Powder Technology 258 (2014) 304–323

Contents lists available at ScienceDirect

Powder Technology

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

Numerical investigation of mixing and orientation of non-spherical particles in a model type fluidized bed

T. Oschmann, J. Hold, H. Kruggel-Emden *

Ruhr-Universitaet Bochum, Universitaetsstrasse 150, D-44780 Bochum, Germany

ARTICLE INFO

Article history:
Received 9 December 2013
Received in revised form 25 February 2014
Accepted 1 March 2014
Available online 16 March 2014

Keywords:
Fluidization
Complex shaped particles
Computational fluid dynamics
Discrete element method
Granular materials
Simulation

ABSTRACT

A numerical investigation of mixing in a model type fluidized bed is performed based on the three-dimensional discrete element method coupled with computational fluid dynamics (CFD). Particle motion is represented by the discrete element approach applying clustered spheres as well as polyhedrons for the particle shape representation. On the CFD-side fluid flow around individual particles is not resolved, but averaged over cells larger than the particles. Various elongated particle shapes are considered including cylinders, plates and cuboids. Comparisons to spherical particles are made. Thereby, the main focuses are mixing which is assessed by the Lacey index, bed height progression and averaged particle orientation. The investigated particle/fluid systems are rich in detail. Large deviations are obtained for the different particle shapes considered. Mixing as well as bed height progression is also strongly influenced by the particle shape. Especially the shape representation accuracy has strong influence on the results as mass and projection area get altered. Significant variations can be obtained for the preferred particle orientations taken up in regions close to the vessel walls in contrast to the interior of a fluidized bed which clearly limits the ability to evaluate processes inside fluidized beds based on visual observations from the exterior only.

1. Introduction

The basic mechanisms of particle mixing in fluidized beds are scientifically well understood and closely linked to bubble formation and motion. In the wake of a rising bubble particles are transported upwards; in the close vicinity of a bubble particles are locally moving downwards resulting in an overall convective circulation in the vertical direction of the fluidized bed [1–3]. Large scale vertical circulation patterns form out due to bubble/wall interaction which triggers a particle downflow close to the walls and up in the center of the fluidized bed [4]. Horizontal mixing is induced by horizontal motion as well as interaction of bubbles [5,6]. Especially at the fluidized bed surface horizontal mixing is strong due to splashing [2].

So far no generally applicable simple physical or empirical models exist to predict the influence of operating parameters on the mixing in a fluidized bed [7,8]. To close this gap different simulation approaches like two fluid models [9] based on the kinetic theory of granular flow [10] or discrete element approaches (DEM) coupled with continuum models to resolve the fluid flow field (CFD) [7] are applied. Two fluid models despite much effort to improve their accuracy [11–13] are still limited in representing basic flow features [14] as well as mixing and segregation [15]. Combinations of the discrete element method (DEM) coupled with CFD [7,16] are well applicable to particle/gas systems especially when particle sizes are roughly of the same order as the system size. In recent years DEM/CFD approaches have been even extended in few cases to include complex shaped particles [17–22] and prove powerful for the investigation of related flow features.

The combined DEM/CFD-method was firstly applied by Tsuji et al. [23] to model a two-dimensional fluidized bed of spherical particles. Obtained results were rich in detail regarding phenomena like mixing as well as circulating particle motion. Quantitatively the onset of bubble formation and pressure fluctuations matched experimental observations. Later Hoomans et al. investigated the influence of DEM-collision parameters and compared obtained DEM/CFD-results with experimental investigations involving spherical glass beads resulting in a good match [24]. Xu and Yu [16] simulated the gas/solid flow in fluidized beds and were capable of observing several dynamic flow features attributed to fluidized beds on different scales from the system scale down to the single particle level. Rhodes et al. [7] firstly considered mixing of uniform spherical particles in fluidized beds by a DEM/CFD-approach. Based on the Lacey Index [25] they investigated the dependency of mixing on operational parameters such as fluid velocity, particle size and density. An internally circulating two-dimensional fluidized bed was considered by Bin et al. [26] clearly identifying the increased lateral mixing compared to a conventional fluidized bed. Limtrakul et al. [27] analyzed particle motion by the DEM/CFD-approach for uniform and bidisperse spherical particles. Experimental findings on the particle circulation as well as on operational parameters enhancing mixing were confirmed. Depending on the differences in particle size

* Corresponding author. Tel.: +49 234 32 27362; fax: +49 234 32 14 227.
E-mail address: kruggel-emden@leat.rub.de (H. Kruggel-Emden).

http://dx.doi.org/10.1016/j.powtec.2014.03.046

and density segregation was observed for certain operational parameters. The first three dimensional fluidized particle system was modeled successfully by Feng et al. [28] where the particle motion was considered in 3-D and the fluid motion was still simplified in 2-D. Based on a weighted Lacey mixing index [25] differently sized fluidized particles were investigated in a bidisperse system. Special attention was given to the influence of the initial packing state on the mixing dynamics. The conditions leading to mixing and segregation in the particle system were analyzed. Mixing was identified as fast and segregation as a gradual process. On the particle level the phenomena leading to mixing and segregation were investigated. Strong fluctuations in the spatial and temporal distribution of particle/particle forces and particle/fluid forces were identified. At the same time the influence of the coupling framework of the particle and the fluid phase within the combined DEM/CFD-framework on mixing and segregation processes was also addressed by Feng and Yu [29]. Two schemes were analyzed theoretically and compared against experimental data on segregation in gas/particle systems favoring the scheme applied in the works [28,16] and others.

In full 3-D mixing of spherical particles was firstly considered by Chaikittisilp et al. [30] for inclined fluidized beds. Good agreement between experimental investigations and simulations were found pointing out that an inclination of 10° triggers the best mixing compared to other alignments. Nakamura et al. [31] firstly addressed mixing in rotating fluidized beds based on the DEM/CFD-method. Rotating fluidized beds are favorable for the fluidization of fine particles as adhesive forces could be overcome by the combination of drag and centrifugal forces. Obtained experimental results indicated an excellent agreement with numerical results and an empirical mathematical correlation on mixing was proposed for rotating fluidized beds.

More recently micro phenomena related to mixing were addressed. Tian et al. [32] focused on the phenomena triggering mixing in systems with inclined distributor plates or uneven gas feed and identified different convective, diffusive and shear mixing mechanisms. Feng and Yu [33] extended their earlier work [28] on spherical bidisperse particles addressing a wide range of gas velocities. Mixing and segregation mechanisms were identified on the particle level and discussed regarding their influence on flotsam and jetsam particle fractions. Mixing and segregation of equally sized spherical particles with varying density were addressed by Di Renzo et al. [34] by a DEM/CFD-approach and a map of the mixing/segregation in dependence on the fluid velocity and the density ratio was derived. The influence on mixing of immersed objects like tubes which are of importance to fluidized beds in which heat is extracted was investigated by a DEM-LES-scheme by Gui et al. [35]. Zhao et al. investigated flow structure formation and mixing by the DEM/CFD-method in downers [36] and combinations of risers and downers [37] by 2-D simulations. A good agreement was found when comparing obtained numerical results to experimental investigations. The mixing was identified to be strongly related to the initial flow configuration at the inlet in downers and strong backmixing was encountered in risers. Residence time distributions which were derived are rather wide in risers and narrower in downers.

With several DEM/CFD-simulations being performed in 2-D, Feng and Yu [38] addressed differences between 2-D and 3-D by comparative

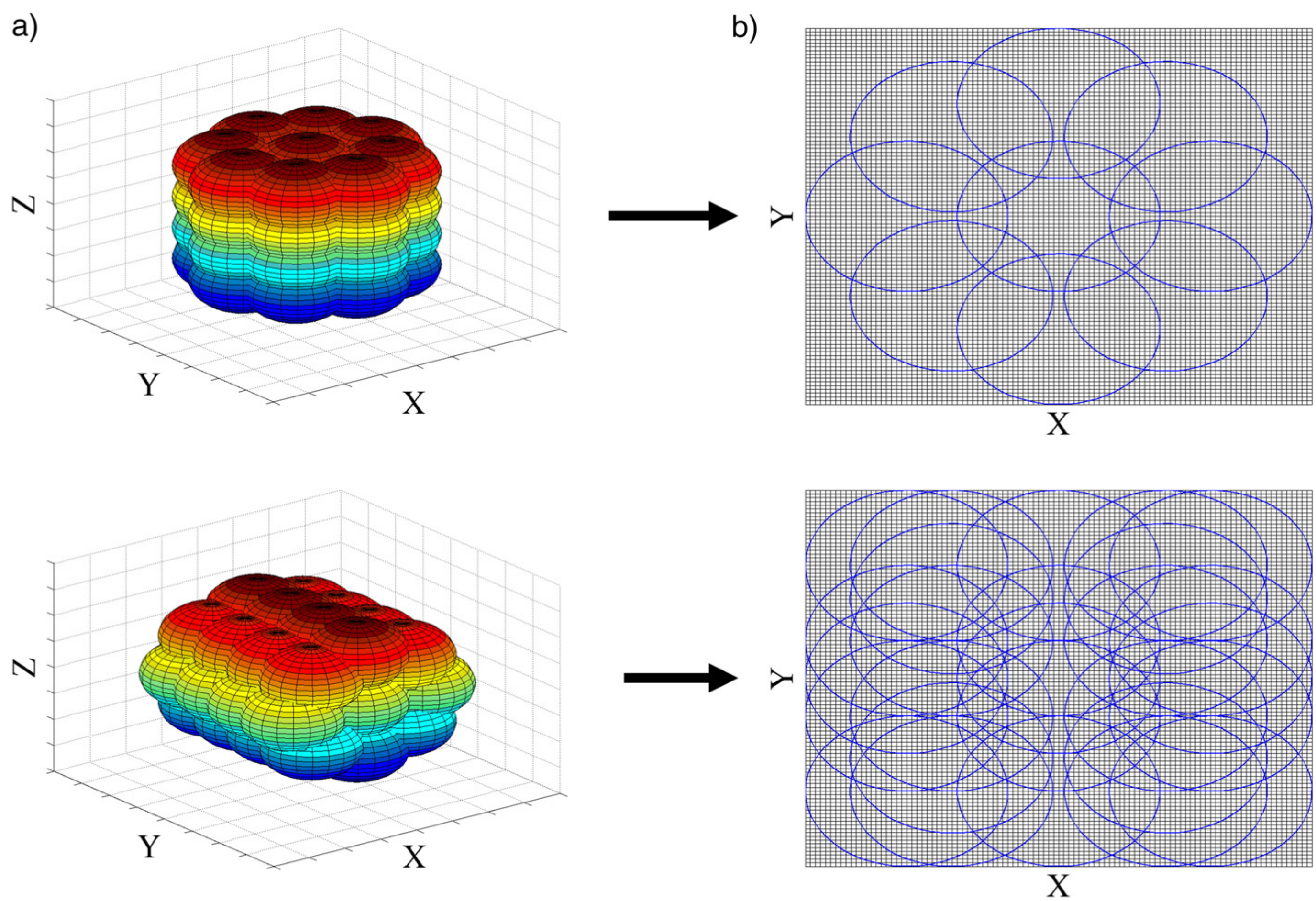

Fig. 1. Two examples for the calculation of the projection area, a) clustered sphere particles with specific orientation, b) the resulting projection areas for the x,y-plane calculated for a grid resolution of 100 × 100.