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Original Research Paper

Development of an empirical wall-friction model for 2D simulations of pseudo-2D bubbling fluidized beds

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ABSTRACT

Pseudo-2D fluidized beds have been crucial for the understanding of the dynamics of gas-particle systems. In these systems the distance between the front and back walls is narrow, which restricts and creates a resistance to the solids motion, leading to a different flow behaviour compared to fully 3D systems. This interaction of the particle motion with the walls can be significant and should not be neglected in numerical simulations. The present work develops a new model to easily account for the friction effect between the walls and the particles in a pseudo-2D bed. The model is based on experimental results combined with simplifications of the shear force on a wall provided by the kinetic theory of granular flows. The dependence on the particle diameter and bed thickness is directly introduced in the model through the use of a straightforward expression that is easy to code and does not lead to numerical divergence. To test the model two beds of different thickness were simulated, and the resulting time-averaged solids concentration and velocity as well as bubble properties were compared with experiments. It is shown that the numerical results with the new wall-friction model improve the prediction of the standard 2D-simulations.

1. Introduction

Fluidized beds have several applications in chemical and process industries, such as fluid catalytic cracking (FCC), gasification, combustion of solid fuels, Fischer–Tropsch synthesis, drying and coating [1]. Despite the fact that fluidized beds have been used for these processes since the 1920s and great progress has been made, some aspects of fluidized bed dynamics are still far from being fully understood and, hence, they constitute active fields of research. These aspects include, for example, general bed dynamics, gas interaction with particles, particle mixing, bubble formation, behaviour of fuel particles in fluidized bed reactors, segregation, agglomeration, vibrofluidization and scaling-up of the bed behaviour [2–9]. Therefore, there is a need of experimentation and modelling of fluidized beds. In this regard, pseudo-two-dimensional (pseudo-2D) beds, which are lab-scale beds of simplified geometry, have been crucial for the understanding of the dynamics of gas-particle systems. Pseudo-2D fluidized bed systems typically have a transparent front wall in order to allow optical access to the system. The back 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. Thus, the bed volume enclosed between the front and back walls has a small thickness.

Numerical simulations, either using Eulerian–Eulerian two-fluid models (TFM) [10–12], Eulerian–Lagrangian approaches, such as discrete element models (CFD-DEM) [13,14], or a combination of both strategies [15], can be a very effective complementary tool to experiments for achieving a detailed analysis of the hydrodynamics of complex gas–solids flows [16,17]. The CFD-DEM strategy is based on a Lagrangian simulation of each particle trajectory coupled with an Eulerian simulation of the bulk gas flow. The gas–solid interaction is computed through semi-empirical closure models to reduce the level of detail required in the solution of the gas phase. In the TFM approach, the gas phase and the particles or solids phase are treated as two interpenetrating and continuum media in an Eulerian framework using the conservation equations of fluids. As in the case of the Eulerian–Lagrangian approach, the two-fluid simulation of fluidized beds requires the use of closure models for the gas–solids interaction, but also constitutive closures are needed for the solid stress which are usually based on the granular kinetic theory [11] through the concept of granular temperature, accounting for the random fluctuations of particles' velocity. CFD-DEM simulations have a larger computational cost because

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Nomenclature

A_{loc}	local surface area (m^2)
A_L	lateral area (m^2)
A_T	cross-sectional area (m^2)
B	bubble phase probability (–)
C	dense phase probability (–)
c	particle–wall interaction coefficient ($kg/(m^2\ s)$)
D_b	bubble diameter (m)
D_h	hydraulic diameter (m)
d_s	particle diameter (mm)
e_s	particle restitution coefficient (–)
$\vec{F}_{fric,front}$	local frictional of the front wall (N)
$\vec{F}_{fric,back}$	local frictional of the back wall (N)
f	friction coefficient for liquids (–)
$\vec{f}_{fric}$	frictional force per unit volume (N/m^3)
$\vec{g}$	gravity (m/s^2)
g_0	the radial distribution function at contact (–)
H	bed height (m)
h_0	static bed height (m)
$\bar{\bar{I}}$	unity matrix (–)
K_{gs}	drag force between gas and solids ($kg/(m^3\ s)$)
k_Θ	diffusion coefficient for granular energy (kg/(ms))
L	duct length (m)
N_f	normal contribution to the shear stress (Pa)
$\vec{n}$	unit normal (–)
ΔP	pressure drop (Pa)
p	gas pressure (Pa)
p_s	solids pressure (Pa)
Re	Reynolds number (–)
t	time (s)
U	superficial gas velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
$\vec{v}_g$	gas velocity in each computational cell of the TFM (m/s)
$\vec{v}_s$	bulk solids velocity in each computational cell of the TFM (m/s)
$\vec{v}_{sl}$	the slip velocity between the particles and the plate (m/s)
v	liquid velocity (m/s)
$\vec{V}$	velocity vectors (m/s)
V_b	bubble vertical velocity (m/s)
V_y	time-averaged solids vertical velocity (m/s)
x	horizontal coordinate (m)
y	vertical coordinate (m)
y_{cm}	vertical position of the centre of mass of the bed (m)
W	bed width (m)
Z	bed thickness (m)

Greek letters

α_g	gas volume fraction (–)
α_s	solids volume fraction (–)
$\alpha_{s,max}$	the solids concentration at closest random packing (–)
$\alpha_{s,th}$	threshold in the solids volume fraction for the bubble detection (–)
γ_Θ	collisional dissipation of Θ (m^2/s^2)
μ	Coulomb coefficient of friction (–)
μ_g	gas viscosity (Pa s)
μ_s	solids viscosity (Pa s)
Φ	specularity coefficient (–)
ϕ	angle of internal friction (deg)
$\bar{\bar{\sigma}}_c$	collisional-translational contribution to the stress tensor (Pa)
$\bar{\bar{\sigma}}_f$	frictional contribution to the stress tensor (Pa)
ρ_g	gas density (kg/m^3)
ρ_s	solids density (kg/m^3)
τ_{bc}	bulk shear stress in the direction of the slip velocity (Pa)
$\bar{\bar{\tau}}_g$	gas stress tensor (Pa)
$\bar{\bar{\tau}}_s$	solids stress tensor (Pa)
Θ	granular temperature (m^2/s^2)

they solve the individual motion of each particle and the collisions between them. As a consequence, CFD-DEM simulations can reproduce the micro-scale of the bed concerning the particles' dynamics provided the number of particles is not very large (i.e. typically small-sized beds). Finally, the most detailed Eulerian–Lagrangian simulation strategy for fluidized beds is the direct numerical simulation (DNS) of the fluid flow surrounding solid particles together with the Lagrangian description of the particles' interaction. In the DNS approach, lattice Boltzmann methods are normally used (see for example, [18,3]), although finite volume schemes are also employed [19]. The direct simulation of gas-fluidized beds is quite attractive since all the bed physics can be reproduced from first principles. However huge computational resources are required, restricting DNS simulations to beds with a relatively small number of particles. Therefore TFM simulations are currently the most suitable strategy for the simulation of both the macro- and meso-scales of the bed when the number of particles involved is high. This allows for the simulation of medium and moderately-large sized beds commonly used in laboratory research and pilot plant testing. For this, reliable submodels are required for incorporating in TFM the micro-scale of the interactions between gas, particles and walls of the bed.

In pseudo-2D beds the front and the back walls restrict and create resistance on the solids motion, leading to a different flow behaviour compared to fully three-dimensional (3D) systems [20,21]. For beds of small thickness, the effect of the front and the back walls on the particle motion can be significant and should not be neglected in numerical simulations of pseudo-2D beds, as initially reported by Li et al. [22] and Hernández-Jiménez et al. [23]. Moreover, 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 [24,25,22,26]. These studies recommended the use of 3D simulations instead of 2D in order to get a more accurate prediction of pseudo-2D gas–solid fluidized beds, i.e. the wall effect must be included in the simulations. However, 3D simulations require much more computational resources than 2D simulations.

Recently, Li and Zhang [21] implemented a model for 2D simulations to account for the front and back wall effects in a pseudo-2D gas–solid fluidized bed without the need of a 3D simulation. Their model relied mainly on the kinetic theory of granular flows applied to shear forces and granular temperature balances on the wall. The equations of these balances assume isotropy and simple shear in the granular flow. Li and Zhang [21] introduced the shear force imposed by the front and back walls as a body force acting on the solids flow and a source term in the granular temperature equation. They assumed that collisions between particles and walls are of sliding type. Maps of concentration of solids fraction and profiles of vertical velocity of the solids phase were analysed by Li and Zhang [21] and the velocity profiles were compared with reported experimental results. They obtained results with their 2D modified model that improved those obtained when the system