Advanced Powder Technology 24 (2013) 537–548

Contents lists available at SciVerse ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Numerical simulation of flow behavior of liquid and particles in liquid–solid risers with multi scale interfacial drag method

Liu Guodong [a,b,*], Wang Peng [a], Wang Shuai [b], Sun Liyan [b], Yang Yunchao [b], Xu Pengfei [b]

[a] *School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150001, China*
[b] *School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China*

ARTICLE INFO

Article history:
Received 30 May 2012
Received in revised form 23 September 2012
Accepted 24 October 2012
Available online 26 February 2013

Keywords:
Liquid–solid riser
Multi scale interfacial drag coefficient
Kinetic theory of granular flow
Euler-Euler two fluid model

ABSTRACT

Formation of particle clusters in liquid–solid circulating fluidized beds significantly affects macroscopic hydrodynamic behavior of the system. A multi scale interfacial drag coefficient (MSD) is proposed to determine effects of particle clusters on the mesoscale structure, by taking momentum and energy balance of dense phase, dilute phase and interphase into account. Based on the transportation and suspension energy-minimization method, the multi scale interfacial drag coefficient model used in this work is combined with the Euler–Euler two fluid model to simulate the heterogeneous behaviors of liquid–solid circulating fluidized bed. It was found that the reduction in drag coefficient is at least an important factor for the simulation of clusters formation, and the core-annulus flow is observed in the riser. The liquid–solid flow regime was significantly affected by the down-flow of particles in the form of clusters near the walls of the riser. The calculated concentration of particles inside the riser compared reasonably well with the available experimental data obtained by Razzak et al.

1. Introduction

Liquid–solid circulating fluidized bed (LSCFB) is widely used in the fields of biotechnology, food science, wastewater treatment, petrochemical and metallurgical processing due to its attractive features, such as high-efficient liquid–solid contact, favorable mass and heat transfer, high operation flexibilities, reduced back mixing of phases.

Fluidization of solid particles with liquid had been considered as a uniformly dispersed homogenous process, which was different from a heterogeneous gas solid process. However, some of the researchers found that the liquid–solid fluidization is heterogeneous. The heterogeneity of liquid–solid circulating fluidized bed was first discovered by Liang et al. [1,2]. Zheng et al. [3] used a fiber-optical probe tested the radial flow structure of a liquid–solid circulating fluidized bed, they also confirmed the existence of the radial non-uniformity of particles. Razzak [4] employed both electrical resistance tomography (ERT) and optical fiber probe to measure the local particle concentrations, and observed the radial non-uniformity of particle concentrations at different liquid superficial velocities. With both methods Razzak found that particle concentration was higher in regions close to the wall and low in the central area, and both the particle concentrations and radial non-uniformity increased with superficial particle velocity. Roy et al. [5] used gamma-ray computed tomography to measure the time-averaged cross-sectional distribution of particle concentrations at several elevations. The particle concentration profile was found to be relatively uniform across the cross section of the riser, with marginal segregation near the walls, and the particle back mixing at the wall was found according to the negative component of time-averaged particle velocity. Shilapuram et al. [6], Natarajan et al. [7], Hashizume and Morita [8] and Wang et al. [9] also obtained the same result through experiments.

Recently, Computational fluid dynamic (CFD) modeling has become a viable tool for simulating the dynamic processes that take place in the liquid–solid circulating fluidized beds to get a better understanding of the liquid–solid two-phase flows. Roy and Dudukovic [10] used a Euler- Euler two-fluid model, coupled with the kinetic theory of granular solids, to simulate the flow behaviors in liquid–solid circulating fluidized bed. The model was shown to be capable of predicting the liquid and particles residence time distributions in the riser as well as the particle velocity and concentrations. Razzak et al. [11] employed the kinetic theory based on Eulerian–Eulerian two-phase model to simulate the particle viscosity and particle pressure, which took the particle–particle collisions and the effect of lift force upon flow behavior into account, but neglected the effect of virtual mass force. And a drag model proposed by Wen and Yu was adopted for liquid–solid interactions. Cheng and Zhu [12,13] made a comprehensive study on the

---

* Corresponding author at: School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150001, China. Tel.: +86 0451 8641 2258; fax: +86 0451 8622 1048.

E-mail address: gdliu@hit.edu.cn (G. Liu).

0921-8831/$ - see front matter Crown Copyright © 2012 The Society of Powder Technology Japan. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.apt.2012.10.007

Nomenclature

C_{d0}	drag coefficient of single particle
C	drag coefficient
d_p	particle diameter, m
d_c	cluster diameter, m
e	restitution coefficient
f	volume fraction of dense phase
F	force acting on each particle or cluster, N
g	gravity, m/s^2
g_o	radial distribution function at contact
k_p	conductivity of fluctuating energy, kg/m s
m_{den}	number of particles in the dense phase per
m_{dil}	number of particles in the dilute phase per
N_{st}	suspension and transportation energy, W/kg
p	fluid pressure, Pa
p_p	particle pressure, Pa
D	diameter of the riser, m
H	height of the riser, m
Re	Reynolds number
$\boldsymbol{u}_l$	liquid velocity, m/s
$\boldsymbol{u}_p$	particle velocity, m/s
U_l	superficial liquid velocity, m/s
$U_{l,den}$	liquid superficial velocity of the dense phase, m/s
$U_{l,dil}$	liquid superficial velocity of the dilute phase, m/s
U_p	superficial particle velocity, m/s
$U_{p,den}$	superficial velocity of particles in the dense phase, m/s
$U_{p,dil}$	superficial velocity of particles in the dilute phase, m/s
$U_{s,den}$	superficial slip velocity in dense phase, m/s
$U_{s,dil}$	superficial slip velocity in dilute phase, m/s
$U_{s,int}$	superficial slip velocity of interphase, m/s
V	control volume, m^3
$V_{l,den}$	liquid volumes of dense phases in the control volume, m^3
$V_{l,dil}$	liquid volumes of dilute phases in the control volume, m^3
V_{den}	the volume of dense phase in the control volume, m^3
V_{dil}	the volume of dilute phase in the control volume, m^3
x	transverse distance from axis, m
z	vertical distance, m

Greek letters

β	drag coefficient with structure in a control volume, kg/m^3 s
γ_p	collisional energy dissipation, kg/m s^3
ε_{dil}	porosity in the dilute phase
ε_{den}	porosity in the dense phase
$\varepsilon_{p,dil}$	particle concentration in the dilute phase
$\varepsilon_{p,den}$	particle concentration in the dense phase
ε_l	porosity
$\varepsilon_{\max}$	maximum porosity for particle aggregating
ε_p	particle concentration
$\varepsilon_{p,\max}$	particle concentration at packing
θ	granular temperature, m^2/s^2
μ_l	liquid viscosity, kg/m s
μ_p	granular viscosity, kg/m s
ρ_l	liquid density, kg/m^3
ρ_p	particle density, kg/m^3
τ_l	liquid stress tensor, Pa
τ_p	particle stress tensor, Pa
φ	Specularity coefficient
ξ_p	bulk viscosity of particles,

Subscripts

c	cluster
den	dense phase
dil	dilute phase
int	interphase
l	liquid phase
p	particle phase
w	wall

modeling and simulation of hydrodynamics in LSCFBs using both similitude method and computational fluid dynamics (CFD) technique. There are also other models [14,15] which have played important roles in simulating the liquid–solid flow behaviors in liquid–solid risers. However, all these research have not taken the multi-scale effect into account in the liquid–solid risers.

Considering the formation of clusters in the liquid-particle two-phase system, the flow structure consists of the flow of dispersed particles and the flow of clusters in the bed. This results in the reduction of drag force [16] between the liquid phase and the solid phase, and effect on the interaction between phases. Thus, the drag model is important in simulating the interphase momentum transfer between the liquid and particle phases. There are a number of average-based drag models available in the literature for simulating the liquid-particle interactions, which include the Wen and Yu [17], Gidaspow [18], O'Brien and Syamlal [16] drag models and Di Felice et al. [19] analyzed a number of various experimental data in the literature and proposed a new correlation for the drag force. Yang and Renken [20] proposed a constant *a* and Archimedes number as a function of the famous Richardson–Zaki [21] function for simulating the liquid–solid interphase drag force. These correlations mentioned above are originally developed on the basis of experiments with homogeneous systems, and may lose their validity for simulating heterogeneous flow since they do not take into account the structure of particle clusters in the risers. For the upper dilute region of the riser in CFBs, numerical simulations with these drag correlations are generally in good agreement with such experimental findings. However, it is difficult for such simulations to describe the lower part of the riser, because higher particle concentrations are usually found in such regions in most experiments since the distribution in circulating fluidized beds is heterogeneous.

Liquid–solid drag laws are mostly derived from data at uniform particle concentrations, as a result, they can be applied to CFD on condition that the porosity within a computational cell is uniform. When in the case of the particle clusters smaller than a computational cell, the effect of inter-particle forces leading to particle agglomeration and hence reduced drag force is not accounted for. Since the drag coefficient is strongly dependent on the meso-scale structure in a control volume. Joachim Werther et al. [22] tested different drag correlations by Syamlal et al., Gidaspow and the EMMS models to determine the momentum exchange between the two phases in gas–solid CFBs, they discovered that the EMMS model provided a comparatively better prediction of the momentum exchange between two phases in the dense region. In present work, the interphase momentum transfer coefficient between liquid and particle phases is derived with the basic principle of energy minimization multi-scale (EMMS) model [23]. The relation between drag coefficient and the meso-scale structure parameters is investigated. Present approach is incorporated into the Eulerian–Eulerian two-fluid model. The kinetic theory of granular flow which uses a function to describe the turbulent kinetic energy of particles by introducing the concept of granular temperature of particles is employed for closure. Comparisons of the results