Chemical Engineering Journal 321 (2017) 184–194

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Hydrodynamic and solids residence time distribution in a binary bubbling fluidized bed: 3D computational study coupled with the structure-based drag model

Zheng Zou [a], Yun-long Zhao [a,b], Hu Zhao [a,b], Li-bo Zhang [a,b], Zhao-hui Xie [a], Hong-zhong Li [a,b,*], Qing-shan Zhu [a,b]

[a] State Key Laboratory of Multi-phase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, P.O. Box 353, Beijing 100190, PR China
[b] University of Chinese Academy of Sciences, Beijing 100049, PR China

HIGHLIGHTS

- The RTD and fluidized structure of binary gas-solid phases system were simulated.
- The simulated results show a reasonable agreement with the experimental value.
- The computed MRT of binary mixture is less than that of single system.

ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form 16 March 2017
Accepted 24 March 2017
Available online 27 March 2017

Keywords:
Fluidization
RTD
Structure-based drag model
Binary particles drag
CFD

ABSTRACT

The simulation of bubbling fluidized beds (BFB) residence time distribution (RTD) based on the structure-based drag model are conducted for the single and binary gas-solid phases systems, a comparison of computed results with experimental data proves that our model is applicable to both systems with better accuracy. The revised drag coefficient (H_d) increases with decreasing the gas velocity or increasing the particle diameter. The increase of the feed rate could improve the solids flow pattern to be close to the plug flow, while increasing gas velocity or bed height would lead to a wider RTD. The particles in the binary mixture are in more diffusion-oriented movement so as to have less MRT (mean residence time) than that of the single system. The coarse particles with longer MRT are simulated to accumulate into the bed bottom with a slower vertical velocity.

1. Introduction

The continuous BFB have been widely used in many industrial processes, for they can provide an effective mass transfer rate and excellent uniform temperature distribution with high production efficiency due to the well mixing of solids and gas phases. As an important parameter to characterize the fluid mixing quality and the solids processing time, the RTD has a great impact on the optimum of fluidized beds [1]. And the plug flow that all solids have the same residence time reduces the irregularity and instability of the bed induced by the gas flow, which has been considered to be the desirable flow pattern for the continuous fluidized reactor at all times [2–4]. Generally, fluidized beds comprise binary or more types of particles (different sizes and/or densities) with distinct fluidized characteristic and respective solid RTD, which impose a major role on the flow pattern and the fluidized reaction conversion, ultimately. Therefore, a correct understanding of the flow behavior and the solids RTD of polydisperse system is very important for the industrial applications of BFB [5,6].

It is confirmed that the particles differing in physical property are tend to separate during the bubbling fluidization. The light and/or small particles aggregate in the top part of bed, while the heavier and/or larger particles sink to the bed bottom, and this phenomenon is essentially induced by the different interactions among the drag force, gravity, gas-phase turbulence, particle collision and so on [7–10]. Extensive experimental and theoretical researches have been conducted to investigate the segregation behavior (solids distribution, fluidization regimes characterization, segregation index, etc) and the affecting factors (the differences in

* Corresponding author at: State Key Laboratory of Multi-phase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, P.O. Box 353, Beijing 100190, PR China.

E-mail address: hzli@ipe.ac.cn (H.-z. Li).

http://dx.doi.org/10.1016/j.cej.2017.03.110
1385-8947/

Notation

Latin letters

A_0	Distributor area per orifice, m^2
$c(t)$	Concentration of the tracer at time of t, dimensionless
$C_{fr,ik}$	Friction coefficient, dimensionless
$\overline{C_D}$	Drag coefficient, dimensionless
C_{Db}	Drag coefficient in the bubble phase, dimensionless
C_{De}	Drag coefficient in the emulation phase, dimensionless
d_h	Hopper diameter, mm
d_p	Particle diameter, μm
d_w	Downcomer diameter, mm
D_b	Bubble diameter, mm
D_i	Inside diameter of the bed column, mm
e_{ik}	Coefficient of restitution for particles collisions, dimensionless
$E(t)$	Residence time distribution function, s^{-1}
f_b	Ratio of the bubble phase, dimensionless
F_d	The total drag force on the particles in a unit volume of bed, N/m^3
$F(t)$	Cumulative residence time distribution function, dimensionless
g	Gravitational acceleration constant, m/s^{-2}
g_i	Radial distribution function, dimensionless
g_{ik}	Constitutive function, dimensionless
G_{in}	Feed rate of solids, kg/s
G_{out}	Discharging fluxes of solids, kg/s
h	Height above air distributor, mm
h_w	Bed height, mm
H_d	Heterogeneous drag index, dimensionless
h_{out}	Outlet height, mm
h_{int}	Initial bed height, mm
I_{2D}	Second invariant of the deviatoric stress tensor, dimensionless
$k_{\Theta_{s_i}}$	Diffusion coefficient for granular energy, Pa s
P	Pressure, Pa
Re	Reynolds number, dimensionless
t	Time, s
$\hat{t}$	Computed mean residence time, s
u	Real velocity, m/s
u_g	The superficial gas velocity, m/s
u_{mf}	the minimum fluidization velocities, m/s
U_s	Superficial slip velocity between gas and particles, m/s
U_{sb}	Superficial slip velocity between bubble and emulsion, m/s
U_{se}	Superficial slip velocity in the emulsion, m/s
W	Bed weight, kg
$\triangle z$	Grid interval spacing, mm
$\triangle t$	Time interval, s
x,y,z	Direction coordinate, dimensionless

Greek letters

β	Drag coefficient, kg/m^3 s
δ	The deviation, dimensionless
ε	Phase holdup, dimensionless
$\gamma_{\Theta_{s_i}}$	Collisional dissipation of energy, $J/(m^3\ s)$
Θ	Granular temperature, m^2/s^2
$\overline{\overline{\tau}}$	Stress-strain tensor, Pa
λ	Bulk viscosity, kg/(m s)
ϕ	Angle of internal friction, °Mass fraction, dimensionless
μ_g	Gas viscosity, Pa·s
$\mu_{s,col}$	Particle collisional shear viscosity, kg/(m s)
$\mu_{s,kin}$	Particle kinetic shear viscosity, kg/(m s)
$\mu_{s,fr}$	Particle frictional shear viscosity, kg/(m s)
ρ_s	Solid density, kg/m^3
ρ_g	Gas density, kg/m^3
τ	Experimental mean residence time, s
ξ_{ik}	Drag force coefficient, kg/(m s)

Subscripts

ave.	Average data
cal.	Calculation result
e	Emulsion phase
exp.	Experimental data
g	Gas phase
G	Mass flow rate
i,k	Control variable
m	Mass
M	Mixture phase
N	The number of solids phase
p	Solid particle
s	Solid phase or structure-based drag correlation model
t	Time or tracer phase
tot	Total

Abbreviation

BFB	Bubbling fluidized beds
CFD	Computational fluid dynamics
LBM	Lattice-Boltzmann method
KTGF	Kinetic theory of granular flow
MRT	Mean residence time
RTD	Residence time distribution

density and size of particles, the gas velocity, feed composition and so on) [11–14]. Theoretical, the segregation/mixing behavior would result in the RTD discrepancy between the binary particles; meanwhile, both the mass/heat transfer and chemical reaction mainly depend on the solids RTD. So the matching degree between the optimum reaction time and the RTD for each solid species would be the key issue to the high quality of product for the BFB reactor. Surprisingly there has been no publication available to the above point so far, even if only few experimental data just about the global solids RTD of mixture system could be found occasionally [15–17].

With the rapid development of computational ability, computational fluid dynamics (CFD) has become a valid and effective approach to study the hydrodynamics of fluidized beds. As for the widely used multi-Eulerian approach to simulate the behavior of binary gas-solids systems, the success of model mainly depends on the correction of the effective inter-phase drag force [18–20]. Generally speaking, the polydisperse drag laws available in the literature could be classified into two types: (i) the *ad hoc* treatment of polydisperse laws [21–27], which just replaces the particle diameter and slip velocity by the species corresponding parameter, and assumes that the species drag force is equal to that of a monodisperse system with the same solid volume fraction; and (ii) LBM-base drag laws [28–30], the individual drag force on species for the polydisperse system is given by a correction to the normalized averaged drag force that calculated from a monodisperse drag law. Obviously, all of the above approaches only focus on how to derivate the polydisperse drag from the existing monodisperse drag, which simply assumes the homogeneous fluidized condition and has been deeply proved to overestimate the drag coefficient between phases generally [31–34]. Whereas, only Zhou et al. [18] have modified the drag correlation obtained from homogeneous fluidization by the extension of EMMS to the binary gas–solid flow within the circulating fluidized bed (CFB),