribution, frequency, rising path and so on in SCW fluidized bed have not been investigated before, which may be significantly different from that in the fluidized bed under ambient conditions or elevated pressure conditions. An understanding of bubble dynamics in SCW fluidized bed is very necessary and of practical guiding significance. Due to the extreme circumstance in SCW fluidized bed, experiment of SCW fluidized bed is very difficult and usually expensive to be carried out and some features are out of reach for now. In recent years, thanks to the rapid development of computer technology, numerical simulation is becoming a more and more important and powerful tool in the investigation on fluidized bed. Discrete element method (DEM) has been extensively adopted in fluidized bed investigation since first combined with computational fluid dynamic (CFD) by Tsuji et al. (1993) to study fluidized bed. In DEM simulation, the motion of solid phase is obtained by tracking individual particle along the system. Recently, DEM–CFD method has been employed by many researchers to study fluidized bed (Helland et al., 2000; Rhodes et al., 2001; Kafui et al., 2002; Limtrakul et al., 2003; Pandit et al., 2005; Zhu et al., 2008; Olaofe et al., 2011; He et al., 2012; Yang et al., 2013).

The goal of this paper was to study the effect of operating condition on flow structure and bubble dynamics in fluidized bed. Two sets of DEM simulation, one was fluidized by SCW, and the other by atmospheric water vapor at the same temperature, were conducted. The superficial velocities were increased step by step to elucidate the effect of operating condition on regime transitions and flow structure. The concept of entropy in thermodynamics is introduced in this paper to make a quantitative analysis of solids mixing in gas fluidized bed and SCW fluidized bed. Besides, the Flood fill method from image processing was introduced in this paper to deal with bubbles in fluidized bed. The highly automated in-house written procedure made the investigation of bubble dynamics based on the analysis of a large number of bubbles possible. Bubble physical properties such as equivalent diameter distribution, frequency, rise path and so on, in gas fluidized bed and SCW fluidized bed were studied in this paper.

Mathematic model and method

Mathematic model

In this work, the discrete element method (DEM) and computational fluid dynamic (CFD) were coupled to study the two-phase flow characteristics in gas fluidized bed and SCW fluidized bed. In DEM–CFD model, the fluid phase was treated as continuous phase whose motion was defined by equations of continuity and momentum balance based on local mean variables on fluid cells. Particle motion is obtained by solving conservation equation of linear momentum (Newton's second law of motion) and angular momentum. As to the collision between particles, soft-sphere contact model was adopted to estimate the colliding force due to its ability to deal with the multiple collisions. The governing equations can be found in previous work (Lu et al., 2014).

The key issues in the mathematic model are the interaction forces especially the drag force in gas/liquid fluidization processes. It has been concluded by Deen et al. (2007) that, the Gidaspow (1994) drag model, i.e.: the combination of Ergun (1952) equation and the Wen and Yu (1966) equation, is most frequently used in gas–solid fluidized bed. Due to the low density and viscosity of the gas, additional forces such as visual mass force and lubrication force are usually ignored.

In solid–liquid fluidization, the interaction between liquid and particles is usually more complicated. The contribution of additional forces may need to be taken into account due to the two-phase density ratio close to unity or the viscosity of liquid is high. Among these previous numerical works of solid–liquid flow based on DEM, Li et al. (1999) studied the bubble wake behavior in gas–liquid–solid fluidization systems using a combined CFD–VOF–DPM method. The forces exerted on a particle from liquid consisted of the drag force which was calculated from the