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Transversal bed motion in rotating drums using spherical particles: Comparison of experiments with DEM simulations

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ABSTRACT

Experimental investigations and numerical simulations with the discrete element method (DEM) were carried out to improve the understanding of the movement and mechanical interaction of particles in rotary kilns. The focus is on the bed movement in the rolling motion mode with rotational speeds varying between 3 and 15 rpm. Characteristic parameters for this system are the Froude number, the dynamic angle of repose, the thickness of the active layer and the particle velocity on the bed surface and at the wall. These parameters were measured in rotating drum experiments, computed in DEM simulations and compared with each other. When available, analytical and/or semi-empirical macroscopic models were included in the comparison. Both the DEM simulations and the analytical macroscopic models show good agreement with the experiments in general. The wide range of parameters considered, like drum diameter, particle diameter and rotational speeds, provide a comprehensive reference data set.

1. Introduction

Rotary kilns play a vital role in the basic materials and minerals processing industry with prominent examples being cement kilns, the thermal treatment of waste or contaminated soil as well as grinding and drying processes. In almost all of these processes the combined mass and heat exchange within the moving granular solid and the strong interaction with the kiln walls and a passing fluid are essential for the system performance. However, a pre-requisite for the description of heat transfer is the detailed knowledge of the movement of the granular material as a whole and, in addition, statistics on the details of the movement, which is the content of the current paper.

For the limiting case of large numbers of small particles in kilns of large diameters and length, several theoretical models and analytical descriptions of the bed geometry, the motion type (rolling motion, slumping), and axial and radial material transport were developed in the past and employed in the design. Such models express for example the dynamic angle of repose and the thickness of the active layer in the rolling motion as a function of Froude number and filling height [1–4]. Based on this information numerical heat transfer models were developed [5,6] which, in conjunction with individually measured parameters, allow a "first order" approximation and are indeed quantitatively valid for the industrial cases considered.

However, it should be noted that the details of the mixing process and the heat transfer within the so-called active and passive layers (chapter 5.2) and time histories of individual particle temperatures or their statistics are still unknown.

Discrete Element (DEM) Simulations coupled with fluid flow computations (CFD) can provide insight into the movement of the bed material and the associated processes (e.g. heat transfer). Unfortunately, due to the time and memory resources required, the number of particles within industrial scale systems is far too large to be actually considered in this kind of computations.

Nevertheless, although limited in the number of particles DEM simulations are a first step to a deeper understanding of the underlying physical processes and give insight into bulk internal data which are difficult or impossible to obtain from measurements. Therefore, DEM simulations are a useful tool to provide information needed to improve the macroscopic models mentioned above.

The current paper can be seen as a first preparatory step in the evaluation of heat transfer using DEM. During steady state operation two boundary processes, the heat exchange at the wall of the kiln and the heat exchange at the free surface of the bulk are important. The particle velocity at the free surface and, to a lesser extent the slip between particles and the wall control the heat transfer within the bed material. A correct thermal description requires a verified mechanical behaviour at these positions.

Therefore the current paper compares the measurements of angle of repose and particle free surface velocity (mean values and frequency

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distributions) with DEM simulations. In addition, the active layer thickness deduced from DEM simulations is compared with an analytical model of Liu et al. [7]. Finally, the velocity slip between particles and the rotating wall, which is not directly accessible in experiments, is evaluated from the DEM simulations.

2. Previous work

Several experimental investigations of rolling solid motion in rotary kilns and rotating drums (the two notions are deliberately used in this paper to distinguish between industrial scale and bench-top systems) have been carried out; most of the studies were conducted to develop a description of the overall material movement in technical systems and often for specific materials. DEM simulations of rotating drums were mostly focused on the comparisons of the dynamic angle of repose and the active layer thickness with corresponding measurements.

According to Henein [2] and Ding [8], the dynamic angle was found to be independent of the rotational speed, and Spurling [3] found that the dynamic angle of repose is constant or increases very slowly with the circumferential velocity. In contrast, according to Hill and Kakalios [9], Khakhar et al. [10], Yamane et al. [11], Dury et al. [12], Khosropour et al. [13], and Orpe and Khakhar [14], the dynamic angle of repose increases nearly linearly with the rotational speed. A wide range of rotational speeds, materials and drum diameters was investigated; this may be a reason for the apparent contradictions between the results mentioned.

Yang et al. [15] used DEM simulations to obtain the dynamic angle of repose and the particle velocity for a small drum diameter of D = 100 mm using only one particle diameter. Alizadeh et al. [16] compared DEM simulations with experimental data and explains why it may provide physically sound results even when non-real particle properties are used. The influence of particle shape and shape approximation on particle mechanics with DEM was investigated by Höhner et al. [17] using polyhedra and smoothed polyhedra to approximate the particle shape with the focus on the dynamic angle of repose and mixing.

Nan Gui et al. [18] analysed the particle mixing and heat conduction in rotating drums. Longitudinal and transverse mixing was investigated by Finnie et al. [19] and Arntz et al. [20]. The focus was on the mixing behaviour at high filling degrees (more than f = 20%) and not on the dynamic angle of repose and the active layer thickness in the rolling motion at lower filling degrees, which are important parameters to calculate the heat transfer in rotating drums.

Shi et al. [21] investigated the heat transfer in rotating drums with interstitial gases by coupling DEM and CFD. The focus was on the gas within the bulk and not on the mechanical behaviour and the conductive heat transfer between the wall and the particles. Furthermore, it would be very interesting to compare these results with experiments.

Liu et al. developed an analytical solution predicting the bed motion in rotary kilns in the rolling motion mode [7]. In the moving bed two distinctive zones with differing behaviours can be identified in the rolling motion mode. These are the passive layer on the bottom and the active layer on the top of the bulk. The two zones are separated by a boundary line [22]. The active layer thickness was calculated for different drum and particle diameters, and in the current paper the analytical model is compared with numerical simulations to investigate the quality of the DEM simulations for the bed behaviour in rotating drums. An analytical solution for the average particle velocity on the bed surface was developed by Mellmann and Specht [4] and is now compared with simulations and experiments in this work.

3. Experimental setup

The test rig shown in Fig. 1 was used for the measurements. The drums were made out of steel tubes with a length of 500 mm, a wall thickness of 2 mm and diameters D of 200, 300 and 400 mm. The inner wall of the drums is lined with sandpaper to provide a defined roughness.

The drum was driven by an electric motor with 1.5 kW and controlled by a frequency converter to obtain constant rotational speeds in the range of 1 to 35 rpm. Rotational speeds between 3 and 15 rpm were used in the current experiments to ensure the rolling motion mode.

A glass pane at the front provides optical access and allows recording of the bed movement at this wall to determine the dynamic angle of repose as well as the velocity of the particles on the bed surface.

A digital camera system (IDS U-Eye 1245LE), as shown in Fig. 1, was used to record the particle movement at the front wall. For the determination of the dynamic angle of repose the available frame rate of 20 fps was sufficient. The angle of repose was extracted from recorded videos by a software-tool; the associated variance in the experiments was about one degree. The surface detection procedure is based on the Canny Algorithm and is described in detail in [23]. A partial regression line is computed from the points detected at the surface and the angle with the horizontal is calculated. The error of the detection procedure is about 0.8%.

The measurement of the particle velocities on the bed surface requires higher frame rates; a high speed camera (Type Optronis CL600) providing 250 fps was used for this purpose (Fig. 1). A two-frame motion estimation algorithm proposed by Farnebäck [24] was used to determine the displacement field for each image (the analysed image compared to both the previous and the subsequent image) based on polynomial expansion. In this case the variance of the measured values was 0.014 m/s, with an error of about 2.4%.

The investigated bed materials considered were monodisperse glass spheres with four different diameters (d_P = 3, 5, 7 and 12 mm) and with the material properties shown in Table 1.

Filling degrees of f = 10% and f = 20% were investigated, where the filling degree is defined as:

$$f = \frac{V_{bulk}}{V_{drum}} = \frac{l_{drum} * A_{bulk}}{l_{drum} * A_{drum}} \tag{3–1}$$

with drum volume V_{drum}, volume of the particles V_{bulk}, depth of the drum l_{drum} and cross-sectional area A.

The Froude number used in the following to characterise the individual experiments is defined as the ratio of centrifugal force to gravitational force:

$$Fr = \frac{\omega^2 * R}{g} \text{ with } \omega = \frac{2 * \pi * n}{60} \tag{3–2}$$

with rotational frequency n, drum radius r and gravitational force g.

4. DEM

In a discrete description (DEM) the movement of each single particle in the bed is described by simultaneous integration of Newton's and Euler's equations whilst incorporating all interactions amongst the particles, the wall and free surfaces [25–27]. The discrete element code of LEAT [28–31] was used in this study to simulate the rotating drum with spherical particles. The particles are considered as soft spheres. The linear spring dashpot model is used for normal and tangential forces. To allow for particle rolling both translational and rotational motion are resolved. Further details on the mechanical models used may be found in [23].

The parameters used in the simulation were the same as in the experiments. From the diameters of the drums and particles used a size ratio D/d between 28.57 and 133.33 results. In contrast to the experiments, where the drum had a fixed length of 500 mm (LEAT), the length of the simulated drum is always 20 times the particle diameter. Thereby the influence of the sidewalls on the result in the centre