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Improvement of the simulation of fuel particles motion in a fluidized bed by considering wall friction

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HIGHLIGHTS

- Fuel particle motion in a pseudo-2D bed is simulated.
- A TFM–DEM hybrid model is used to describe the three phases in the bed.
- A wall-friction model is also used to account for the wall effect.
- Simulation results are compared with experiments for different fuel particle densities.
- The inclusion of the wall-friction term improves the time-scale numerical results.

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ABSTRACT

The mixing of fuel particles is a key issue on the performance of fluidized bed reactors. In this work, the motion of a non-reactive fuel particle in a pseudo-2D bubbling fluidized bed operated at ambient conditions is simulated employing a hybrid-model and introducing a new friction term that accounts for the effect of the bed vessel front and rear walls. The hybrid-model, implemented in the code MFIX, simulates the dense and gas phases using a Two-Fluid Model (TFM) whereas the fuel particles are modeled using a Discrete Element Method (DEM). The importance of the present hybrid-model is that the interaction of the continuum phases with the fuel particles behavior is fully coupled.

To improve the accuracy of the simulated fuel particle motion in a bubbling fluidized bed, a model accounting for the effect of the bed front and rear walls on the continuum solid phase is combined with the hybrid-model. The rising and sinking velocity of the fuel particles, the circulation time and statistical parameters associated to the location of the fuel particle in the bed were obtained from the simulations and compared with experimental measurements. According to the results, the prediction of these parameters is clearly improved when the friction term is included in the simulation.

1. Introduction

Fluidized beds are characterized by a high thermochemical conversion of solid fuel particles due to their great heat and mass transfer efficiency [1]. The study of the mixing of fuel particles in the whole bed during thermal conversion processes is a key issue for the proper design of a fluidized bed reactor [2]. The fuel particle mixing is characterized by the time spent by the fuel particle in the bed (i.e. the residence time), the capability of the fuel particle to move in the horizontal and vertical directions, (i.e. the axial and lateral dispersion) and the time needed for its thermochemical conversion (i.e. the thermochemical conversion time).

Several experimental works present in the literature are focused on the motion of fuel particles in pseudo-2D and 3D fluidized beds. Pseudo-2D fluidized bed systems typically have a transparent front wall to allow optical access to the system and the rear wall of the bed is separated to the front wall by a narrow distance to ensure that the visualization is representative of the whole system. In most of the studies available in the literature, the tracer particles are considered as objects, varying in density, shape and/or size to the bed material. It was observed that these objects sink to the bottom of the bed close to its lateral walls, following the motion of the dense phase, and rise through the center of the bed, affected by the bubbles ascension [3–7]. This motion pattern is characteristic of bubbling fluidized beds composed of a single mixing cell [5]. Additionally, the rising process of an object consists in a series of small jumps due to the effect of different passing bubbles [8]. This phenomenon was also experimentally

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Nomenclature

C_{sp}	coefficient of friction between unlike solids [–]
c	particle-wall interaction coefficient [kg/m^{2}s]
D_b	bubble diameter [m]
d_p	siscrete particle diameter [m]
d_s	dense phase particle diameter [m]
e_{sp}	coefficient of restitution [–]
$\vec{F}_c$	net contact force on each discrete particle [N]
$\vec{F}_d$	total gas-solid drag force on each discrete particle [N]
$\vec{F}_T$	net sum of all forces on each discrete particle [N]
$\vec{f}_{fric}$	frictional force per unit volume [N/m^3]
$\vec{g}$	gravity [m^2/s]
$g_{0,sp}$	radial distribution function at contact [–]
H	bed height [m]
h_0	static bed height [m]
h_{fb}	the average bed height [m]
I	moment of inertia [kg m^2]
$\bar{\bar{I}}$	unity matrix [–]
K_{gs}	drag force between gas and solids [kg/m^3 s]
K_{pg}	drag force between discrete particle and gas [kg/m^3 s]
K_{ps}	drag force between discrete particle and solids [kg/m^3 s]
k_Θ	diffusion coefficient for granular energy [kg/ms]
m	mass [kg]
N_j	number of jumps [–]
P_{N_j}	relative frequency of the number of jumps needed by a fuel particle to reach the bed surface [–]
P_{db}	percentage of time that the fuel particle is located inside the bed [%]
P_{fb}	percentage of time that the fuel particle is located at the freeboard [%]
p	geometrical fitting parameter of the number of jumps [–]
p_g	gas pressure [Pa]
p_s	solids pressure [Pa]
$\vec{T}$	net torque acting on each discrete particle [N m]
t	time [s]
U/U_{mf}	dimensionless gas superficial velocity [–]
U_{mf}	minimum fluidization velocity [m/s]
$\vec{V}$	velocity vector for discrete particles [m/s]
$\vec{v}_g$	gas velocity in each computational cell of the TFM [m/s]
$\vec{v}_p$	discrete particle velocity [m/s]
$\vec{v}_s$	solids velocity in each computational cell of the TFM [m/s]
W	bed width [m]
$\vec{X}$	position vector for discrete particles [m]
x	horizontal coordinate [m]
y	vertical coordinate [m]
Z	bed thickness [m]

Greek letters

α_g	gas volume fraction [–]
α_s	solids volume fraction [–]
Δs	grid size in the computational domain [m]
γ_Θ	collisional dissipation of Θ [m^2/s^2]
λ_i	bulk viscosity [Pa s]
μ_g	gas viscosity [Pa s]
μ_s	solids viscosity [Pa s]
$\bar{\alpha}_s$	normalized solids volume fraction [–]
$\bar{\bar{\tau}}_g$	gas stress tensor [Pa]
$\bar{\bar{\tau}}_s$	solids stress tensor [Pa]
Φ	angle of internal friction [deg]
ρ_b	bulk density of the bed [kg/m^3]
ρ_g	gas density [kg/m^3]
ρ_p	discrete particle density [kg/m^3]
ρ_s	dense phase particle density [kg/m^3]
Θ	granular temperature [m^2/s^2]
$\vec{\omega}$	angular velocity [rad/s]

characterized by [6] using a neutrally buoyant object, i.e. an object with a density similar to that of the bed bulk, and objects with different densities and sizes [9], provided that the objects showed a proper circulation throughout the whole bed. Furthermore, [9,10] studied, in pseudo-2D and 3D lab-scale fluidized beds, the influence of the density and size of the objects on their circulation time in the bed. In a very similar system, [11] showed that fuel particles follow a ballistic path when they are ejected by the bubbles in the freeboard, which means that fuel particles motion out of the dense bed is only affected by gravity. Other related works have used a Monte Carlo method to reproduce the motion of fuel particles inside a pseudo-2D bed [12] and the behaviour of a fuel particle in a industrial reactor, obtaining results in very good agreement with experimental results available in the literature [13].

Complementary to the experimental studies, numerical simulations, either Eulerian-Eulerian Two-Fluid Models (TFM) [14–16], Eulerian-Lagrangian approaches such as discrete element models (DEM) [17,18], or a combination of both strategies (coupled TFM-DEM) [19], can be a very effective complementary tool to experiments to achieve a detailed analysis of the hydrodynamics of complex gas-solids systems such as fluidized beds [20,21]. In the TFM approach, the gas phase and the particles or solids phase are treated as two interpenetrating continua in an Eulerian framework, using the conservation equations of fluids. The DEM strategy is based on a Lagrangian simulation of each particle trajectory coupled with an Eulerian simulation of the bulk gas flow. In the coupled TFM-DEM hybrid model, the gas and solid phases are modeled as two interpenetrating continua combined with the simulation of discrete particles. This strategy has demonstrated to be of great interest for the simulation of particle segregation [22,23]. Due to its unique characteristics, the coupled TFM-DEM hybrid model can be also employed to characterize the motion of fuel particles inside the bed. In a previous work, [19] used this hybrid model to compare simulation results of the motion of a fuel particle with experimental data extracted from the literature [6]. The comparison showed great accordance in the results related to the location of the fuel particle in its motion throughout the whole bed.

Furthermore, [24] and [25] reported that the effect of the front and the rear walls on the particles motion can be significant and should not be neglected in numerical simulations of pseudo-2D beds. The wall effect in numerical simulations of gas-solids pseudo-2D systems has been investigated in several numerical studies using either TFM or CFD-DEM models, demonstrating its relevance [26–30]. Recently, [31] developed an empirical model to easily account for the particle-wall interaction effect in pseudo-2D fluidized beds. The model allows for the simulations of the wall-friction effect in pseudo-2D beds using a 2D domain instead of a more computationally demanding 3D domain. The results obtained by [31] showed that the incorporation of the wall-friction model produces a clear improvement of conventional 2D simulations.

In the present work, the motion of a fuel particle in a pseudo-2D bubbling fluidized bed is simulated employing a hybrid TFM-DEM model and introducing the new friction term associated to the wall effect proposed by [31]. Therefore, in this work, the effect of the change of the fluid-dynamics of the bed, produced by friction of the dense phase with the front and rear walls, on the motion of fuel