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Dynamics of granular flows down rotating semi-cylindrical chutes

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Abstract

The behavior of spherical particles flowing down a three-dimensional chute, inclined at fixed angle, is commonly simulated by a discrete element method (DEM). DEM is nowadays a standard tool for numerical studies of e.g. gas-solid fluidized beds. We have modified DEM for the simulation of rotating granular flows. In view of future extensions aimed at, for example, segregation studies of (rotating) bi- and polydisperse granular flows or mixtures of two kinds of granular particles with different densities, several validation steps are required. In a first step we compare DEM simulations with experiments of monodisperse spherical glass particles flowing through a rotating semi-cylindrical chute inclined at a fixed angle and constant flow rate. Different measurement techniques such as Particle Image Velocimetry and Particle Tracking Velocimetry are used to measure the averaged surface velocity of the particles and the bed height in the chute. We observe that the prevailing flow patterns depend strongly on the rotation rate of the chute. The streamwise and the spanwise particle velocities are influenced by the centrifugal and Coriolis forces, where with increasing rotation rate the particles are moving increasingly sideways. We find that the details of the particle feeding pattern are important only for the particle flow near the entrance of the chute, whereas after a relatively short distance the particle flow depends only on other factors such as the mass rate, inclination angle and rotation rate. Our DEM model predictions agree well with the experimental measurements for bed height and surface velocity.

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1. Introduction

Granular materials play an important commercial role in many applications such as chemical engineering, pharmaceutical industry, agriculture, mining, metallurgical processing and energy production. The industrial applications concern the processing of granular materials with varying particle properties, such as size, density and non-uniformity in shape. During these processing steps (transportation, charging, discharging, etc.) segregation may occur, which is undesirable when a homogeneous mixture is required in, for example, the metallurgical and pharmaceutical industries.

In blast furnaces operated in the metallurgical industry, granular materials such as sinter, pellet, coke and limestone are charged from the top of a hopper into the burden surface of the furnace through an inclined rotating chute. Such particulate flows tend to segregate during the hopper discharge process and on the rotating chute as a result of differences in material density, size and shape. Thus, a better (and fundamental) understanding of the phenomena, allowing for a better control of the flow behavior of granular materials on the rotating chute, is very important for the smooth and efficient working of a blast furnace. The first step towards generating this understanding is to study monodisperse granular spherical particles on an inclined rotating semi-cylindrical chute by employing laboratory experiments and numerical studies of model systems.

Previous experimental work has been done on granular flows on inclined chutes because of its practical importance in industry applications, like transportation [1-7]. The discrete element method (DEM) developed by Cundall and Strack is one of the most useful and reliable simulation tools for the numerical analysis of granular flow behaviour in industrial applications. Recently, several DEM simulation studies have focused on the flow behaviour of granular material on the rotating chute, but validating the method both qualitatively and quantitatively against real and relevant experiments is still needed.

In this paper, we investigate flows of monodisperse spherical particles down a rotating semi-cylindrical chute inclined at fixed angle of 25 degrees by DEM and validate the method both qualitatively and quantitatively by comparing with experimental results of averaged streamwise and spanwise surface particle velocities and the averaged bed height. The paper organised as follows: In Section 2 we present a summary of the simulation model, in Section 3 the experimental setup and in Section 4 the measurement techniques are briefly reviewed. In Section 5 validation of simulations by experimental results are presented. Finally, we give our conclusions in Section 6.

2. Discrete Element Model

The DEM developed by Cundall and Strack (1979) has been applied successfully to simulate many granular flow systems [12]. This DEM is based on a standard linear spring/dashpot soft-sphere model, wherein separate springs and dashpots are defined for normal and transversal displacements. The velocities, positions and contact forces of the particles are calculated at every fixed time step via a first order time integration. For more details on the implementation of this soft-sphere model we refer to the work of Van der Hoef et al. [13] and Deen et al. [14].

The translation and rotation of every individual particle $a$ in the system is described by Newton’s equations:

$$m_a \frac{dv_a}{dt} = m_a g + F_c^a$$
For completeness, we note that in preliminary simulations we have studied the effect of pressure and drag forces induced by co-flowing interstitial gas in both nonrotating and rotating chutes. For our particles (3 mm glass spheres) we found no significant change in results. Therefore, we ignore gas-induced forces in the rest of our analysis [15].

2.1. Coriolis and centrifugal forces

Our simulations take place in a co-rotating frame of reference. As a consequence, pseudo-forces arise due to the non-inertial motion of the system. Every individual particle $a$ in the rotating system experiences an additional Coriolis force and centrifugal force, both of which are added to the equation of motion eq. (1),

$$I_a \frac{d\omega_a}{dt} = T_a$$

We found no significant change in results. Therefore, we ignore gas-induced forces in the rest of our analysis [15].

(2)

Similarly, every particle will experience an additional Coriolis torque, which must be added to eq. (2)

$$\begin{align*}
(F)_{\text{rotating}} &= (F)_{\text{stationary}} - 2m_a(\Omega \times v_a) - m_a(\Omega \times [\Omega \times r_a]) \\
(T)_{\text{rotating}} &= (T)_{\text{stationary}} - I_a(\Omega \times \omega_a)
\end{align*}$$

When applying Eq. (4) the true angular momentum (i.e. when viewed from an outside inertial system) is exactly conserved.

3. Experimental setup and procedure

Figure 1. The experimental setup with rotating table facility and PTV cameras.
In Fig. 1 we give a schematic representation of the side view of the experimental setup. The experimental equipment includes a hopper for storage of particles and a collection tank. A vacuum pump is attached to the top of the hopper to recycle the granular material from the collection tank. The mass rate is measured through a dynamic weighing scale, the surface information such as particle bed height and the surface particle velocity field is measured through a PTV camera arrangement. The granular material is stored in a hopper at the top end of the chute. To minimise rotational flow of the granular material inside the hopper prior to deposition on the chute, the rotation axis passes through the centre of the hopper. The flow region of the experimental setup consists of a semi-cylindrical plexiglas chute. The interior of the chute is 1 m in length and 7 cm in diameter. The whole chute is fixed from bottom to a strong metal plate of 1 cm thick to minimise vibrations due to the particles poured from the hopper mouth to the chute surface at the inlet. The inclination angle of the chute (defined with respect to the horizontal) is adjustable between 0 and 60 degrees. At the end of the chute, a collecting tank is placed on a dynamic weighing scale to measure the flow rate.

The whole setup is mounted on a rotating table, so that the flow is measured in the non-inertial frame of reference. All the hardware constituting the focusing system and the measurement system is located on the top of the table or surface below it as shown in figure 1. The equipment is remotely controlled from an adjacent room for safety precautions during the rotating experiments.

The following steps are used during the start-up of the experiments. First, the granular particles (3 mm glass spheres) are filled in the top hopper. The rotating table is accelerated until it reaches the desired steady rotation rate. Then an experiment is started by opening the outlet of the hopper by remote control, and the granular material flows in downward direction along the length of the chute. At the end of the chute, the granular material is collected into the collection tank. Measurements are made continuously until the hopper is depleted. The time range during which steady-state flow conditions apply is determined after the experiment by analysing the time dependence of mass, height and velocity measurements.

4. Measurement techniques

4.1. Particle image velocimetry

PIV has also been successfully applied to granular systems recently. In this work PIV has been applied to study the particle flow patterns in an inclined rotating semicylindrical chute. A short description of the technique is given in this section. The interested reader is referred to the work of Westerweel et al. for further details [16].

The basic principle of PIV is to record two images with a short time delay, \( \Delta t \), and determine the displacement, \( s(x, t) \), of the particles between the two images with a spatial cross-correlation algorithm on two consecutive images. The instantaneous velocity can now be obtained by dividing the peak displacement \( \bar{s}_p \) with the time delay \( \Delta t \) between the images and the magnification \( M \) (in pixels per meter) of the image, i.e.

\[
\bar{v}_p(x, t) = \frac{\bar{s}_p(x, t)}{M \Delta t}
\]

The PIV pairs of images are postprocessed using the commercial software package DaVis (Lavision). A multipass algorithm using interrogation zones of 32x32 px (with 50% overlap) and 16x16 px (0% overlap) was employed to reconstruct the corresponding vector images. After all post-processing, a time-averaged velocity field is obtained from a sequence of instantaneous velocity fields obtained over a time interval during which the flow is steady.

4.2. Particle Tracking Velocimetry

The 3D Particle Tracking Velocimetry (3D-PTV) technique is a flexible non-intrusive image analysis based flow
measurement technique. The idea of 3D-PTV was introduced by Chang and Taterson [17], and was further developed by Racca and Dewey [18]. The ETH group published papers in which they illustrate the algorithm used in the code in more detail. Mass et al.[19], Malik et al. [20], Willneff and Gruen[21], Willneff [22-23]. In these works 3D-PTV was used to reconstruct the three-dimensional positions of the particles and derive the velocities of tracer particles in the flow from three synchronized camera images. In Figure 1 a sketch is provided of our experimental set-up, including the camera positions used for 3D-PTV measurements. The particles used are blue particles having the same diameter and properties as the bulk of the flowing particles. To find the three-dimensional coordinates of the tracer particles, we match the image of a particle on one camera to the images of the same particle on the other two cameras. Each position on a camera image corresponds to a tracer particle that exists somewhere along a ray in space. The three-dimensional position of the particle is determined by finding rays from the three cameras that intersect. Converting image positions to rays in space requires a camera model and an accurate calibration to determine the parameters of the model. To obtain the calibration parameters, we imaged a calibration plate (body) consisting of an array of dots with known coordinates. From camera images of the calibration plate positioned at different heights we measure the positions of each dot. A polynomial fit of these measured positions to the calibration model gives the necessary calibration parameters for that camera. The images were recorded with 2000 fps to improve the tracking of particles. The post-processing of images is done for 10000 images of each camera by modified ETH Zurich software to get the 3D position of particles. In this work we used the bed height obtained from PTV and the surface velocity from PIV for validation of the DEM.

4.3 Calculation of bed height from PTV

The post-processing of the PTV can be done with different approaches. The main output of the PTV images consists of particle tracks along the chute. In this research, the aim is to determine the particle bed height at different positions in the chute. Therefore, several steps are undertaken to extract the desired information from the PTV data. In this paragraph, these steps are discussed. To find an accurate value for the bed height along the length of the chute and for different positions in the width direction of the chute, the particle track density is determined. We assume that the bed height is the height above the chute bottom plane at which the local track density is the highest. In order to determine the local track density, the chute volume is divided into cells and the number of particle tracks crossing through the cell is counted. Subsequently, for each column of cells, the local maximum of the density can be ascertained, and thus the position of the bed height is known (on cell basis). It should be mentioned that the number of cells for the calculations is 250 (length) x 28 (width) x 100 (height). Applying this method for each cell position in the length direction, the bed height profile can be obtained for a certain section in the width direction. Since this data is quite noisy, a Gaussian filter is used to smooth the curve.

4.4 Simulation and experimental settings

The physical properties of the spherical glass particles and the conditions for the simulation and experiment are shown in Table 1. In our DEM simulations the chute is initially empty, as is the case in the physical experiments. Simulations are carried out for a constant mass flow rate at the inlet of the chute. We introduce the particles at the top of the chute near the entrance in a rectangular area with arrangement of the particles in a bcc-lattice, with a mass flow rate of 2.9 kg/s, which is equal to the mass flow rate of the experiments.

<table>
<thead>
<tr>
<th>Summary of the parameters used in the computational and experimental studies</th>
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<tbody>
<tr>
<td><strong>Computational conditions</strong></td>
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<tr>
<td>Length of chute</td>
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<tr>
<td>Diameter of chute</td>
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</table>
5. Results and discussion:

To be able to compare experiments and simulations, we have determined the first point at which the bed height and surface flow velocity match between experiment and simulation for a non-rotating chute at an angle of inclination of 25 degrees. In all subsequent figures, we have shifted the origin (for distance along the flow direction) to this point. It is important to have exactly the same distance to the rotation axis in both simulations and experiments. In detail, in both our simulations and in our experiments the axis of rotation is cutting through the bottom plane at a distance of 0.035 m before the point of origin determined above.

5.1 Validation: comparison with experimental results

In this section we validate the model for different rotation rates of the chute and fixed inclination angle by comparing with streamwise surface particle velocity, spanwise surface particle velocity and particle bed height profile. The major effect of chute rotation is a sideways deflection of the particle stream due to Coriolis forces present in the frame of reference co-rotating with the chute. This is confirmed in Fig. 2, which shows snapshots of the steady-state flow of monodisperse particles in a chute inclined at 25 degrees for different rotation rates, where colors indicate the magnitude of the velocity of the particles.

\[
\begin{align*}
\Omega &= 0 \text{ rpm} \\
\Omega &= 16 \text{ rpm}
\end{align*}
\]
Figure 2. Top view snapshots of steady-state granular flows, flowing from left to right through a chute inclined at 25 degrees. The chute is rotating with a rotation rate of 0 rpm or 16 rpm. Greyscale: experiments. In the simulation snapshots, particles are colored according to their streamwise velocity, from blue to red for low to high velocity.

5.1.1 Streamwise surface particle velocity in the width-wise direction

Figure 3 shows the streamwise surface particle velocity as a function of width-wise position at four different streamwise positions, for rotation rates 0 rpm (non-rotating chute), 4 rpm, 8 rpm and 16 rpm. The stream-wise positions are at z = 0.0 m, 0.2 m, 0.4 m and 0.6 m. The simulation results (lines) are compared with experimental results (symbols). The figures show that in the non rotating case the streamwise velocity is zero near to walls and it is higher in the middle of chute. Moreover, as the rotation rate increases, the particles move sideways causing a slight increase in velocity. Again we find good agreement between the simulation and experimental results.

Figure 3. Stream-wise particle velocity along the width of the chute inclined at 25 degrees for a rotation rate of 0 rpm, 4 rpm, 8 rpm and 16 rpm. Symbols are experiments, lines are simulations

5.1.2 Spanwise surface particle velocity in the width-wise direction
Figure 4 illustrates the spanwise surface particle velocity along the width of the chute at different cross sections in the length of the chute. The simulation results are compared with experimental results for different rotation rates of the chute at an inclination of 25 degree. We observe that the magnitude of the spanwise velocity first increases and then decreases for consecutive streamwise positions. This corresponds to the process of sideways motion induced by Coriolis forces. The maximum span-wise velocity increases with increasing rotation rate. In all cases, rather good agreement is found between experiments and simulations.

![Figure 4. Spanwise particle velocity along the width of the chute inclined at 25 degrees for a rotation rate of 0 rpm, 4 rpm, 8 rpm and 16 rpm. Symbols are experiments, lines are simulations](image)

5.1.3 Bed height along the length of the chute

Figure 5 shows the bed height as a function of position along the length of the chute, for a chute inclined at a fixed angle of 25 degrees. The bed height is averaged over the centreline of the chute using a width of 0.5 cm. The simulated bed height results (lines) are compared with PTV results (symbols). For the non-rotating chute the bed height is nearly same for the different width-wise positions. As the rotation rate of the chute increases, the bed height decreases in the centre of the chute. Some deviations between simulation and experiments are observed, but generally the agreement is good.
6. Conclusions

In this work we have compared DEM simulations with laboratory experiments of granular flows through an inclined rotating semicylindrical chute, which is commonly used in bell-less charging of the blast furnace in steel industry. The key objective of the work was to validate the computational model with experimental results. Comparison of the simulation results with findings from experiments showed that the DEM model correctly reproduces the main features of the (rotating) granular flow: the streamwise and spanwise surface particle velocity, as well as the particle bed height.

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