Powder Technology 235 (2013) 180–191

Contents lists available at SciVerse ScienceDirect

Powder Technology

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

Two- and three-dimensional computational studies of liquid–solid fluidization

Kai Zhang [a,*], Yanjun Guan [a], Xiuying Yao [b], Yunning Li [c], Xianfeng Fan [c], Stefano Brandani [c]

[a] Center of Chem Eng for Clean Energy, North China Electric Power University, Beijing 102206, China
[b] State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China
[c] School of Engineering, The University of Edinburgh, Edinburgh EH9 3JL, UK

ARTICLE INFO

Article history:
Received 1 June 2012
Received in revised form 15 September 2012
Accepted 30 September 2012
Available online 9 October 2012

Keywords:
Liquid–solid fluidization
Hydrodynamics
CFD modelling
2-D and 3-D simulation

ABSTRACT

The present work compares the hydrodynamics in the 2-dimension (2-D) and 3-dimension (3-D) liquid–solid fluidized beds using a simple two-fluid model suggested by Brandani and Zhang (2006). This model considers the effect of the particles dispersed on the momentum equations into the inviscid model A of Gidaspow (1994). Numerical simulations are conducted in the platform of CFX 4.4, a commercial CFD code, together with user-defined FORTRAN subroutines. Based on the independence of mesh size and time step in the 2-D bed, detailed hydrodynamics are compared numerically in the 2-D and 3-D beds after a sudden change in the liquid inlet velocity and the physical property of the liquid–solid system. The computational results show that the bed height, surface height and vertical solid holdup profile within the 2-D and 3-D beds are in the good agreement after a decrease in the liquid inlet velocity or an increase in the liquid–solid density difference and liquid viscosity. However, the differences of surface height and vertical solid holdup profile are found between the 2-D and 3-D simulation when the liquid inlet velocity is increased or the particle diameter is decreased.

1. Introduction

Liquid–solid fluidized beds have been widely employed in chemical, environmental, and hydrometallurgical processes due to their good transfer characteristics between solid particles and liquid medium, controllable profile of solid concentration through adjusting the superficial fluid velocity, and simple operation in comparison with mechanically agitated tanks. The successful scale-up, design and operation of liquid–solid fluidized beds mainly depend on the accurate prediction of the hydrodynamics within the beds [1–3]. Although several phenomenological models have been developed through experimental and theoretical investigations [4–7], these models are only suitable for a limited range of operating conditions.

Computational fluid dynamics (CFD) has a potential to predict the detailed hydrodynamics of fluidized beds, especially in the regions where measurements are difficult or impossible to achieve. The available CFD models for liquid–solid systems are usually grouped into two main categories: the continuum–continuum approach (Eulerian–Eulerian approach) at a macroscopic level which is represented by the two-fluid models (TFM), and the continuum–discrete approach (Eulerian–Lagrangian approach) at a microscopic level which is mainly characterized by the combination of CFD and discrete element method (CFD–DEM) [8]. In the theoretical frame of TFM, the conservation equations of mass and momentum are solved individually by each phase together with momentum transfer between the two phases. As a result, the simulation heavily depends on drag force between two phases and solid stress rheology. Although many CFD predictions were conducted to understand the hydrodynamics in liquid–solid fluidized beds, the drag force and the solid stress are still obtained through empirical or semi-empirical formulae (see Section 2). General consensus on the selection of appropriate versions therefore does not emerge.

Up to now, the CFD simulations of liquid–solid fluidized beds are mainly conducted in the two-dimensional (2-D) framework largely because three-dimensional (3-D) computational domains need more computer resources, and the two-phase models available are very complicated, even in the frame of TFM. Panneerselvam et al. [2] simulated the hydrodynamics of a liquid–solid fluidized bed using ANSYS CFX-5 software, and compared the computational hydrodynamics with the experimental results from Limtrakul et al. [3]. They found that the 3-D simulations provided more accurate prediction of solid motion than the 2-D ones. Recently, a simple TFM [9] was used to predict the overall bed voidage [10] and bed contraction behaviour [11] in 2-D liquid–solid fluidized beds. The simulated result showed that the overall bed voidage of 0.805 predicted by the simple TFM was closer to the experimental value of 0.815 in comparison with the computational value of 0.784 based on the kinetic theory of granular flow [12].

Aiming to advance the predictive capability of CFD models in liquid–solid fluidized beds and to reveal the difference of 2-D and 3-D simulations, this work firstly reviews the inter-phase drag force and particle-phase viscosity for the liquid–solid systems, and then investigates into the effect of mesh size and time step on the solid

* Corresponding author. Tel.: +86 10 61772413.
E-mail address: kzhang@ncepu.edu.cn (K. Zhang).

0032-5910/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.powtec.2012.09.046

holdup profile in a 2-D fluidized bed. The influence of liquid inlet velocity, liquid–solid density difference, liquid viscosity, and particle diameter on the hydrodynamics, including bed height, bed interface height, and vertical distribution of solid holdup, is compared in 2-D and 3-D fluidized beds by using the simple TFM suggested by Brandani and Zhang [9].

2. CFD simulations based on the two-fluid model

The momentum transfer between particles and fluid is of significant importance in modelling fluidized beds. The existing simulations on liquid–solid systems have been demonstrated that drag force and particle-phase rheology have a great influence on the hydrodynamics in the beds. Different drag force models and two kinds of methods for treating the particle-phase viscosity are therefore reviewed in details as below.

2.1. Drag force between liquid and particle phases

Momentum transfer between particles and fluid results from the drag exerted by the interstitial fluid on the particulate phase. Therefore, several drag-force models [13–17] and their modifications have been developed to simulate the hydrodynamics in liquid–solid fluidized beds, such as: (1) the Dallavalle model [13] used by Yao et al. [11], Zhang et al. [12], Chen et al. [18,19], and Gibilaro [20]; (2) the Richardson and Zaki model [14] by Doroodchi et al. [21] and modified particle drag coefficient by Dallavalle correlation [22]; (3) the Wen and Yu model [15] by Roy and Dudukovic [23], Cheng and Zhu [24,25], Gevrin et al. [26], Razzak et al. [27], Fan et al. [28], and modified particle drag coefficient by Ihne correlation [29] or by Schiller and Nauman correlation [30]; and (4) the Joshi model [16] by Reddy and Joshi [31]. Gidaspow [17] combined the equations proposed by Wen and Yu [15] and Ergun [32], which was used to simulate the liquid–solid two-phase flow by Rodriuez-Rojo and Cocero [33] and Yan et al. [34]. To avoid the discontinuity at the solid holdup of 0.2, Wang et al. [35] introduced a switch function into the Gidaspow model.

Clearly, none of the drag models mentioned above is suitable for all CFD to simulate the hydrodynamics. Cornelissen et al. [12] indicated that the Gidaspow model [17] predicted a higher voidage than the Wen and Yu model [15] in comparison with their experimental data. Panneerselvam et al. [2] found that the drag models proposed by Gidaspow [17], Di Felice [36] and Syamlal and O'Brien [37] could predict the solid flow patterns in a liquid–solid fluidized bed, but the Gidaspow model gave the best agreement with the experimental results from Limtrakul et al. [3]. Huang [38] concluded that the model proposed by Beetstra et al. [39] gave better agreement with the experimental data than the models proposed by Gidaspow [17] or Wen and Yu [15].

2.2. Kinetic theory of granular flow for liquid–solid flows

The kinetic theory of granular flow (KTGF) is an extension of the classical kinetic theory of gases [40], which was developed for gas–solid fluidized beds by Ding and Gidaspow [41]. This theory was firstly employed to predict the solid velocity, solid holdup, and liquid and solid residence time distributions in a liquid–solid circulating fluidized-bed riser by Roy and Dudukovic [23], and showed a good agreement with the measurements using the γ-ray computed tomography and computer-automated particle tracking. Subsequently, Doroodchi et al. [21] explored the effect of inclined plates on the expansion behaviour of solid suspensions in a liquid-fluidized bed. Lettieri and her co-workers investigated numerically the regime transition [29], and the stability and expanding/contracting behaviour of homogeneous fluidization [22]. Cornelissen et al. [12] carried on the CFD simulations in the liquid–solid fluidized beds and qualitatively evaluated by experimental data from the literature and their own experimental results. Panneerselvam et al. [2] simulated the hydrodynamics and flow patterns in a liquid–solid fluidized bed and obtained adequate agreements with the solid holdup, solid motion and turbulence parameters measured by Limtrakul et al. [3]. Similar to Panneerselvam et al. [2], Wang et al. [35] conducted the 2-D simulations of flow behaviours in a liquid–solid fluidized bed based on the experimental findings of Limtrakul et al. [3]. Gevrin et al. [26] analyzed the granular pressure and temperature in the liquid-fluidized beds and demonstrated a satisfactory agreement with experimental granular pressures for both low and high inertia particles. Later, Gevrin et al. [30] developed a statistical model based on the KTGF to describe the solid–liquid fluidization and focused on the unsteady structures by compared with the experimental data in the literature. Fan et al. [28] examined the non-uniformity in a liquid–solid fluidized bed with identical parallel channels. Recently, Yan et al. [34] reported the 3-D numerical simulation of a tubular loop propylene polymerization reactor under the steady state conditions, and compared the simulated results with the classical predictions and the data measured from a pilot plant. In additional, the KTGF was used to simulate the liquid–solid circulating fluidized beds by Cheng and Zhu [24,25] and Razzak et al. [27], the supercritical fluidized bed by Rodriuez-Rojo and Cocero [33], and the binary particle mixtures by Reddy and Joshi [31].

The KTGF can determine both the solid stress and solid pressure for closing the momentum equations of particle phase. However, the low-velocity liquid–solid fluidized beds are simpler than typical gas–solid fluidized beds since the hydrodynamics are more homogeneous rather than turbulent. The collisions among particles within the beds are greatly attenuated or absent due to the liquid film separating particles when they approach each other [42]. A turbulence-free model is therefore proposed in the literature [12,22,26,38].

2.3. Zero particle-phase viscosity for two-phase flows

The particle-phase viscosity is taken into consideration when solid particles are described as a continuous medium in the TFM. As an alternative approach, the viscous terms were excluded in the momentum conservation equations when additional forces were introduced [9,43–50]. A typical example is the particle bed model (PBM), which was developed by Foscolo and Gibilaro [45,51] in 1-D formation, extended into the 2-D framework by Chen et al. [18,19] and summarized in the book written by Gibilaro [20]. Di Renzo and Di Maio [8] investigated the transient behaviours of liquid–solid fluidization by using DEM–CFD method and compared the computational findings with the predictions by the PBM. They found that the new equilibrium voidage was more smoothly and easily reached when decreasing, rather than increasing, the liquid velocity, which was in agreement with the gravitational instabilities [20]. Renganathan and Krishnaiah [52] investigated the unsteady state voidage of an inverse liquid–solid fluidized bed after a step change in fluid velocity and obtained a good agreement between the experimental results and predictions by the PBM. However, the PBM suffered from an inconsistency, since the fluid phase momentum balance should be affected by a force term if it is added to the particle phase momentum equation and was due in part to fluid–particle interactions. A simple model was suggested by Brandani and Zhang [9] based on the inviscid TFM of [17], and considered the effect of the dispersed particle phase on both fluid and particle momentum equations in a quasi-equilibrium state. This model was able to predict the homogeneous (or bubbling) fluidization of Geldart type A (or B) particles [53] and the jet behaviour validated by the experimental data [54–56] in the gas-solid system. The model was evaluated by Busciglio et al. [57,58] and Yan et al. [59]. Recently, this model was attempted to predict the hydrodynamics of 2-D liquid–solid fluidization after a step change in liquid velocity [10,11]. As mentioned previously, the overall bed voidage