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Original Research Paper

Prediction of equilibrium mixing state in binary particle spouted beds: Effects of solids density and diameter differences, gas velocity, and bed aspect ratio

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ABSTRACT

The state of solids mixing can be considered as a key factor in accomplishment of high efficiency and a uniform product in gas–solid fluidized-beds operating with several different particle sizes. In the present work, coupled DEM–CFD approach was used to carefully investigate the mixing process of binary particles in flat-bottom spouted beds. In this regard, simultaneous effects of particle specifications, operating conditions, and bed dimensions on the equilibrium mixing state of solid mixture were evaluated in detail. Moreover, taking into account the contribution of various parameters, the obtained simulation results were used to draw a correlation for predicting the equilibrium mixing index of similar spouted beds. In addition, the upper limit of particle specification difference and the appropriate bed dimensions to achieve a specific mixing index value was determined. Furthermore, the performance capability of spouted and conventional gas–solid fluidized beds regarding solids mixing was compared in detail.

1. Introduction

Uniform mixing of particles in gas–solid fluidized beds is a predominant factor whenever high efficiency and uniform product are required. In addition, the rates of heat, mass, and momentum transfer between internals of these beds and the prevailed mixed or plug flow regimes in gas–solid fluidized beds, rigorously depend on the mixing pattern of the solid particles. Therefore, in the design of a gas–solid fluidized bed for a specific type of solid mixture, determination of the perfect operating conditions and bed dimensions to achieve a specific mixing state is a key factor. In this regard, simultaneous study of effects of solid specifications, operating conditions, and bed dimensions is indispensable. Numerous studies have been conducted on solids mixing in gas–solid fluidized beds, using experimental [1–4] and theoretical [5–7] approaches to investigate the bed hydrodynamics considering one type [8–11] or various types of particles [12–17], and to analyze the solids flow pattern [18] as well as the quality and quantity of solids mixing in these beds. However, few works were concerned with the evaluation of solids mixing phenomenon with simultaneously considering various particle specifications, bed dimensions, and operating conditions.

The inherent complexity associated with solids movement in gas–solid fluidized beds along with large number of particles close to the gas bubble or a jet; make it a tremendously difficult task to evaluate the exact movement pattern of solids in a laboratory-scale bed. To be more precise, being unable to observe inside of these beds, can even make this task impossible [7,19]. Therefore, numerical treatments of solids mixing have attracted much attention in recent years. In this regard, the discrete element method (DEM) was first introduced so innovatively in 1979 by Cundall and Strack [20] and then was extended by Tsuij as a soft-sphere approach [21] and Hoomans as a hard-sphere approach [22]. Using DEM enables us to examine several important parameters such as gas velocity, particle velocity, exerted forces on a single particle, and porosity simultaneously, which is quite difficult task through experimental techniques. In DEM approach, each particle can be tracked separately (i.e., Lagrangian approach) allowing perfect exploration of the bed behavior including solids mixing.

In the present work, DEM–CFD simulations were conducted to analyze mixing and segregation phenomena of binary solid mixtures in pseudo-3D spouted beds. In this regard, we focused on the effects of density and diameter differences of particles, inlet gas velocity, and bed aspect ratio. DEM–CFD code developed in our research group at Sharif University of Technology was used to determine the position of all light and heavy particles at each time step. As the first step, to validate the predictions of the

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Nomenclature

AR	aspect ratio (dimensionless)
Ar	Archimedes number (dimensionless)
a, $\dot{a}$	parameters (dimensionless)
b, $\dot{b}$	parameters (dimensionless)
c, $\dot{c}$	parameters (dimensionless)
C_D	drag force coefficient (dimensionless)
d_p	particle diameter (m)
d^*	jetsam-to-flotsam diameter ratio (dimensionless)
e_{pp}	restitution coefficient between particles (dimensionless)
e_{pw}	restitution coefficient between particles and walls (dimensionless)
$\boldsymbol{F}$	force (N)
$\boldsymbol{g}$	gravitational acceleration (m s^{-2})
$\boldsymbol{I_p}$	particle moment of inertia (kg m^2)
K	effective spring stiffness (N m^{-1})
Mi	Lacey mixing index (dimensionless)
N	number of sampling cells (dimensionless)
Re	Reynolds number (dimensionless)
$\boldsymbol{T}$	net torque (N m)
$\boldsymbol{u}$	gas velocity (m s^{-1})
u^*	dimensionless superficial gas velocity (u/u_{mf}) (dimensionless)
V	particle volume, m^3
$\boldsymbol{v}_p$	particle velocity (m s^{-1})
W	bed width (m)
$\overline{X}$	solid mass fraction (dimensionless)
$\Delta x \times \Delta y$	cell size (m^2)
Δt	time step (s)

Greek symbols

ρ^*	jetsam-to-flotsam density ratio (dimensionless)
ρ	particle density (kg m^{-3})
σ^2	standard deviation of particles distribution (dimensionless)
λ	mixing index decay constant (s^{-1})
μ_{pp}	friction coefficient between particles (dimensionless)
μ_{pw}	friction coefficient between particles and walls (dimensionless)
μ_f	fluid viscosity (Pa s)

Subscripts

e	equilibrium state
f	flotsam component
j	jetsam component
m	perfectly mixed
mf	minimum fluidization
s	completely segregated

developed code, simulation results were compared against experimental data in terms of pressure drop and bed expansion at different inlet gas velocities. Then, simulation of spouted beds with different density and diameter ratios and different bed aspect ratios within a range of inlet gas velocity was conducted. Obtained simulation results were used to draw a correlation for mixing index as a function of solid specifications, operating conditions, and bed dimensions. In addition, the dependency of the equilibrium mixing index of bed on the solid specifications and inlet gas velocity for different bed dimensions are presented and fully discussed using the developed correlation. Moreover, the maximum value of achievable equilibrium mixing index for different bed dimensions and particle specifications is discussed. Finally, the mixing state of uniform fluidized beds and spouted beds is carefully compared.

2. Mathematical model and simulation conditions

2.1. Model

DEM modeling of solid and gas phases and their interactions was performed the same as the method described by Zhong et al. [23] in detail. In this regards, the particle phase is modeled by discrete element method and the $k-\varepsilon$ turbulence model was used to model the gas phase. A brief description of the modeling approach is presented as follows:

2.1.1. Solid phase

In the present work, soft-sphere approach [21] was applied for the present simulation runs. It is worth noting that contrary to the hard sphere approach [22], particles are allowed to have a small overlap and multiple collisions in the soft-sphere treatment of the particles. In the latter, the interparticle forces were modeled using three parameters, i.e., spring, dashpot, and damper [21], and multiple and long-time contacts were considered as well. Governing equations applied for a particle include the linear and angular momentum conservation equations are as follows:

$$m_p \frac{d\boldsymbol{v}_p}{dt} = \boldsymbol{F}_{contact} + \boldsymbol{F}_{drag} + \boldsymbol{F}_{Saffman} + \boldsymbol{F}_{Magnus} + m_p\boldsymbol{g} \quad (1)$$

$$\boldsymbol{I}_p \frac{d\boldsymbol{\omega}_p}{dt} = \boldsymbol{T}_p \quad (2)$$

where m_p and $\boldsymbol{v}_p$ are mass and the velocity of a particle, respectively. $\boldsymbol{I}_p$ and $\boldsymbol{\omega}_p$ are the particle moment of inertia and angular velocity, respectively. $\boldsymbol{T}_p$ is the net torque resulted from the tangential contact force. $\boldsymbol{F}_{contact}, \boldsymbol{F}_{drag}, \boldsymbol{F}_{Saffman}$, and $\boldsymbol{F}_{Magnus}$ are, respectively, the contact force, drag force, Saffman lift force, and the Magnus lift force exerted on a particle. In the present work, the lift forces exerted on each particle should not be neglected because the particle diameter and the gas velocity gradient around the particle are large [23]. Equations applied to evaluate the required parameters are summarized in Table 1. Particle–particle and particle–wall contact forces are described in terms of normal, $\boldsymbol{F}_{cnij}$, and tangential, $\boldsymbol{F}_{ctij}$, forces and modeled according to the well-known spring, dashpot, and friction mechanical model as fully described by Zhong et al. [23]. In the present work, Ergun and Wen and Yu drag models [24,25], Mei et al. lift force model [26], and Oesterlé formulation [27] were used successfully to evaluate the drag, Saffman, and Magnus forces, respectively. The governing equations used for the evaluation of the interaction forces can be found in Ref. [28].

2.1.2. Gas phase

In CFD–DEM approach, the gas phase is treated in a way similar to that used in the conventional two-fluid model [29]. Because the simulated system is a flat spouted-bed with a depth of 0.015 m, the motion of the gas phase in the third dimension can be neglected and gas phase hydrodynamics can be solved in two dimensions [13]. Thus, the governing equations for the gas-phase including the overall conservation of mass and momentum equations [30] can be expressed as

$$\frac{\partial(\varepsilon\rho_g)}{\partial t} + \frac{\partial(\varepsilon\rho_g u_j)}{\partial x_i} = 0 \quad (20)$$