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Dynamic modelling of fluidisation in gas-solid bubbling fluidised beds

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ABSTRACT

Formation of fluidised bubbles in a fluidised bed has significant impact on the design and scale-up of the bubbling fluidised bed. To fully understand bubble motions in the fluidised bed, fluidised bubble dynamics in a gas-solid fluidised bed is investigated using CFD-DEM numerical simulation. To reveal the mechanism of bubble formation in the bubbling fluidised bed, the time autocorrelation approach is adopted to identify bubble occurrence at different bed height positions. A non-dimensional correlation accounting for the effect of local velocity field on the bubble size, which is obtained by modifying the Darton's model, is proposed for predicting the bubble size at given bed height positions. The non-dimensional correlation for predicting the size of the fluidised bubbles at various given bed height positions is obtained by regression based on the CFD-DEM modelling results. The simulation results indicate that small bubbles with high passing frequency dominate in the bottom region of the fluidised bed, while large bubbles are formed in the zone close to the free surface of the fluidised bed. The probability of the appearance of large bubbles increases as the height measured from the bottom of the fluidised bed increases, which may be attributed to the coalescence of small bubbles; this is also reasonably consistent with the results predicted using the Darton's model and experimental observations. It was observed that the sizes of the fluidised bubbles at the given height positions correlate with the local dynamic parameters characterised by the Reynolds number and the dimensionless height ratio.

1. Introduction

Particle tracking methods (Lagrangian tracking), such as the discrete element method (DEM) can be used to predict the dynamic behaviour of particles in the domain of interest or system with high accuracy, although relatively high computational cost restrains the amount of traced particles and the size of the simulated system [1,2]. This approach treats the solid phase as discrete particles whose motion is entirely modelled using the Lagrangian frame, while the carrier fluid phase is described by the Eulerian frame. The collision process modelled with the soft sphere or the hard sphere approach has been proposed to express the interactions between particles [3]. Peng et al. [4,5] carried out 2D CFD-DEM simulations of chemical looping combustion (CLC) cold flow model to investigate the effects of mixing and segregation of solid mixtures on flow behaviour in a bubbling fluidised bed fuel reactor and seqentially conducted 3D simulations to investigate the effects of operation parameters on the performance of the CLC system. It has been reported that the decreased size ratio of solid mixtures could improve the mixing of solid carriers [4] and that the fluctuations in solid circulating rate is caused by the turbulent regime in the air reactor [5]. Banerjee and Agarwal [6] adopted CFD-DEM modelling to simulate multiphase flow in the coal-direct spouted fluidised bed chemical looping combustion (CD-CLC) and reported that fluidisation in the fuel reactor depends highly on the density of bed material. Olaofe et al. [7] studied the motion of a single bubble in a pseudo 3D fluidised bed using CFD-DEM simulations and observed that the introduction at the bottom of the fluidised bed with a small width and the particle size have few effects on the fluidised bubble motion. The flood fill method was introduced by Lu et al. [8] to analyse bubble behaviour in the pseudo 3D fluidised bed based on the simulation results of the CFD-DEM model. Bubble characterisation was successfully obtained by this method, although the accuracy of the results predicted by this method relies on the refinement of the grid size. As most cases that aim at exposing bubble behaviour are based on the 2D fluidised bed, studies on 3D cylindrical fluidised bed are rarely presented. Compared with the pseudo 2D fluidised bed, bubbles in a cylindrical fluidised bed may occur in the central region, which results in the bubble identification, and using image analysis methods can be extremely difficult owing to failure of the non-intrusive approach.

To predict the bubble frequency and bubble size in the fluidised bed, various models and correlations have been proposed. Mori and Wen [9] investigated the effects of the bed diameter and the geometry of the perforated plate on the bubble size and growth rate by introducing an assumption that bubbles formed by the gas above the minimum fluidising velocity would grow along the centreline of the bed. Darton

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Table 1
Simulation conditions and parameters.

Solid phase	
Particle density	2350 $kg \cdot m^{-3}$
Particle diameter	0.15 mm
Initial bed height	0.12 m
Normal spring stiffness	200 N/m
Restitution coefficient	0.9
Solid time step	0.0001 s
Fluid phase	Nitrogen
Gas viscosity	1.663×10^{-5} Pa·s
Gas density	1.138 $kg \cdot m^{-3}$
Fluid time step	0.0005 s

et al. [10] proposed a model for the coalescence of bubbles in a gas-solid fluidised bed. In the model, the bubble size is considered to be proportional to the superficial gas velocity and catchment area in the distributor, as well as the height in the fluidised bed. Maurer et al. [11] recently investigated the effects of rise velocity distribution on the bubble size using ultra-fast X-ray tomography and proposed empirical correlations to describe it. The correlations of the bubble size and velocity distribution obtained by experimental data fitting are obtained as a function of the column size, fluidisation number, and the height of the fluidised bed. Puncochar et al. [12] proposed a new formula to model the swarm rise speed of cap-shaped gas bubble in the fluidised bed and noted that the added mass coefficient used in the formula depends highly on the geometrical configuration of the bubbles in the fluidised bed. Zhuang et al. [13] proposed a stochastic bubble developing model and applied it in the CFD-DEM modelling of a 2D fluidised bed in order to predict particle movement. The model accounts for the effects of bubbles on particle motion and successfully predicted the development and structure of the gas bubbles.

This paper presents the use of 3D CFD-DEM numerical modelling to investigate the hydrodynamics of gas-solid bubbling fluidised bed. The frequencies of bubble occurrence at different height positions were identified. A non-dimensional correlation based on the modification of the Darton's model is proposed, in which the effect of local hydrodynamics on the bubble size was taken into account.

2. Mathematical modelling

2.1. Governing equations

In the CFD-DEM model, Navier-Stokes equation governs the motion of the gas phase, while the solid phase is modelled by discrete particles whose motion is tracked by Newton's second law in a Lagrangian framework.

2.1.1. Gas-phase

The mass and momentum conservation equations for the gas phase without chemical reaction, aggregation, breakage phenomena, and phase change are given by [14]:

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g\right) + \nabla \cdot \left(\varepsilon_g \rho_g u_g\right) = 0 \qquad (1)$$

Table 2
Gas phase inlet conditions for simulation cases.

	Case 1	Case 2	Case 3	Case 4
Gas inlet flow rate (m^3/h)	1.26	1.69	1.26	1.69
Diameter of velocity inlet (m)	0.07	0.07	0.012	0.012
Gas inlet velocity (m/s)	0.09	0.12	1.55	2.07
Inlet velocity distribution	Uniform	Uniform	Non-uniform (air chamber considered)	Non-uniform (air chamber considered)

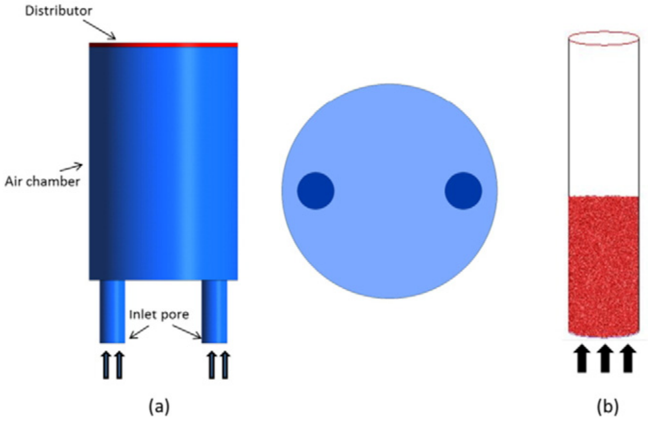

Fig. 1. Schematic of (a) gas inlet set; (b) 3D fluidised bed laden with particles.

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g u_g\right) + \nabla \cdot \left(\varepsilon_g \rho_g u_g u_g\right) = -\varepsilon_g \nabla p_g + \nabla \cdot \left(\varepsilon_g \tau_g\right) + \varepsilon_g \rho_g g + f_{sg} \qquad (2)$$

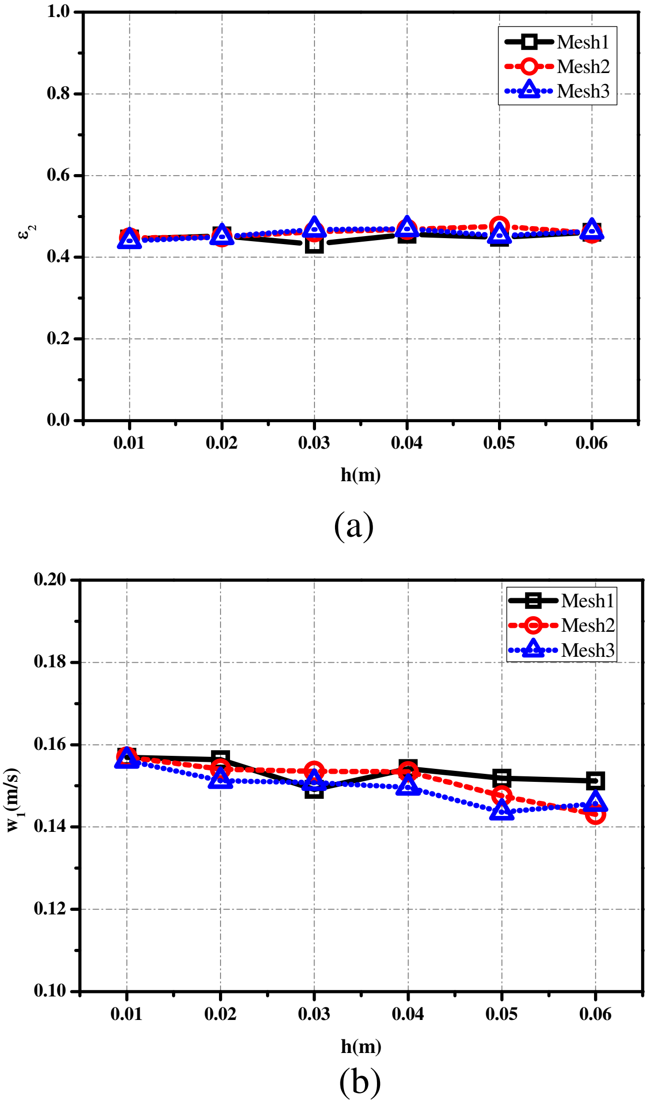

Fig. 2. Mesh dependency check with (a) area-averaged solid phase volume fraction; (b) gas phase velocity.