Advanced Powder Technology 27 (2016) 2342–2353

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

CFD-DEM investigation of transition from segregation to mixing of binary solids in gas fluidised beds

Zhengbiao Peng [a,*], Yusif A. Alghamdi [a], Behdad Moghtaderi [a], Elham Doroodchi [a,b,*]

[a] Priority Research Centre for Frontier Energy Technologies & Utilisation, The University of Newcastle, Callaghan, NSW 2308, Australia
[b] Priority Research Centre for Advanced Particle Processing & Transport, The University of Newcastle, Callaghan, NSW 2308, Australia

ARTICLE INFO

Article history:
Received 29 March 2016
Received in revised form 29 July 2016
Accepted 29 August 2016
Available online 9 September 2016

Keywords:
Mixing
Segregation
Particle dispersion
Gas-solid fluidised bed
DEM-CFD
Particle-particle collision
Particle-fluid interactions

ABSTRACT

Gas-solid fluidised beds are widely used in chemical, petrochemical, pharmaceutical, biochemical and powder industries. Particles used in gas-solid fluidised beds often differ in size and/or density, thus have the tendency to segregate under certain operating conditions. The results of our earlier work (Alghamdi et al., 2013) showed that for a given binary mixture, the transition from segregation to mixing occurred when the superficial gas velocity was increased over a critical value. In this study, force analysis at particle scale, including particle-particle, particle-wall and particle-fluid interacting forces, has been performed to investigate the underlying mechanisms that drive the occurrence of the transition.

The results showed that as the superficial gas velocity increased, the system exhibited three sequential states: segregated, transition, and mixed. The vertical fluid force acting on the particles was found to be responsible for the occurrence of the transition from segregation to mixing, at which the bulk density of the heavy (small) particle species became smaller than the actual density of the light (large) species. After the occurrence of the transition, the particle collisional effects were dominant over the fluid viscous effects in governing the gas-solid two-phase flow. After the system became mixed, the net force of fluid and particle net weight forces conversely tended to separate the particles. However, the particle dispersion induced by particle collisions counterbalanced the particle segregation, acting as the main mechanism driving the good mixing of the binary particle species. The simulation results were in good agreement with the experimental data.

1. Introduction

Gas-solid fluidized beds are often encountered in minerals, chemical, pharmaceutical and food processing industries as it offers a high quality contact between solid particles and the fluid phase. The solid particles used in these processes are in the dispersed form in nature often differing in both size and density. Therefore, there is a tendency for the particles to segregate or mix under certain operating conditions.

Whilst a good mixing is vital in some industrial processes such as in the manufacture of pharmaceuticals, ceramics and plastics where a uniform distribution of particles is essential, it becomes troublesome when particle segregation is desired as in the solid classifiers where particles of different properties need to separate. It has been found universally that the fate of segregation or mixing is determined by the combining effects of particle properties (e.g., size and density ratios and shape), particle species composition and the operating conditions (i.e., superficial gas velocity) [1–7]. Therefore, in the design of a gas-solid fluidised bed for a specific type of solid mixture, determination of the optimum operating conditions is a key factor to achieve a specific distribution state of the particles, i.e., segregated or mixed. Remarkably, it has been shown previously that for a given mixture of solids in gas fluidised beds, the binary solids transit from segregation to mixing when the superficial gas velocity was increased over a certain value [1,5,7–9]. Hence, a good understanding of the transition, in particular its dependence on the superficial gas velocity is pivotal for design of the operating conditions.

Moreover, the particles used in previous studies were mostly either equal-size [1–3] or equal density [4–6]. The mechanisms governing the mixing and segregation in these systems are relatively well understood, and have been found closely related to

* Corresponding authors at: Priority Research Centre for Frontier Energy Technologies & Utilisation, The University of Newcastle, Australia. Tel.: +61 2 4033 9204; fax: +61 2 4033 9095.

E-mail addresses: zhengbiao.peng@newcastle.edu.au (Z. Peng), elham.doroodchi@newcastle.edu.au (E. Doroodchi).

http://dx.doi.org/10.1016/j.apt.2016.08.024
0921-8831/

Nomenclature

Symbols

C_d	drag coefficient, –
d_p	particle diameter, m
E	energy dissipation rate, –
$\mathbf{g}$	gravitational acceleration, m/s^2
$\mathbf{f}_c$	collision contact forces, N
$\mathbf{f}_f$	total fluid forces, N
$\mathbf{f}_d$	fluid drag force, N
$\mathbf{f}_{s\text{-}g}$	forces acting on gas by the solid particles, N
I	moment of inertia, –
M	mixing index, –
m	mass, kg
N_{pc}	number of particles in the cell c, –
h_S	height of small particles, m
h_L	height of large particles, m
p	pressure, Pa
$\langle\overline{q_p^2}\rangle$	"small scale" fluctuating kinetic energy of the solid phase, m^2/s^2
r	particle radius, m
Re_p	particle Reynolds number, –
St_p	particle Stokes number, –
t	time, s
$\mathbf{T}_c$	collisional contact, N m
$\mathbf{T}_r$	rolling resistance torque, N m
$\langle\overline{u_p'^2}\rangle$	particle velocity variance, m/s
$\mathbf{u}_g$	gas velocity vector, m/s
U_{sf}	superficial gas velocity, m/s
U_{mf}	particle minimum fluidisation velocity, m/s
U_t	particle terminal velocity, m/s
$\mathbf{v}$	particle velocity vector, m/s
V_c	volume of computational cell c, m^3
y	dimensionless parameter to calculate drag force on binary solids, -

Greek letters

β	interphase momentum exchanging coefficient, –
ε	local void fraction, –
Δp	pressure drop, Pa
δ_i	fractional volume of particle i in a computational cell, –
μ_g	gas viscosity, kg/(m s)
μ_{roll}	particle rolling coefficient, –
ρ	density, kg/m^3
τ_f	viscous stress tensor of the gas phase, –
ψ	normalised net mass flow flux, g/s
ϕ	solid concentration, –
φ	ratio of the total force to the magnitude of particle net weight force, –
$\boldsymbol{\omega}$	particle angular velocity, rad/s

Subscripts

ave	average
f	fluid
g	gas phase
i, j	particle index
p	particle phase
s	solid phase
x, y, z	direction
u, v, w	components of velocity

the air bubble dynamics. However, mixing and segregation of particles with both size and density differences were more complex, showing greater dependency on particle species hydrodynamics and operating conditions. To date, there have been very few studies focusing on the mixing and segregation phenomenon of the binary systems in both size and densities differences [7,8]. The results reported previously for equal-size or equal-density systems could not be directly applied in such systems [9]. A good understanding of the mechanisms driven the occurrence of the transition from segregation to mixing for binary mixtures of particles differing in both size and density is still largely lacking.

It is known that the increase in superficial gas velocity directly leads to the change in interphase momentum exchange. It thus seems plausible that there is a relationship between the fate of mixing or segregation and the forces acting on the particles. As the motion of particles is mainly governed by the forces due to particle-particle, particle-wall and particle-fluid interactions, detailed information on the forces might help explain the particle segregation and mixing, hence shed light on the mechanisms driving the occurrence of the transition.

However, such forces information at particle-scale is extremely difficult (if not impossible) to attain through experimental approaches. The numerical model based upon the methodology of computational fluid dynamics and discrete element model (CFD-DEM) has become increasingly popular in the research of such particulate systems. In the technique of CFD-DEM, the motion of each particle is solved directly based on the Newtonian equation of motion. A wealth of information on individual particles such as position, velocity and forces can be obtained at a time instant. The CFD-DEM approach has been successfully applied to describe the hydrodynamics of gas-solid flow [10,11] and mixing and segregation in gas fluidized beds [3,12,13].

In this study, a three dimensional CFD-DEM model has been developed and applied to investigate the mixing and segregation phenomenon of binary mixture of solids with both size and density differences. Detailed information of the particles was monitored and the force analysis was performed to analyse the occurrence of transition from segregation to mixing as the superficial gas velocity increases in a miniaturised fluidised bed. Experimental setup of the miniaturised fluidised bed was also built up and experiments were conducted for the validation of the established mathematical model.

2. Mathematical model

The CFD-DEM model developed previously by the authors [11,12] was applied to solve the gas-solid two-phase flow. For brevity, the model is briefly described as below. More details of the model can be found in our earlier work [11,12].

2.1. Governing equations

The fluid flow was solved by the local averaged continuity and momentum equations of the continuum,

$$\frac{\partial(\varepsilon\rho_g)}{\partial t} + \nabla\cdot(\varepsilon\rho_g\mathbf{u}_g) = 0 \tag{1}$$

$$\frac{\partial(\varepsilon\rho_g\mathbf{u}_g)}{\partial t} + \nabla\cdot(\varepsilon\rho_g\mathbf{u}_g\mathbf{u}_g) = -\nabla p + \nabla\cdot\tau_f + \mathbf{f}_{s\text{-}g} + \varepsilon\rho_g\mathbf{g} \tag{2}$$