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Numerical analysis of residence time distribution of solids in a bubbling fluidized bed based on the modified structure-based drag model

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ABSTRACT

The residence time distribution (RTD) of solids and the fluidized structure of a bubbling fluidized bed were investigated numerically using computational fluid dynamics simulations coupled with the modified structure-based drag model. A general comparison of the simulated results with theoretical values shows reasonable agreement. As the mean residence time is increased, the RTD initial peak intensity decreases and the RTD curve tail extends farther. Numerous small peaks on the RTD curve are induced by the back-mixing and aggregation of particles, which attests to the non-uniform flow structure of the bubbling fluidized bed. The low value of t_{50} results in poor contact between phases, and the complete exit age of the overflow particles is much longer for back-mixed solids and those caught in dead regions. The formation of a gulf-stream flow and back-mixing for solids induces an even wider spread of RTD.

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Introduction

As a suitable technology for industrial-scale implementation, bubbling fluidized beds (BFB) have been applied in diverse industrial processes such as those involved in petroleum, metallurgy, and combustion. Meanwhile, it is well known that the residence time distribution (RTD) of solids is a major issue in the fluidizing process because it characterizes the fluid mixing quality that represents the main advantage of a fluidized bed over the gas-solid reactors, such as rotary kiln, shaft furnace and so on. Therefore, it is essential to understand and analyze the RTD to better design and operate BFBs (Smolders & Baeyens, 2000; Zhang & Xu, 2015).

Because the conversion rate from solid to gas changes with time, the RTD has a paramount effect on the performance of a fluidized reactor. It is usually the very first thing to be determined before a chemical engineer considers the fluidizing apparatus (Heesink, Klaus, & Van Swaaij, 1994). A literature survey on the study of BFB RTDs is summarized in Table 1, from which it can be seen that the RTD of the solid phase has mainly been obtained experimentally or from an RTD model.

Recently, with the rapid development of computational simulation techniques, computational fluid dynamics (CFD) has become an increasingly powerful tool with which to investigate complex fluidized flows. Additionally, the hydrodynamic properties of solids and gas have an important influence on the RTD characteristics of solids. So, to study fully the functional effect of the flow field on the RTD and predict it accurately, it is essential to analyze the RTD by means of CFD. This approach can give much more information about the local values of phase holdups and their spatial distributions, especially in regions where physical measurements would be either difficult or impossible. Previous research has thus far concentrated on the RTD of circulating fluidized beds (CFBs) and has found some factors that impact on the RTD, such as particle diffusion capacity and back-mixing (Chan, Seville, Parker, & Baeyens, 2010; Shi et al., 2015; Smolders & Baeyens, 2000). However, to our knowledge, few studies have attempted to simulate the RTD of a BFB. Because the hydrodynamics and flow patterns of a BFB are quite different to those of a CFB, it is essential to investigate BFB RTDs numerically and predict them precisely for the purposes of scale-up and optimization.

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Nomenclature

Latin letters

A_0	Distributor area per orifice, m^2
$c(t)$	Concentration of tracer at time t
C_D	Drag coefficient
C_{Db}	Drag coefficient in the bubble phase
C_{De}	Drag coefficient in the emulsion phase
d_p	Particle diameter, μm
D_b	Bubble diameter, m
e	Coefficient of restitution for particle collisions
$E(t)$	Residence time distribution function, min^{-1}
f_b	Ratio of the bubble phase
F_d	Total drag force on particles per unit volume of bed, N/m^3
$F(t)$	Cumulative residence time distribution function
g	Gravitational acceleration constant, m/s^2
g_0	Radial distribution function
G_{in}	Feed rate of solids, kg/s
h	Height above air distributor, m
H_d	Heterogeneous drag index
h_{out}	Outlet height, m
h_{int}	Initial bed height, m
I_{2D}	Second invariant of deviatoric stress tensor
k	Diffusion coefficient for granular energy, Pa s
m	Weight of solids, kg
P	Pressure, Pa
Re	Reynolds number
t	Time, min
$\hat{t}$	Computed average residence time, min
u	Real velocity, 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

Greek letters

β	Drag coefficient, $kg/(m^3\,s)$
δ	Deviation
ε	Phase holdup
γ	Collisional dissipation of energy, $J/(m^3\,s)$
Θ	Granular temperature, m^2/s^2
$\bar{\bar{\tau}}$	Stress–strain tensor, Pa
λ	Bulk viscosity, kg/(m s)
ϕ	Angle of internal friction, ∘
μ_g	Gas viscosity, Pa s
ρ_p	Solid density, kg/m^3
ρ_g	Gas density, kg/m^3
τ	Mean residence time, min

Subscripts

cal.	Calculation result
e	Emulsion phase
exp.	Experimental data
g	Gas phase
xps	Mass flow rate
i	Control variable
m	Mass
p	Solid particle
s	Solid phase or structure-based drag correlation model
t	Time or tracer phase
t_c	Calculated tracer property

Abbreviations

CFD	Computational fluid dynamics
KTGF	Kinetic theory of granular flow
MRT	Mean residence time
RTD	Residence time distribution

With respect to the CFD modeling of BFBs, the local flow structure has a profound effect on the accuracy of hydrodynamic predictions (Chen, Li, Lv, & Zhu, 2015; Li, 2010; Lv, Li, & Zhu, 2014; Wang, Zou, Li, & Zhu, 2014). Conventional drag models assume simple homogeneous fluidized conditions, but they generally overestimate the drag coefficient between phases. Among the various modified drag models (Gao, Chang, Xu, Lan, & Yang, 2008; Ghadirian & Arastoopour, 2016; Milioli, Milioli, Holloway, Agrawal, & Sundaresan, 2013; Nikolopoulos, Papafotiou, Nikolopoulos, Grammelis, & Kakaras, 2010; Sarkar, Sun, & Sundaresan, 2014), the prominent structure-based drag correlation model proposed by Li (2010), Lv et al. (2014), and Wang et al. (2014) takes into account the influence of meso-scale structure on the momentum transfer between phases within a BFB. This model has exhibited accurate predictions across a wide range of applications and is considered to be a valid means of computing non-uniform flows (Gao et al., 2015; Geng, Zhong, Shao, Chen, & Jin, 2015; Lungu, Zhou, Wang, & Yang, 2015; Vashisth, Ahmadi Motlagh, Tebianian, Salcudean, & Grace, 2015).

In this paper, the RTD of a BFB is obtained by numerical simulation based on the modified structure-based drag model. The RTD characteristics are investigated fully on the basis of the simulation results. In addition, the computed holdups of solids and tracers, the velocity distributions, and the flow structures are studied comprehensively.

Mathematical modeling

Physical model

For a BFB, the mean residence time (MRT) of particles is usually much shorter than the time needed for them to mix after being fed in. Yagi and Kunii (1961) assumed the fluidized flow to be completely mixed and proposed the RTD function $E(t)$ of a BFB to be

$$E(t) = (1/\tau)\exp(-t/\tau), \tag{1}$$

where $\tau = W/G_{in}$ represented the MRT. They conducted verification experiments using a non-reacting bubbling fluidized system with solids fed continuously into the bed bottom and discharged through the overflow tube. As shown by their results illustrated in Fig. 1, close agreement between theory and experiment justified the assumption of complete mixing for the particles in the BFB.

The present simulation was conducted in accordance with the procedures of Yagi and Kunii (1961). A schematic of the BFB is displayed in Fig. 2, and detailed simulation parameters are given in Table 2. The bed solids were zinc blends (Geldart-group B). To obtain the actual residence time, the tracer properties (e.g., density, diameter) were set to those of the zinc blends instead of those of the coke particles used in the original experiment. In contrast to the relatively short traveling times of tracers within a CFB, BFB residence times are at least several minutes. Hence, it would be too

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