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A numerical study of bed expansion in supercritical water fluidized bed with a non-spherical particle drag model

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ABSTRACT

Supercritical water (SCW) fluidized bed is a novel biomass gasification reactor which uses SCW as fluidized medium and non-spherical particles as bed materials. In this paper, a new non-spherical particle drag model was developed for the sphericity between 0.6 and 1. The drag model was applied to simulate the two phase flow in the SCW fluidized bed. We also conducted an experimental study to verify the model. The simulated results of bed expansions agree well with experimentally measured data in the ambient, sub-critical and supercritical zones. With increasing superficial velocity, a transformation from homogeneous to the bubbling fluidization mode in the SCW fluidized bed with Geldart-B particles was observed by the numerical simulation. The fluidization regime of the SCW fluidized bed evolved from a pseudo-homogeneous expansion to heterogeneous expansion with an increasing temperature, which can be viewed as an intermediate fluidization between the classically bubbling and homogeneous fluidization.

1. Introduction

Supercritical water (SCW) fluidized beds have been used for gasifying biomass and coal for hydrogen production (Lu et al., 2008; Guo and Jin, 2013). The concept of SCW fluidized bed reactor was proposed first by Matsumura and Minowa (2004). Then, Lu et al. (2008) developed a SCW fluidized bed reactor for hydrogen production by gasifying wet biomass. The reactor could avoid plugging, increase the hydrogen yield and improve gasification efficiency. However, the two phase flow characteristics in SCW fluidized bed are still unclear. At present, little work has focused on this area and precisely predicted models of the two phase flow in SCW fluidized bed have not been achieved because of the complex interactions between SCW and irregular particles.

Numerical simulation is a useful method to study on the hydrodynamics and detailed information about multiphase flow phenomena. For a fluid–solid flow system, good simulation results were greatly dependent on the drag force model, which is a necessary term for describing the momentum transfer between solid and fluid phases (Loha et al., 2012; Huang, 2011). Particles in the fluidized bed are almost irregular for practical industry application. The drag coefficient of an irregular particle obviously diverges from that of a simple sphere in an infinite flow field (Zastawny et al., 2012; Wang et al., 2011). Particle shape is an important factor that greatly affects the drag force suffered by a moving particle. Fluid generates a higher drag force of a non-sphere particle than a spherical particle at the same relative velocity (Venkiteswaran et al., 2012). The drag equations of a single sphere or non-sphere particle in an infinite flow field have been studied through experimental and theoretical methods, but little attention was focused on the drag force of non-sphere particles in the multiphase system.

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Nomenclature

Ar	Archimedes number ($Ar = gd_v^3\rho_f(\rho_s-\rho_f)/\mu_f^2$)
Cd	drag coefficient of single particle in infinite fluid
Cd_s	drag coefficient of single particle in suspension
C_D	standard drag coefficient in Gidaspow drag model
d	particle diameter (m)
D_n	discrimination number
$F(\alpha_b)$	bubble accumulation fraction
g	acceleration due to gravity (m/s^2)
K_1	a function of sphericity
K_2	a function of sphericity
n	index function
n_s	the number of particles in a unit suspension
P	pressure (Pa)
P{}	probability
Re	Reynolds number
u	superficial fluid velocity (m/s)
u_{mf}	minimum fluidization velocity (m/s)
Y	dimensionless parameter

Greek letters

α_s	solid fraction
ε	voidage
γ	function
κ	volume shape factor
$\lambda(\varepsilon)$, $\lambda'(\varepsilon)$	function of voidage
ρ	density (kg/m^3)
σ_{α_s}	solid fraction standard deviation
ψ	sphericity

Subscripts

d	drag force
ds	drag force of particle in suspension system
f	fluid
fs	interaction between fluid and solid phases
o	initial state
s	particle phase
t	terminal state
v	equivalent diameter of sphere with equal volume

Current drag models which can be incorporated in the Eulerian two flow model include two types: one is the conventional drag model, such as the models of Wen and Yu (1966), Gidaspow (1994) (a combination of the Wen and Yu equation and the Ergun equation), Syamlal and O'Brien (1988), and Di Felice (1994), and the other was the structure based model, such as the EMMS drag model (Wang et al., 2010). Among those models, the Ergun drag model can describe the effect of particle shape on the drag coefficient (Ergun, 1952). However, this model is not suitable for the conditions of high voidage. Gidaspow (1994) believed that the Ergun equation was not valid while voidage was above 0.8. Shah et al. (2012) used this equation for the high solid fraction ($\varepsilon < 0.78$). Therefore, many researchers have tried to develop the expressions of drag force suffered by a single non-spherical particle in the particles-fluid system under high voidage conditions.

In the literature, the non-spherical particle drag models in the particles-fluid system were obtained by many ways. Firstly, the non-spherical particle drag model can be achieved by experimental measurement of fluidization and sedimentation experiments of non-spherical particles, such as Xie and Zhang (2001). They fluidized 10 kinds of agriculture particles with different shapes in laminar regime, and used Stokes shape factor to character the drag of non-spherical particles. The method was very useful, but limited to the Reynolds number and sphericity range due to restricted experimental materials. The second method is that the item Cd_0 in original Wen and Yu model ($Cd = Cd_0\varepsilon^{-2.65}$) was replaced by a single non-spherical particle drag model without changing the voidage function ($\varepsilon^{-2.65}$), such as Ren et al. (2014) and Cronin et al. (2010). Obviously, this method ignored the effect of sphericity of particles on the voidage function. The other approach was numerical simulation of the flow passing over particle group, such as Beetstra et al. (2007) and Shardt and Derksen (2012). The method was hard to be conducted for irregular particles. Developing non-spherical particles drag model for application in wide range of particle Reynolds number and sphericity was necessary to simulate flow patterns evolution from homogenous to bubbling, even to turbulence for non-spherical particles.

SCW fluidized beds are also a typical non-spherical particle fluidized bed, and modeling the supercritical fluidized bed has not been studied widely. Potic et al. (2005) applied a DPM model to qualitatively simulate a micro-fluidized bed with an inner diameter of 1 mm. The model provided consistent flow structures with the tested results in the sub-critical and supercritical zones. Lu et al. (2014) simulated the fluidization process in the SCW fluidized bed through a CFD-DEM study. Vogt et al. (2005a) developed a compromised model to compute the movement of bubbles in a supercritical CO_2 fluidized bed on the basis of empirical correlations. The model describes local fluid dynamics within the supercritical CO_2 fluidized bed by treating the surrounding emulsion phase as a continuum and bubble as the other phase. Rodriguez-Rojo and Cocero (2009) simulated a supercritical CO_2 fluidized bed with an Eulerian two flow model incorporating the classical drag model of Gidaspow (Gidaspow, 1994). However, little work has been conducted to consider the fluidization in the SCW fluidized bed.

In this paper, a drag equation was proposed to determine the momentum transfer between non-sphere particles and fluid in a dilute suspension system. Two phase flow in SCW fluidized bed was simulated by a multi-fluid Eulerian model coupled with a combination drag of the non-spherical particle drag model and the Ergun equation. Comparisons of bed expansion processes in the SCW fluidized bed predicted by the non-sphere particle drag model and the conventional Gidaspow drag model were conducted for different operating conditions. The effects of water states on the fluidization were investigated in ambient, sub-critical, supercritical and steam zones.

2. Experimental system

The schematic diagram of the SCW fluidized bed testing system is shown in Fig. 1. The system consists of a main tested system and a cooling system. The main system includes a tank, two high-pressure pumps, a damper, two heat regenerators, an electric heater, a fluidized bed, bypass pipes, two coolers, two regulating valves, two mass flow meters and a back pressure valve. Deionized water is pumped from the tank to the damper, heat regenerator I and II and the electric heater,