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Experimental and numerical study of fluidization and pressure drop of spherical and non-spherical particles in a model scale fluidized bed

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ABSTRACT

A laboratory scale fluidized bed was examined experimentally and numerically involving differently sized wooden Geldart-D particle shapes. Simulations were performed with a coupled DEM–CFD approach, which involves a drag force model that realizes for the particle shape and orientation. To validate the drag force model and to learn more about the fluidization behavior of non-spherical particles the pressure drop, particle height and orientation distributions were analyzed. To gain comparable data from the experiments, a PTV-MATLAB script was developed to detect particles and determine their orientations and heights. Experimental and numerical results are in good agreement for most particle types; differences in the pressure drop can be allocated to mismatching particle heights or orientations. Differences in the particle height distribution are a result of particles that stack up in corners or close to the vessel walls. It was found that despite these local deviations the DEM–CFD can accurately reproduce the orientation behavior of elongated particles, which with increasing velocity align themselves with the flow. For elongated particles below a certain elongation ratio this behavior could not be observed, which was confirmed by both experiments and simulations.

1. Introduction

Fluidized beds are widely used in mechanical process engineering, energy technology and processing technology and are often attributed to operational problems [1–4]. Some of these problems are directly related to the particle orientation, e.g. segregation of elongated particles from equidimensional particles. To overcome them and to additionally improve product quality or enhance energy efficiency, experimental and numerical investigations are available as viable tools. As experimental investigations are costly at industrial scales and cannot easily be scaled up from laboratory size experiments, the simulation and detailed analysis of fluidized bed processes is not only of academic but also of industrial interest. Furthermore the usually dense two-phase systems in fluidized beds are not easily examined experimentally. Optical approaches like fiber optical probe (FOP), laser Doppler velocimetry (LDV), particle tracking velocimetry (PTV), and particle image velocimetry (PIV) [5] are often limited to the outer planes of a fluidized bed or are invasive; noninvasive techniques for the investigation of the interior of a bed like positron emission particle tracking (PEPT), radioactive particle tracking (RPT), magnetic particle tracking (MPT) or radio-frequency identification (RFID) are whether difficult to apply or still in development [6,7]. In contrary simulations provide reliable, full access into the fluidized bed if being properly validated, without interrupting the particle motion or flow processes. As fluidized beds are multi-phase systems, approaches that combine two simulation frameworks offer a high level of accuracy. The coupled discrete element method (DEM)–computational fluid dynamics (CFD) approach, which combines discrete particle tracking with a cell-averaged fluid simulation, has proven capable for the simulation of fluidized beds with spherical particles in the past [8–13]. The discrete element method developed in 1979 dates back to Cundall and Strack [14] and since then has been applied in a wide range of fields. The first coupled DEM–CFD simulation to describe a fluidized bed was performed by Tsuji et al. [15] as early as 1993 for a two dimensional system of 2400 spherical particles. With increasing computational power three dimensional systems including up to 4.5 million particles became possible, recently [16]. A comprehensive review of the developments and applications of the DEM for spherical particles was given by Zhu et al. [17,18]. However, spherical particles are only able to describe real systems, meaning systems that comprise of complex shaped particles, to a limited degree. Large, non-spherical particles are especially of interest for refuse-derived fuel and biomass [19], drying applications [20], food processing [21] and bulk solid handling [22]. Therefore, in recent years the implementation of complex shaped particles gained more and more attention [23–27]. A review on recent developments of the DEM

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including the realization of complex shaped particles was given by Lu et al. [28], who consider the particle shape as one of the most important factors to be considered in DEM simulations.

Complex shapes can be expressed through multiple methods including super quadrics, polyhedrons and clustered spheres [26]. The approximation quality can thereby vary from very rough to very fine and will affect the run time of the simulation. Where a compromise between accuracy and speed should be drawn, needs to be examined individually [29]. Polyhedrons are able to represent angular shapes accurately with low polygon counts, while with increasing polygon counts not only model type particles (cubes, cuboids, pyramids, tetrahedrons, etc.), but also real particles with uneven surfaces and edges can be approximated [30]. As fine approximations are difficult to obtain, automated solutions were developed in recent years. Latham et al. [31] presented a method utilizing a 3D laser ranging system to capture irregular geometries into 3D models. Williams et al. [32] developed an image based segmentation technique that is able to acquire particle shapes.

A first contribution to the simulation of two-phase systems involving non-spherical particles was made by Zhong et al. [33], who investigated cylindrical particles approximated through clustered spheres with the DEM–CFD utilizing the drag force model by Tran Cong et al. [34] during dilute flow in a fluidized bed. However, this approach is not suitable for dense particle systems as the influence of the void fraction is not appropriately considered. Recently an improved and very versatile drag force model for single, complex shaped particles was proposed by Hölzer and Sommerfeld [35]. This model in combination with a model for the representation of the void fraction by Di Felice [36] has been used in many recent DEM–CFD-studies addressing complex shaped particles such as in the investigation by Hilton et al. [37], who simulated a fluidized bed involving four types of complex shaped particles, expressed through super quadrics. A modification of the model by Di Felice [36] was proposed by Rong et al. [38]. Results obtained by Hilton et al. [37] showed that in fluidized systems the particle shape has a strong influence on the pressure drop and traditional correlations like the Ergun-equation [39] were not able to correctly reproduce this. A similar modeling approach to [37] was chosen by Zhou et al. [40] who simulated ellipsoidal and oblate particles and who thereby confirmed that the general flow behaviors of the examined particles could be reflected through the DEM–CFD. Corn-shaped particles consisting of clustered spheres were examined by Ren et al. [41,42] in a spouted bed. They examined the approximation quality of particles clustered with different accuracy. Oschmann et al. [43] compared among other shapes ideal cylinders approximated by either polyhedrons or clustered spheres and found a faster mixing rate for clustered particles. Other gas–solid systems that have been examined by the DEM–CFD include pneumatic conveying [44,45] and fixed beds [46].

So far obtained numerical and experimental results indicate that in fluidized systems that involve complex shaped particles the particle orientation is an important factor that influences the process quality [47,48] and the fluidization behavior [43,49] and should therefore be analyzed further. Image analysis of fluidized beds has been widely used to examine voids and bubbles [50,51] and particle velocities on the basis of the particle tracking velocimetry (PTV) [52]; PTV can also be used to study the orientations of particles. Experimental investigations of the orientation distributions of cylinders and cubes in pipe flow have been performed by Zitoun et al. [53] and numerical investigations by Ku and Lin [54] and Zhang et al. [55]. The orientations of cylindrical particles with different elongation ratios were examined numerically and experimentally by Cai et al. [56] in fluidized beds. The tendency of elongated particles to align themselves with the flow was confirmed in all three studies. In the DEM particle orientations are crucial for the contact detection and determination of the rotational movement. Furthermore local porosities can vary depending on the particle orientation, so that a fixed bed of equal overall porosity involving complex shaped particles behaves differently than a packing consisting of spheres [46].

To test the validity of the DEM–CFD to precisely predict particle orientations, to gain further knowledge about the particle shape influence on particle orientation in gas–solid flows and to further validate the applicability of the implemented DEM–CFD submodels for the drag force calculation [35,36], a comparative experimental and numerical study with a fluidized bed operated with 13 differently sized and shaped particle classes is carried out. A particle tracking script was derived and validated to perform PTV. It is implemented in Matlab and allows detecting particle positions and orientations of selected particles in the experiments. Based on this, a comparison with DEM–CFD simulation is possible, where particle positions and orientations are inherently available over time.

2. Methodology

2.1. DEM–CFD approach for the simulation of fluidized beds

In this study an Eulerian–Lagrangian approach was used to describe the fluidized system. Hereby particles are tracked discreetly, while the fluid phase is modeled as a continuum by solving the volume averaged Navier–Stokes equations [17]. In the DEM the translational and rotational motion is obtained by integrating Newton's and Euler's equations of each particle given by

$$m_i \frac{d^2 \overrightarrow{x}_i}{dt^2} = \overrightarrow{F}_i^c + \overrightarrow{F}_i^{pf} + m_i \overrightarrow{g}, \tag{1}$$

$$\hat{I}_i \frac{d \overrightarrow{W}_i}{dt} + \overrightarrow{W}_i \times \left(\hat{I}_i \overrightarrow{W}_i \right) = \Lambda_i^{-1} \overrightarrow{M}_i, \tag{2}$$

with the particle mass m_i, particle acceleration $d^2 \overrightarrow{x}_i / dt^2$, contact force $\overrightarrow{F}_i^c$, particle/fluid force $\overrightarrow{F}_i^{pf}$, gravitational force $m_i \overrightarrow{g}$, angular acceleration $d \overrightarrow{W}_i / dt$, angular velocity $\overrightarrow{W}_i$, external moment resulting out of contact or particle/fluid forces $\overrightarrow{M}_i$, the inertia tensor along the principal axis $\hat{I}_i$ and the rotation matrix converting a vector from the inertial into the body fixed frame Λ_i^{-1}.

Complex shaped particles are modeled through the polyhedron method, which allows to precisely reproduce angular shapes by compositing triangles. The triangular surface mesh that represents the particle makes it necessary to adjust the contact detection model, so that a common plane algorithm [26] is used as a basis. Contact force laws are applied similarly as used for spherical particles [57,58]. A linear spring damper model is used to provide the normal component of the contact forces

$$\overrightarrow{F}^n = k^n \delta \overrightarrow{n} + \gamma^n \overrightarrow{\nu}^n_{rel}, \tag{3}$$

where k^n is the spring stiffness, δ the virtual overlap, $\overrightarrow{n}$ a normal vector, γ^n a damping coefficient and $\overrightarrow{\nu}^n_{rel}$ the normal velocity in the contact point. Both k^n and γ^n determine the coefficient of normal restitution between particles e^n_{PP} as well as particles and walls e^n_{PW}. For the calculation of the tangential forces a linear spring limited by the Coulomb condition is used

$$\overrightarrow{F}^t = min\left(k^t \left| \overrightarrow{\xi} \right|, \mu_C \left| \overrightarrow{F}^n \right| \right) \cdot \overrightarrow{t}, \tag{4}$$

where k^t is the stiffness of a linear spring, μ_C is the friction coefficient, $\overrightarrow{\xi}$ is the relative tangential displacement and $\overrightarrow{t}$ is the tangential unit vector. No rotational friction is considered.

Computational fluid dynamics (CFD) in an Eulerian framework is used to describe the fluid phase. Hereby the inside of the fluidized vessel is meshed with a hexagonal Cartesian grid. The fluid velocity is then addressed as a spatially averaged quantity in each cell. The fluid properties and velocity vector of each cell is then passed on to the DEM through the CFD-framework. The equation of continuity (Eq. (5)) and