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Bubble dynamic wave velocity in fluidized bed

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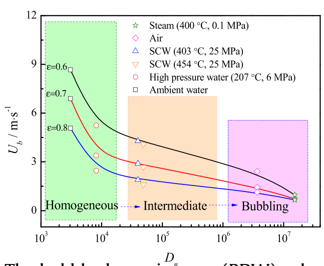
HIGHLIGHTS

- A new concept of bubble dynamic wave velocity was proposed.
- The expression of bubble dynamic wave velocity was derived.
- Bubble dynamic wave velocity can characterize different bubbling systems.

GRAPHICAL ABSTRACT



The bubble dynamic wave (BDW) velocity could characterise the bubble characteristics of different fluid-solid system and transformations form a homogeneous fluidization to intermediate and then to bubbling fluidization, as shown in Fig. 1. The BDW velocity in supercritical water (SCW) fluidized bed is an intermediate velocity between the ambient and high-pressure water-solid system (classical homogeneous system) and steam or air-solid system (classical the bubbling system) , which indicates the SCW fluidized bed is an intermediate fluidization.

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ABSTRACT

Experimental and numerical investigations have validated that the supercritical water (SCW) fluidized bed has bubbling fluidization state, which obviously diverges from the classical gas–solid fluidized bed. It is difficult to apply the classical bubbling parameters including diameter and rising velocity to characterise the bubbles within the SCW fluidized bed due to the unattainable measurements in the high temperature and pressure conditions. This paper derived bubble dynamic wave (BDW) velocity to establish a theoretical description of the bubbling characteristics for different bubbling systems. The BDW velocity is a propagation velocity of interface wave between bubble and emulsion phase induced by the perturbation of bubble volume. The expression of the BDW velocity was derived by treating emulsion phase as compressible fluid. The BDW velocity of the SCW fluidized bed (intermediate fluidization) shows an intermediate value between air or steam–solid system (classical bubbling fluidization) and ambient water–solid system (classical homogenous fluidization). Further, the BDW energy was derived to characterise the fluid dynamic in meso-scale. The variation trend of BDW energy with superficial velocity was consistent with that of the measured meso-scale energy of differential pressure fluctuation signals. This paper provided a new parameter of BDW velocity for describing the characteristics of bubbling fluidized bed.

1. Introduction

Supercritical water (SCW) fluidized bed has been used as a kind of gasification reactors for utilizing wet-biomass, coal and waste disposal (Lu et al., 2008; Guo and Jin, 2013; Jin et al., 2010; Chen et al., 2013). The two phase flow characteristics of the SCW fluidized bed show

Abbreviations: BDW, bubble dynamic wave; SCW, supercritical water; DP, differential pressure

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great divergences from the classical gas–solid fluidized bed and the classical liquid solid fluidized bed. Lu et al. (2014, 2015a) predicated flow pattern transition processes from fixed bed to homogenous and then to bubbling for Geldart-B particles based on simulated investigations by CFD–DEM method and Eulerian two fluid model. Lu and Wei (2015) further validated this processes through experimental study of the SCW fluidized bed. Many divergences of bubbling phenomena were found between supercritical fluidized bed and the classical gas–solid fluidized bed. The bubbles in the SCW fluidized bed were scattered and much smaller than the classical gas–solid fluidized bed under the same fluidization number and the path of bubble in the SCW fluidized bed is more tortuous compared to the gas–solid fluidized bed (Lu et al., 2015b). The special bubbling was also found in supercritical CO_2 fluidized bed (Vogt et al., 2005; Marzocchella and Salatino, 2000). Vogt et al. (2005) found the measured bubbles in the supercritical CO_2 fluidized bed were quite small. The state of fluid is one of the main factors of the different bubbling characteristics (Lu et al., 2015a). Based on the investigations of Lu et al. (2015a) and Liu et al. (1996), the fluidizations in supercritical CO_2 and SCW fluidized bed show an intermediate fluidization state between the classical bubbling (aggregative) and the classical particulate fluidizations. The intermediate fluidization can be qualitatively characterized by a peso-homogenous bed expansion with a large number of small bubbles. The parameters of the bubbles were hardly determined by the theory of the classical gas–solid fluidized bed.

Usually, bubble size, bubble rise velocity, bubble path and bubble number are useful for describing the bubbling fluidization. These parameters are commonly determined by correlations based on basic equation and fitting coefficients through experientially measured data (Patil et al., 2005; Karimipour and Pugsley, 2011). It is hard to measure these parameters in SCW fluidized bed due to the high pressure and high temperature conditions. This paper try to theoretically solve the problem of describing the different bubbling phenomenon in the SCW fluidized bed or intermediate fluidization state by proposing a concept of bubble dynamic wave (BDW) velocity.

The wave velocity shows different characteristics in various propagated media, a typical case is the interface wave between water and air showing different propagation velocity in each substance. In the case of bubbling fluidized bed, the interface wave between bubble and emulsion phase is induced by a perturbation of bubble volume, and the wave will propagate through the emulsion phase, which is the mixture of solid and fluid. Both the processes of origination and passage of the wave are related to the properties of emulsion phase and bubble phase and the meso-scale dynamic flow structures, which let the BDW reflect the different bubble characteristics.

The paper established a general meso-scale flow structure model, and then derived the expression of the BDW velocity by a compressible fluid analogy of emulsion phase. The study provided a closure equation of bubble fraction based on principle of energy minimization (Wang et al., 2010).

2. Bubble dynamic wave velocity

Fig. 1 shows a typical bubbling system, which is characterized by superficial fluid velocity u_f, bed average voidage ε, and bubble fraction χ. The emulsion phase and bubble phase constitute the two phase flow structure. The emulsion phase is composed by fluid and solid particles, and the particles are suspended by the fluid. The voidage of bubble phase is approximated one and the voidage of emulsion phase is ε_e. The formation and eruption of bubbles continuously change the bubble fraction χ and produce perturbation. An interrupt of bubble fraction $\delta\chi$ will destabilize the present equilibrium flow condition and generate a dynamic

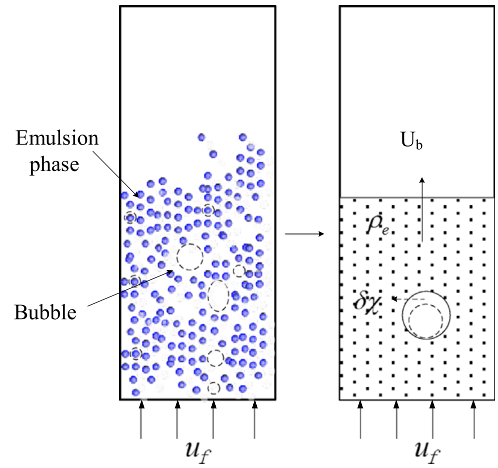

Fig. 1. BDW creation in bubbling fluidized bed.

wave of the interface between emulsion phase and bubbles, as shown in Fig. 1. The BDW is a kind of continuity waves in nature, which is a way that flow state transmit from the present dis-equilibrium to a new steady equilibrium condition. The emulsion phase bears some resemblance to a compressible fluid. It is assumed that the gas–solid mixture in emulsion phase is a continuously compressible medium, the propagation velocity is given by the general expression (Sasic et al., 2007):

$$U_b = \sqrt{\frac{\partial P}{\partial \rho_e}} \tag{1}$$

where P is induced by a pressure impulse and equal to the net force on the bubbles:

$$\delta P = \delta\left[N_b f_b\right] \tag{2}$$

where f_b is a net force on each of the bubbles, and N_b is the number of bubbles in a layer of unit area. The expression of $N_b f_b$ presents the effect of emulsion phase on a layer of bubbles, thus the dimension of $N_b f_b$ is identical to that of pressure. Under the effect, the layer of bubbles are driven up by the emulsion phase and the motion processes of the layer of bubbles are similar to that of waves.

The density of emulsion phase ρ_e in Eq. (1) can be calculated by

$$\rho_e = (1-\varepsilon_e)\rho_s + \varepsilon_e \rho_f \tag{3}$$

where ρ_s, ρ_f and ε_e are the particle density, fluid density and the voidage of emulsion phase, respectively. When bed average voidage ε and bubbles fraction χ are known, the voidage of emulsion phase can be written as

$$\varepsilon_e = (\varepsilon - \chi)/(1-\chi) \tag{4}$$

Therefore, Eq. (1) can be rewritten as

$$U_b = \sqrt{\frac{\partial\left[N_b f_b\right]/\partial\chi}{\partial\left[\rho_e\right]/\partial\chi}} = \sqrt{\frac{(1-\chi)^2}{\left(\rho_s-\rho_f\right)(1-\varepsilon)\chi}\frac{\partial\left[N_b f_b\right]}{\partial\chi}} \tag{5}$$

In the bubble layer, the number of bubbles is

$$N_b = \frac{4\chi}{\pi {d_b}^2} \tag{6}$$

The net force acted on a bubble includes drag and buoyancy force from the emulsion phase:

$$f_b = Cd_{eb}\cdot\frac{1}{2}\rho_e {u_{eb}}^2\cdot\frac{\pi}{4}{d_b}^2 + \left(\rho_e-\rho_f\right)g\cdot\frac{\pi}{6}{d_b}^3 \tag{7}$$

where d_b is the diameter of the bubble, Cd_{eb} is the drag coefficient, and u_{eb} is the slip velocity between emulsion phase and the