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Experiments and meso-scale modeling of phase holdups and bubble behavior in gas-liquid-solid mini-fluidized beds

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HIGHLIGHTS

- A meso-scale flow model for the gas-liquid-solid mini-fluidized bed was built.
- Effect of the bed diameter (macro-scale) was introduced in the meso-scale model.
- Constraint on the bubble coalescence was used for closing the meso-scale model.
- Phase holdups and bubble size in mini-fluidized bed were determined by visual method.

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ABSTRACT

Experiments on the gas-liquid-solid mini-fluidized beds with sizes of 1.45 and 2.3 mm show that the bed diameter has a considerable effect on the phase holdups and gas bubble size, because the macroscopic dimension (macro-scale) in a mini-fluidized bed is close to the dimensions of bubbles (meso-scale) and particles (micro-scale). Hence, the parameter of bed diameter was introduced through the modifications on the energy-minimization multi-scale (EMMS) model for the conventional three-phase mini-fluidized beds to predict the flow behavior of three-phase mini-fluidized bed. These modifications include two correction factors for the liquid and bubble slip velocities and a constraint condition on the bubble coalescence. The correction on the liquid slip velocity is to estimate the effect of column shear stress on the distribution of liquid velocity. The other correction factor is for quantifying the column resistance on the bubble rise. The correction factors were determined by the empirical correlations obtained from the experiments. Similarly, the bubble coalescence constraint is a correlation on the bubble spacing under steady state condition and determined from the experimental data. The modified meso-scale model equations were closed by this constraint condition and the solution of the model met the principle of energy minimization. The model predictions and experimental data agree well within the investigation range of experimental conditions.

1. Introduction

The applications of gas-liquid-solid fluidized beds have considerable importance on the process industries including petrochemical, pharmaceutical, biochemical and environmental engineering, due to their superior performance in heat and mass transfer (Fan, 1989; Yang, 2003). However, because of the complexity of multi-phase system, the scale-up through dimension enlargement requires solving lots of issues in the changes of the hydrodynamics and heat and mass transfer characteristics. With the development of mini- and micro-scale chemical engineering units, the advent of the parallel scale-up approach by quantity replication provides a highly practical solution for the study of the three-phase micro- and mini-fluidized beds (Günther and Jensen, 2006; Jensen, 1999). The three-phase micro- and mini-fluidized beds with the advantageous geometric characteristics have a smaller reaction volume, higher wall flux of unit volume and internal heat mass transfer rate, which makes them safer and more controllable. However, since their hydrodynamic characteristics are quite different from the three-phase fluidized beds in conventional scale, systematical experiments and theoretical studies are necessary.

Recently, a lot of experimental studies have been reported on the gas-solid, liquid-solid and gas-liquid-solid micro- and mini-fluidized beds. The major approaches include the pressure drop

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Nomenclature

$C_{D,b}$	drag coefficient for bubble
D_c	column or bed diameter, mm
d	bubble diameter, μm
d_b	mean bubble diameter, μm
d_e	equivalent bubble diameter, m
d_i	individual bubble diameter, μm
d_p	average particle diameter, μm
$F_{B,b}$	effective buoyancy of single bubble, N
$F_{D,b}$	drag force for single bubble, N
$F_{D,p}$	drag force for single particle, N
$F_{G,p}$	effective gravity of single particle, N
F_g	drag force for particles in unit volume, N/m^3
$F_{l\text{-}s}$	drag force for bubbles in unit volume, N/m^3
f_g	holdup of gas phase
f_N	number frequency of bubble
f_w	holdup of wake phase
H	bed expansion height, mm
H_0	static bed height, mm
k_w	the size ratio of wake to bubble
N_{st}	power consumed for suspending and transporting unit mass of particles, J/(s·kg)
$N_{st,g}$	power consumed by gas phase for suspending and transporting unit mass of particles, J/(s·kg)
$N_{st,l\text{-}s}$	power consumed by liquid-solid phase for suspending and transporting unit mass of particles, J/(s·kg)
U_G	superficial gas velocity, μm/s
U_L	superficial liquid velocity, μm/s
u_b	average bubble rise velocity, μm/s
u_{dc}	particle superficial velocity in the liquid-solid suspension of continuous phase, μm/s
u_{lc}	liquid superficial velocity in the liquid-solid suspension of continuous phase, μm/s
u_m	superficial velocity of the liquid-solid mixture/suspension, μm/s
u_{sc}	superficial liquid slip velocity, μm/s
V_g	gas phase volume, mm^3
$W_{st,l\text{-}s}$	power consumed by liquid-solid phase for suspending and transporting in unit bed volume, J/(s·kg)
$W_{st,g}$	power consumed by gas phase for suspending and transporting in unit bed volume, J/(s·kg)

Greek letters

β	the coefficient for liquid drag force
ε_0	voidage of static bed
ε_{lc}	liquid holdup in the liquid-solid suspension of continuous phase
ε_{lw}	liquid holdup in the liquid-solid suspension of wake phase
ε_s	average solid holdup
ε_{sc}	solid holdup in the liquid-solid suspension of continuous phase
ε_{sw}	solid holdup in the liquid-solid suspension of wake phase
λ_l	correction factor for liquid slip velocity
λ_b	correction factor for bubble slip velocity
μ	liquid viscosity, Pa•s
μ_m	apparent viscosity of the liquid-solid mixture/suspension, Pa•s
ρ	density of gas, liquid or solid, kg/m^3
ρ_m	density of the liquid-solid mixture/suspension, kg/m^3
σ	liquid surface tension force, N/m

Dimensionless group

Eo	Eötvös number, $(Eo = g\,(\rho_m - \rho_g)\, d_b^2/\sigma)$
Eo_e	Eötvös number, $(Eo_e = g\, \rho_l\, d_e^2/\sigma)$
Re	liquid Reynolds number, $(Re\ \rho_l\, D_c\, u_{lc}/\mu_l)$
Re_e	bubble Reynolds number, $(Re_e = \rho_l\, d_e\, u_b/\mu_l)$
Re_p	particle Reynolds number, $(Re_p = \rho_l\, d_p\, u_{sc}/\mu_l)$
Re_b	bubble Reynolds number, $(Re_b = \rho_m\, d_b\, (u_b\, \lambda_b - u_m)/\mu_m)$

Subscripts

0	static
b	bubble
c	column or continuous phase
e	equivalent
g	gas phase
i	individual
l	liquid phase
l-s	liquid-solid phase
m	liquid-solid mixture
max	maximum
min	minimum
p	particle
s	solid phase
st	suspending and transporting
w	bubble wake

analysis and visualization recording by high-speed camera (Liu et al., 2008; Wang and Fan, 2011). These works mainly focus on the determination of the parameters about the hydrodynamic properties, such as the minimum fluidization, bubbling and terminal velocities (Li et al., 2016a; Nascimento et al., 2016; Potic et al., 2005; Rao et al., 2010), the bed expansion ratio or solid holdup (Li et al., 2018; Tang et al., 2016) and the bubble behavior (Li et al., 2017; Li et al., 2016b). The effects of bed diameter and height, fluid and solid particle properties are also investigated and discussed. The differences of micro- and mini-fluidized beds in hydrodynamics is explained by the ideas of wall effect and shear stress of column. (Doroodchi et al., 2012; Xu and Yue, 2009). Additionally, the application studies of micro-fluidized beds also provide comprehensive methods in the field of the pyrolysis (Guo et al., 2016; Yu et al., 2010; Zhang et al., 1994) and photo-catalysis reactions (Yang et al., 2016).

Besides these, the development of hydrodynamic model in the fluidization system is essential to describe the fluid transport properties quantificationally. At present, it has not been proposed a suitable flow model for the three-phase mini-fluidized beds. As for the conventional three-phase fluidized beds there were several semi-theoretical models including generalized wake model (Bhatia and Epstein, 1974) and structural wake model (Fan, 1989) etc. Moreover, the energy-minimization multi-scale (EMMS) method firstly suggested by Li and Kwauk (1994), has been applied to the hydrodynamic model of three-phase fluidized beds. It associates the interactions and conservations at different scales on the basis of the compromise and competition between different flow mechanisms, which was originally used to describe the gas-solid fluidization system. In the EMMS model for three-phase fluidized beds proposed by Liu et al. (2001), the liquid-solid suspension was considered as pseudo-homogeneous at the bubble scale (meso-scale) and discrete at particle scale (micro-scale), so that the interactions, one between bubbles and suspension and the other between solid particles and liquid were balanced and calculated at two scales. The condition of bubble breakup induced by the