Chemical Engineering Science 174 (2017) 238–258

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Three-dimensional fluidized beds with rough spheres: Validation of a Two Fluid Model by Magnetic Particle Tracking and discrete particle simulations

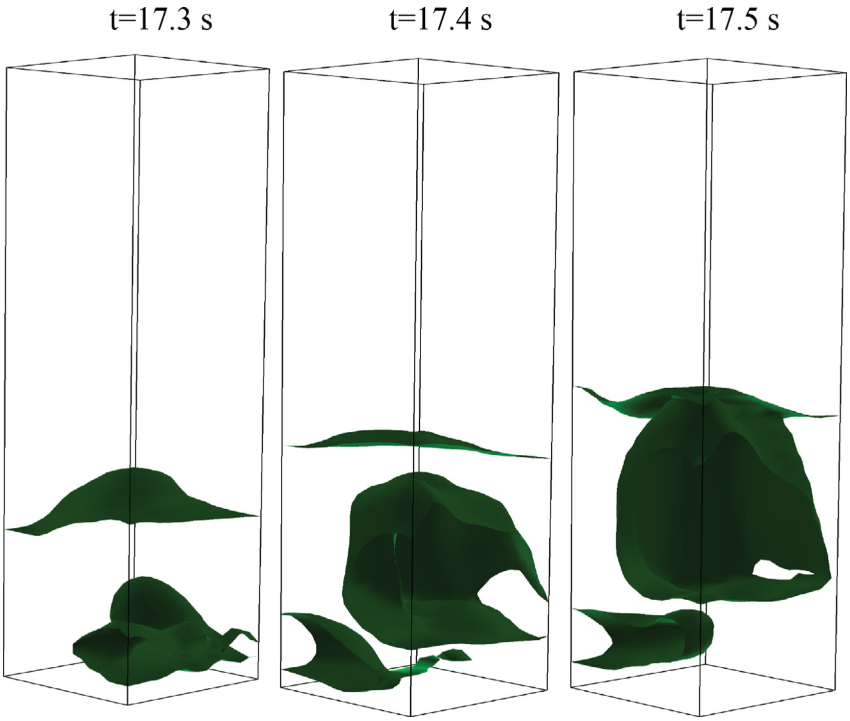
Lei Yang [a], J.T. Padding [b,*], K.A. Buist [a], J.A.M. Kuipers [a]

[a] Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, 5600MB Eindhoven, The Netherlands
[b] Department of Process and Energy, Delft University of Technology, 2628CB Delft, The Netherlands

HIGHLIGHTS

- A two fluid model based on kinetic theory of granular flow for rough spheres is used.
- For the first time the model is validated for full 3D fluidized beds.
- Comparison is made with Magnetic Particle Tracking and detailed simulations
- The results of the new two fluid model are in good agreement with experiments.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 June 2017
Received in revised form 23 August 2017
Accepted 4 September 2017
Available online 8 September 2017

ABSTRACT

Two fluid model simulations based on our recently introduced kinetic theory of granular flow (KTGF) for rough spheres and rough walls, are validated for the first time for full three-dimensional (3D) bubbling fluidized beds. The validation is performed by comparing with experimental data from Magnetic Particle Tracking and more detailed Discrete Particle Model simulations. The effect of adding a third dimension is investigated by comparing pseudo-2D and full 3D bubbling fluidized beds containing

---

* Corresponding author.
E-mail address: J.T.Padding@tudelft.nl (J.T. Padding).

http://dx.doi.org/10.1016/j.ces.2017.09.014

Nomenclature

Roman symbols

$\mathbf{v}$	particle mean translational velocity, m/s
P	pressure, Pa
$\mathbf{F}$	force, N
$\mathbf{T}$	torque, Nm
I	moment of inertia, kg·m^2
$\mathbf{g}$	gravitational acceleration, m/s^2
t	time, s
V	mean contact velocity, m/s
m	particle mass, kg
n	particle number density, m^{-3}
e	normal restitution coefficient
Re	Reynolds numer

Greek symbols

ε	volume fraction
ρ	density, kg/m^3
$\boldsymbol{\tau}$	stress tensor, Pa
β_A	interphase momentum exchange coefficient, kg/(m^{3}s)
Θ	granular temperature, m^2/s^2
κ	thermal conductivity, kg/(m·s)
γ	energy dissipation rate, J/(m^{3}s)
μ	friction coefficient
β	tangential restitution coefficient
λ	granular temperature ratio
θ	contact angle
σ	particle diameter, m
$\boldsymbol{\omega}$	particle rotational velocity, rad/s
δ	overlap, m
η	damping coefficient, kg/s

Abbreviations and subscripts

TFM	Two Fluid Model
DPM	Discrete Particle Model
KTGF	kinetic theory of granular flow
2D	two dimension
3D	three dimension
BC	boundary condition
MPT	Magnetic Particle Tracking
i	in the i direction
t	translation
r	rotation
p	particle
w	wall
s	solid
g	gas

inelastic rough particles. Spatial distributions of key hydrodynamic data as well as energy balances in the fluidized bed are compared. In the pseudo-2D bed, on comparison with the KTGF derived by Jenkins and Zhang, we find that the present KTGF improves the prediction of bed hydrodynamics. In the full 3D bed, particles are more homogeneously distributed in comparison with the pseudo-2D bed due to a decrease of the frictional effect from the front and back walls. The new model results are in good agreement with experimental data and discrete particle simulations for the time-averaged bed hydrodynamics.

Keywords:
Fluidization
Frictional collision
Rough particles
Magnetic Particle Tracking
Two-Fluid Model
Discrete Particle Model

1. Introduction

Gas-solid fluidized beds are widely used in the chemical, petrochemical and metallurgical industries owing to their solids mobility and high heat and mass transfer rates resulting from intensive contact between the gas and the solid particles. To improve and scale up existing processes, it is of utmost importance to understand the hydrodynamics of such gas-solid fluidized beds. However, the collection of detailed experimental data is challenging, costly and becomes rather complicated for large scale three-dimensional (3D) systems because of the lack of optical access. In addition, large scale computational simulations of fluidized beds are often limited to 2D or pseudo-2D systems because of the high computational costs associated with large 3D beds. Fortunately, with the increasing availability of computational power and more efficient numerical schemes, simulations of 3D fluidized beds have become possible. The aim of this paper is to compare prediction of a recently developed computational model for rough sphere fluidization with experiments on 3D dense bubbling fluidized beds, and to highlight differences between pseudo-2D and full 3D beds.

Eulerian-Lagrangian and fully Eulerian models are widely used to simulate gas-solid flows. In these models, the gas phase is described by the volume-averaged Navier-Stokes equations. In the Eulerian-Lagrangian Discrete Particle Model (DPM) (Tsuji et al., 1993; Hoomans et al., 1996; Xu and Yu, 1997) individual particles are tracked in the computational domain where the particle's motion is described by the Newtonian equations of motion. The DPM can account for direct particle-particle interactions in a fundamental and detailed manner. However, due to CPU constraints, only a limited number of particles (O(10^6)) can be treated simultaneously. To reach larger scales, fully Eulerian models are preferred: the Two-Fluid Model (TFM) is better suited for the simulation of large scale gas-fluidized beds. In this approach the solid phase is treated as a second continuum, inter-penetrating with the continuous gas phase. Constitutive equations are solved using additional closure equations for the particle phase (Kuipers et al., 1992). This approach has emerged as a very promising tool because of its computational efficiency. The challenge here is to establish an accurate rheological description of the solid phase, which in most modern TFM simulations is based on kinetic theory of granular flow (KTGF).

The most widely used KTGF models (Ding and Gidaspow, 1990; Nieuwland et al., 1996) have been derived for dilute flows of slightly inelastic, frictionless spheres. In reality, however, granular materials are mostly frictional. The roughness of the granular materials has been reported to have a significant effect on stresses at least in the quasi-static regime (Sun and Sundaresan, 2011). Besides, according to Yang et al. (2017a), the particle surface friction has a strong effect on the solids flow patterns and distribution. From literature, attempts to quantify the friction effect have been somewhat limited. Yang et al. (2016a) derived a kinetic theory of granular flow for frictional spheres in dense systems which includes the effects of particle rotation and friction explicitly. Moreover, this theory has been validated by Yang et al. (2016b) for a pseudo-2D dense gas-solid bubbling fluidized bed.