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Scale-up of bubbling fluidized beds with continuous particle flow based on particle-residence-time distribution

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ABSTRACT

Few studies have investigated scale-up of the residence-time distribution (RTD) of particles in bubbling fluidized beds (BFBs) with continuous particle flow. Two approaches were investigated in this study: first, using well-known scaling laws that require changes in particle properties and gas velocity; second, using a simple approach keeping the same particles and gas velocity for different beds. Our theoretical analysis indicates it is possible to obtain similar RTDs in different BFBs with scaling laws if the plug-flow residence time (t_{plug}) is changed as $m^{0.5}$, where m is the scaling ratio of the bed; however, neither approach can ensure similar RTDs if t_{plug} is kept invariant. To investigate RTD variations using two approaches without changing t_{plug}, we performed experiments in three BFBs. The derivatives $dE(\theta)/d\theta$ (where $E(\theta)$ is the dimensionless RTD density function and θ is the dimensionless time) in the early stage of the RTDs always varied with m^{-1}, which was attributed to the fact that the particle movement in the early stage were mainly subject to dispersion. Using the simple approach, we obtained similar RTDs by separately treating the RTDs in the early and post-stages. This approach guarantees RTD similarity and provides basic rules for designing BFBs.

Introduction

When designing commercial fluidized-bed (FB) reactors with continuous particle flow, it is important to study the residence-time distribution (RTD) of solid particles. For example, to achieve high carbon conversion and cold gas efficiency in bubbling fluidized-bed (BFB) gasifiers, one must find the appropriate RTD of coal in the gasifier. Obtaining the RTD of coal, one can determine the carbon conversion X_C in the gasifier by

$$X_C = \int_0^\infty E(t) X_C(t) dt. \quad (1)$$

Generally, in BFB reactors with continuous particle feeding and discharge, one can consider the residence time of particles in the BFB as a plug-flow time t_{plug}, calculated by

$$t_{plug} = \frac{M_b}{F}. \quad (2)$$

Scaling up a BFB is often performed while keeping the same t_{plug}. However, particle flow in such BFBs deviates much from the plug flow, meaning the same t_{plug} cannot ensure that particles in different BFBs will have similar RTDs.

There are many studies on the scale-up of hydrodynamics in FBs, including the representative scaling laws proposed by Glicksman et al. (Glicksman, 1984; Glicksman, Hyre, & Woloshun, 1993) and Horio et al. (Horio, Nonaka, Sawa, & Muchi, 1986; Horio, Takada, Ishida, & Tanaka, 1986). Glicksman (1984) obtained a full set of scaling parameters for BFB by non-dimensionalizing the mass and momentum equations and their boundary conditions, which was validated by Nicastro and Glicksman (1984) experimentally. Subsequently, Glicksman et al. (1993) derived a simplified version of the scaling law. Horio et al. (Horio, Nonaka, et al., 1986; Horio, Takada, et al., 1986) provided a set of scaling parameters for BFBs based on governing equations of bubbles and interstitial gas dynamics, later

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Nomenclature

B	bed diameter (m)
C	mass concentration of particles (–)
$C(t)$	weight fraction of tracer particles in each mixture discharged out of bed (–)
d	mean diameter of particles (m)
D	particle-dispersion coefficient (m^2/s)
D	tensor of particle-dispersion coefficient (m^2/s)
$E(t)$	RTD density function (s^{-1})
$E(\theta)$	dimensionless RTD density function (–)
f	wake fraction (–)
F	feeding rate of bed material (kg/s)
g	acceleration of gravity (m/s^2)
H	bed height (m)
l	distance from center (m)
L	bed length (m)
m	scaling ratio of bed size (–)
M	particle holdup in bed (kg)
S_1, S_2, S_3, S_4	integrated areas under RTD curve (–)
t	time (s)
u, v, w	particle velocity components in the x, y, and z directions (m/s)
u	tensor of particle velocity (m/s)
U	superficial gas velocity (m/s)
W	bed width (m) or mass of bed materials (kg)
x, y, z	particle coordinates (m)
X	carbon conversion (–)
$X(t)$	carbon conversion at time t (–)

Greek letters

θ	dimensionless time (–)
$\Delta\theta$	dimensionless time interval (–)
τ	characteristic time (s)
ρ	density (kg/m^3)
μ	viscosity (kg/(m s))

Subscripts and superscripts

b	bed
c	carbon or coal or characteristic
g	gas
i	index of sampling data in experiment
L	large bed
m	bed with scaling ratio of m
mf	minimum fluidization
M	middle bed
p	peak of RTD curve, or particle
plug	plug flow
post	post-stage of RTD curve
s	sand
S	small bed
t	treated data
tr	tracer
x, y, z	coordinates
*	dimensionless
0	reference bed

validating their scaling law with experimental data. The simplified Glicksman's law (in the viscous limit or low Reynolds number of particles) has been shown to be equivalent to Horio's law except for the requirement in the former law for the solid–gas density ratio (Sanderson, Lim, Sidorenko, & Rhodes, 2004). Horio's law is given by

$$\left.\begin{aligned}(U-U_{\mathrm{mf}})_{\mathrm{m}} &= m^{0.5}(U-U_{\mathrm{mf}})_0\\ U_{\mathrm{mf,m}} &= m^{0.5}U_{\mathrm{mf,0}}\end{aligned}\right\},\quad \text{similar bed geometry.} \tag{3}$$

The applicability of this scaling law to hydrodynamic similarity in BFBs has been well verified in many studies (Di Maio & Di Renzo, 2013; Horio, Nonaka, et al., 1986; Horio, Takada, et al., 1986; Knowlton, Karri, & Issangya, 2005; Nicastro & Glicksman, 1984; Sanderson & Rhodes, 2003; Sanderson et al., 2004; van Ommen, Teuling, Nijenhuis, & van Wachem, 2006; Wang, Zhang, Brandani, & Jiang, 2009). This applicability indicates that different BFBs have similar particle-momentum equations because Glicksman's law was derived by non-dimensionalizing the momentum equation of particle movement. The parameter $E(t)$ is directly proportional to particle concentration $C(t)$, meaning an RTD can be determined by the following particle-dispersion equation:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=\frac{\partial C}{\partial x}\left(D_{\mathrm{x}}\frac{\partial C}{\partial x}\right)+\frac{\partial C}{\partial y}\left(D_{\mathrm{y}}\frac{\partial C}{\partial y}\right)+\frac{\partial C}{\partial z}\left(D_{\mathrm{z}}\frac{\partial C}{\partial z}\right). \tag{4}$$

This indicates it is necessary to testing whether a similar dispersion equation can be obtained for two geometrically similar BFBs using the scaling law.

Horio et al. (Horio, Nonaka, et al., 1986; Horio, Takada, et al., 1986) found that, if the operation conditions of a BFB satisfy the scaling law, the formation frequency of bubbles changes according to $m^{-0.5}$, where m is the scaling ratio of bed size and $m^{0.5}$ is viewed as the scaling ratio of time. Sanderson and Rhodes (2003) validated that the scaling law can be applied to the distribution of the particle-circulation time in BFBs with a scaling ratio of $m^{0.5}$. This time scale has been used in many other studies for FB scale-up (Briongos & Guardiola, 2005; Schouten, Vander Stappen, & Van den Bleek, 1996; Van den Bleek & Schouten, 1993). However, the BFBs adopted in these studies did not have continuous particle feeding and discharge, a common procedure in practice. Thus, these studies provide little information for scaling up RTDs in BFBs with continuous particle flow. To our knowledge, almost no published studies have investigated the scale-up of particle RTDs in such BFBs.

In the present study, a theoretical analysis was first performed to assess the applicability of reported scaling laws for ensuring the similarity of particle RTDs in BFBs of different sizes. The experiments were then performed to verify the theoretical analysis. By analyzing the experimental data, a simple scaling approach that does not require changes in particle properties or gas velocity was further proposed and verified with experiments.

Theoretical analysis

The preceding particle-dispersion equation (Eq. (4)) can be non-dimensionalized into

$$\underbrace{\frac{\partial C}{\partial t}}_{\text{Unsteady}}+\left(\underbrace{u^*\frac{\partial C}{\partial x^*}+v^*\frac{\partial C}{\partial y^*}+w^*\frac{\partial C}{\partial z^*}}_{\text{Convection}}\right)=\underbrace{\frac{\partial C}{\partial x^*}\left(D_x^*\frac{\partial C}{\partial x^*}\right)+\frac{\partial C}{\partial y^*}\left(D_y^*\frac{\partial C}{\partial y^*}\right)+\frac{\partial C}{\partial z^*}\left(D_z^*\frac{\partial C}{\partial z^*}\right)}_{\text{Dispersion}}, \tag{5}$$