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The simulation of particle flow mechanisms in dustiness testers

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Abstract
Dust generation is a common result of many bulk handling and mining applications and has potentially serious consequences to the surrounding environment as well as workers and nearby community. Companies need to know how much and what type of dust is being generated so they can find ways to reduce this dust. Dustiness testers can be used for this purpose. This paper investigates the rotating drum testers used for dustiness testing of bulk solids and the subsequent discrete element method (DEM) simulation of the particle mechanisms. Preliminary comparisons of the rotating drum designs were undertaken using particle/bulk parameters of a granular “non-dusty” material (polyethylene pellets) to investigate the flow mechanisms to ensure accuracy before pursuing the complexity of simulating small dusty materials. These initial trials involved generating a calibrated material model for the polyethylene pellets via experimental testing to produce the required particle properties, particle-particle and particle-geometry interactions. The calibrated DEM material models and simulations have been based initially on the International standard for dustiness testing. Preliminary investigations of the drum dimensions, rotational speed, volume and location of initial product sample have been performed. The motion of particles in the simulated rotating drums have been compared with that seen in the experimental testing. It is hoped that the proposed simulation methods can provide an accurate way to replicate experimental dustiness testing, with the overall aim of understanding and minimising dust generation.

Keywords
dustiness, testers, particle, mechanisms, flow, simulation

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The Simulation of Particle Flow Mechanisms in Dustiness Testers

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Abstract

Dust generation is a common result of many bulk handling and mining applications and has potentially serious consequences to the surrounding environment as well as workers and nearby community. Companies need to know how much and what type of dust is being generated so they can find ways to reduce this dust. Dustiness testers can be used for this purpose. This paper investigates the rotating drum testers used for dustiness testing of bulk solids and the subsequent discrete element method (DEM) simulation of the particle mechanisms. Preliminary comparisons of the rotating drum designs were undertaken using particle/bulk parameters of a granular “non-dusty” material (polyethylene pellets) to investigate the flow mechanisms to ensure accuracy before pursuing the complexity of simulating small dusty materials. These initial trials involved generating a calibrated material model for the polyethylene pellets via experimental testing to produce the required particle properties, particle-particle and particle-geometry interactions. The calibrated DEM material models and simulations have been based initially on the International standard for dustiness testing. Preliminary investigations of the drum dimensions, rotational speed, volume and location of initial product sample have been performed. The motion of particles in the simulated rotating drums have been compared with that seen in the experimental testing. It is hoped that the proposed simulation methods can provide an accurate way to replicate experimental dustiness testing, with the overall aim of understanding and minimising dust generation.

Keywords: Discrete element method (DEM), dustiness, granular flow, rotating drum, validation

1 Introduction

The handling, transportation and loading or unloading of bulk materials can generate dust [1]. The formation and emission of dust during handling depends on the type of material handling, size distribution of generated particles, and properties of the material [2]. Dust emissions are creating an increasing number of problems in industry, health effects on workers, and leading to defective condition of products in manufacturing processes and parts of machine [3-5]. Dustiness is defined as the propensity of a material to emit dust during handling and a measure of the dustiness of a material can be obtained from dustiness testing (rotating drum methods) [3, 6].

Discrete element modelling (DEM) is becoming an increasingly popular method for the simulation, analysis and visualisation of the flow of granular materials, and as such is used in various models in process engineering and mining. Examples include mixing [7], pneumatic conveying [8], silo and hopper flow [9, 10]. The principle of DEM is to track, in a time stepping simulation, the trajectory, rotation and translation of each element in a system to evaluate its position and orientation, and then to calculate the interactions between the elements themselves and also between the elements and their environment.

This paper presents an experimental investigation into the flow of granular material in the I.S. EN15051 dustiness tester and compares these results to those obtained by DEM Simulation. Each dustiness test requires a total amount of 35 ml of material and the drum rotates at 4 rpm.

This study proposes the principle of modelling shapes by using spherical clusters which are applied here in a 3D rotating drum. Some physical properties of polyethylene pellets were studied including particle volume, particle weight, particle size, particle shape, particle density, loose-
poured bulk density, angle of repose, coefficient of restitution, coefficient of static friction and coefficient of rolling friction. The paper also illustrates a 3D DEM simulation of particles flowing in a horizontal rotating drum and the experiment apparatus is based on the EN15051 rotating drum while maintaining required separating parameters [1]. Simulation conditions are similar to those used in the EN15051[1] experiment, in order to validate at the same time the simulation method at a particle scale. A cylindrical drum of radius (r) rotates at a constant angular velocity. The drum is partially filled with polyethylene pellets using four different locations for the initial location of the product sample; at the front, at the end, in the middle and also spread evenly along the bottom of rotating drum. The DEM methodology has been well calibrated against experimental results to verify validation of DEM material models. The rotating drum method is a frequently employed method due to its ability to simulate a wide range of material handling processes for the estimation of dustiness [11].

2 Dustiness Testers

Dustiness testing is used for powder or granular materials in the rotating drum test under standard conditions [1], shown in Fig 1.

The rotating drum tester used in this paper is based on the International Standard Dustiness Tester [1]. The EN 15051 (Figure 1) laboratory apparatus included a 300 mm inner diameter drum made from stainless steel and the drum rotates at 4 rpm. Inside the drum eight longitudinal vanes are installed and made from stainless steel: 25 mm high by 230 mm long and fixed longitudinally to the internal surface of the drum. The polyethylene pellets used in this method have a volume of approximately 35 cm$^3$ and the experiment runs for 1 minute (as required by the standard).

3 The Discrete Element Method

Polyethylene pellets flowing in rotating drums have been described in many references [12-14]. The motion of each particle is based on rotational and translating motions according to Newton's second law. The equations are as follows.

$$m_i \frac{dv_i}{dt} = \sum (F_{ij}^n + F_{ij}^s + m_i g)$$  \hspace{1cm} (1)

$$I_i \frac{d\omega_i}{dt} = \sum (R_i \times F_{ij}^s - \mu_r R_i |F_{ij}^n| \hat{\omega_i})$$  \hspace{1cm} (2)

Where $m_i$, $I_i$, $v_i$ and $\omega_i$ are the mass, the moment of inertia, translational velocities and rotational velocities of particle $i$, respectively. $F_{ij}^n$, $F_{ij}^s$ and $m_i g$ represent the normal contact force, the tangential contact force imposed on particle $i$ by particle $j$ and gravitational force, respectively. $R_i$ represents a vector from the centre of particle to contact surface, $\mu_r$ represents the coefficient of rolling friction and $\hat{\omega_i}$ is a unit vector equal to $\omega_i$ divided by its magnitude.
The contact force model between the particles and particle-wall are based on a spring-dashpot model and Hertz-Mindlin no-slip model. The magnitude of the normal force between two particles is given as [13]:

\[ F_n = -k_n \Delta x + C_n v_n \]  

(3)

The magnitude of the tangential force is given as:

\[ F_t = \min \{ \mu F_n, k_t \int v_t \, dt + C_t v_t \} \]  

(4)

where \( k_n \) and \( k_t \) are the normal stiffness and tangential stiffness respectively, \( \Delta x \) is the particle overlap, \( v_n \) and \( v_t \) are relative normal velocity and relative tangential velocity respectively, \( C_n \) and \( C_t \) are the normal damping coefficient and tangential damping coefficient respectively, \( C_n \) depends on the coefficient of restitution, \( e \) defined as the ratio of the normal component of the relative velocity after and before the collision.

\[ C_n = -\frac{2\ln(e)}{\sqrt{m_i m_j k_n}} \]  

(5)

\[ m_{ij} = \frac{m_i m_j}{m_i + m_j} \]  

(6)

where \( m_{ij} \) is the reduced mass of two particles \( i \) and particles \( j \).

4 Materials Properties Using EDEM

Materials properties input to EDEM simulations can be divided into two categories; material properties and interaction properties [15-17]. Materials properties are Poisson’s ratio, density and shear modulus. Interaction properties between each particle and particle/geometry are the coefficient of restitution, coefficient of static friction and coefficient of rolling friction. Particle shape and particle size distribution also are modelled appropriately. Table 1 summarises the values of the material properties and the interaction materials.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Polyethylene pellets</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Solid density (kg/m³), ( \rho_p )</td>
<td>907.6</td>
<td>8000</td>
</tr>
<tr>
<td>Particle Loose-poured bulk density (kg/m³), ( \rho_b )</td>
<td>531 – 533</td>
<td>-</td>
</tr>
<tr>
<td>Particle Poisson Ratio (( \nu ))</td>
<td>0.45</td>
<td>0.29</td>
</tr>
<tr>
<td>Particle Shear Modulus (Pa), ( G )</td>
<td>1.17E+8</td>
<td>7.75E+10</td>
</tr>
<tr>
<td>Particle Coefficient of Restitution, ( e )</td>
<td>0.654</td>
<td>0.65</td>
</tr>
<tr>
<td>Particle Coefficient of Static Friction, ( \mu_s )</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Particle Coefficient of Rolling Friction, ( \mu_r )</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The particle density \( \rho_p \) of a granular material is the mass divided by the true volume of the polyethylene pellets and is measured by using a StereoPycnometer machine. Loosed-poured bulk density \( \rho_b \) is the ratio of the mass per unit volume of a polyethylene pellets including the interstitial voids between the particles [18]. In this paper, the mass-volume ratio of the polyethylene pellets was investigated by weighing a container of known volume without the polyethylene pellets material and then gently pouring polyethylene pellets into the container. The polyethylene pellets were poured through conical hopper and allowed to fall a fixed height of 50 mm approximately to the cylindrical 1000 ml container. Excess polyethylene pellet was removed using a ruler to scrape slowly across the top of the cylindrical container, without disturbing the particles settled loosely in the container. Figure 2 demonstrates the effect of loose-poured bulk density versus the coefficient of rolling friction varies in the range 0.01 to 0.2 every 0.05 increased. As the coefficient of rolling friction increases between particles, the voidage consequently increases which reduces the loose-poured bulk density as the relative motion between particles is restricted and the particle dilate. It is clear that the particle shape and size directly affect the packing of cohesionless particles. Shear
modulus \( G \) and Poisson’s ratio \( \nu \) of the polyethylene pellets are described in the literature [16, 17].

The particle coefficient of restitution \( e \) is defined as the ratio of the height of the particle after an impact to the height of the particle before impact using an experiment similar to that described by [9, 15]. The \( e \) value was computed as the ratio of the square root of the height of rebound trajectories that were vertical (particles not rotating) and the initial height of drop. For this purpose 25 polyethylene pellet particles were dropped from a height of 250 mm onto a flat wall surface.

The determination of the coefficient of friction between particle and wall \( (\mu_{s(p.w)}) \) was based on particles beginning to roll or slide on a tilting flat plate (Poly pellets plate, Perspex plate and Stainless Steel plate 150 mm square sheet). At this point, the experiment is stopped and the angle of inclination of the flat plane is measured to calculate the value of coefficient of friction \( (\mu_{s(p.w)}) \). Similar to other researchers [17], the coefficient of friction \( (\mu_{s(p.p)}) \) between the particles is approximated by DEM modelling to match the experiment inclination tester.

The coefficient of rolling friction between particles \( (\mu_{r(p.p)}) \), particle and wall \( (\mu_{r(p.w)}) \) is approximated in DEM modelling to match the experiment [16]. Rolling resistance between particles was measured indirectly using the translating tube slump tester.

The values in Table 1 were used to construct preliminary DEM models for the material. The particle shape and sizing of the polyethylene pellets are shown in Figure 3. 50 polyethylene pellet particles were selected at random from the bulk material to determine particle shape and particle size [20]. Measurements of 3 key particle dimensions were taken for each particle corresponding roughly to the particle length and two perpendicular diameters [18]. The mean particle diameter was taken as the average of all the recorded dimensions: particle diameter (max and min) were 3.84, 3.62 mm respectively and particle length was 4.54 mm.

Figure 2. Effect of loose-poured bulk density and coefficient of rolling friction, 1-Spherical, 2-Spherical, 3-Spherical and 4-Spherical see Figure 3.
The angle of repose ($\alpha$) is the angle of the slope surface formed when a quantity of polyethylene pellets is poured into a heap on the floor [15, 21]. All the experiments were repeated five times for each polyethylene-pellet samples and the average values were reported.

5 Modelling and validation of particle using discrete element method

The aim of the experimental validation undertaken was to determine whether the DEM models developed for polyethylene pellets were able to reliably predict particle flow in a rotating drum. The experimental validation of any numerical model requires comparisons to be made between predicted variables and those actually measured in a laboratory-scale experiment.

In this paper, a model rotating drum of the same dimensions as the simulated rotating drum was built for this purpose (Figure 1). To calibrate the coefficient of rolling friction ($\mu_{r(p,w)}$) between the polyethylene pellets material and wall, the polyethylene pellets were placed on the flat plate (wall), which was tilted gradually until the particles just started to move. The coefficient of rolling friction was adjusted until the angle of inclination of the flat plate in the DEM model matched the experiment [18, 19].

To calibrate the coefficient of rolling friction ($\mu_{r(p,p)}$) between the polyethylene pellets and the coefficient of static friction ($\mu_{s(p,p)}$) between the polyethylene pellets on the angle of repose (see Figure 4), a translating tube slump tester [16] was used with the tube inside diameter (ID) of 60 mm and with polyethylene pellets filled to a height of 180 mm approximately. The translational velocity of the tube was 7 mm.s$^{-1}$ in vertical direction. The angle of repose from the experimental data matches with the DEM data, the coefficient of static friction varies in the range 0.1 to 1 and the coefficients of rolling friction between 0.01 to 0.2 [16, 18].
6 Results and Discussion

The polyethylene pellet flow in the rotating drum was investigated under different conditions: starting location of material inside the drum, particle size and particle shape of the particle model using DEM simulations. In addition, the effect of the coefficient of static friction and rolling friction between materials (particle-particle and particle-wall) on particle flow in the drum was analysed in this study.

6.1 Experimental observation and numerical validation of DEM models for different particle shapes

Experiments were carried out in the laboratory to allow direct comparisons with the DEM simulation results. Particle shapes were compared using 3D DEM simulations, and the material properties described in Table 1 were used for this purpose.

Figure 5 shows the heap profiles formed with the four particle shapes, with the horizontal distance and height distance of the particle heap on the floor. The particle contact in DEM simulations data are very close to the experiment data as the coefficient of rolling friction between particles is 0.2 and the coefficient of static friction between particles is 0.1.

![Figure 5. Comparison between DEM and experiment of the translating tube slump tester](image)

\[
\mu_s(p,p) = 0.2, \mu_r(p,p) = 0.1
\]

Figure 6 shows typical figures of the particle flows in the drum for the experiments and the various particles in DEM models for 1-spherical, 2-spherical, 3-spherical and 4-spherical, different time step, with the drum rotating clockwise and the same starting location for the particles spread evenly along the bottom of the drum. The results in the first row are from experiment and other rows for DEM simulations. Each column is a different time step. It can be seen that zero seconds is the starting position. At 4s the particles start to leave out from the vanes at 96 degree, at 5s the particles leave to the near vanes at 120 degree approximate, all the particles move out from the vanes at 132 degree (5.5s) to the far vanes, especially the spherical cluster shape follows the experiment more closely compared to the 1-sphere model and every 2s the particles move out from the vanes.
Figure 6. Profiles of the experiment (top) and DEM simulation (second row – fifth row):
1S = 1- Spherical; 2S = 2- Spherical; 3S = 3- Spherical; 4S = 4- Spherical

6.2 Particle flow based on different starting locations for the particle

Figure 7 demonstrates typical pictures of the particles flowing for the four different starting locations in the drum, based on the experiments, the various particles in DEM models for 1-spherical, 2-spherical, 3-spherical and 4-spherical, 5s and the angle of the vanes at 132 degree approximate. The results show the particles moving along the wall of the drum, collision with each particle and the near vanes. It can be clearly seen that the middle heap and length heap of the particles provide very similar results. For the front heap and end heap, the particles have not spread evenly along the full vanes at this time.

The particle spread on the vanes and the particles move out from the vanes to the wall surface of the drum for the different particle shape models and the different starting locations are shown in Figure 8 and Figure 9. Figure 8 shows the particle flow for the starting location at the front heap, at the end heap and different particle shape in each time. Both starting locations have similar particle flow and particles begin to spread along the vanes between 13.5s and 15.5s approximately. The particles have spread evenly along the full vanes at 31.5s – 35.5s, all particles move out from the vanes every 2s up to 60s, except the 3-spherical particles model at 23s the particles begin to spread along the vanes and at 54s the particles spread on the full vanes. Figure 9 shows the particles starting at the middle heap and the length heap on the bottom evenly begin to spread on the full vanes by 5s, and the particles move out from the vanes at 9s to 60s. It is clear that the length heap at 3s show some particles moving out from the side of the vanes.
Figure 7. Particle flow for different starting locations at the time 5s

1S = 1-Spherical; 2S = 2- Spherical; 3S = 3- Spherical; 4S = 4- Spherical

Figure 8 Particle flow for different starting location at the front and the end of the drum:
1S = 1-Spherical; 2S = 2- Spherical; 3S = 3- Spherical; 4S = 4- Spherical
7 Conclusion

In this study, DEM models were used to simulate the particle flow in a rotating drum and this was validated by experiments using rotating drum dustiness tester shown in Figure 1. For all the parameter inputs to DEM simulations, using the translating tube slump tester calibrate for four clustered particle shapes (see Figure 3), and the results are summarized in Table 1. The effect of loose-poured bulk density on the particle shape and the coefficient of rolling friction is 0.1 for the spherical cluster and 0.05 for the spherical particle. Bulk density decreases with the increase of either coefficient of rolling friction.

The coefficient of static friction and rolling friction between particle and between particle and wall interaction are approximate, and trial and error method was needed to compare the angle of repose and the height of the heap to match experiment with DEM simulation results. These parameters are the first factors to effect the rotation and motion of a particle.

The results show that the starting locations for the particles in the drum is the most important effect determining how particles begin to flow in the drum. The particles starting in the middle and also spread evenly along the bottom have very similar particle flow from 13s to 60s for all the particle shapes. The particles starting at the front and at the end of the rotating drum show very similar flow characteristics at 35s until 60s (approximate). The particles starting at the front and particle spread evenly along the bottom (at the length) have some particles moving from the side of the vanes, especially in the first 5 seconds.

In all cases, the DEM simulations were based on the parameters given in Table 1. The results in this paper show a difference between experiment and the DEM prediction depending on the coefficient of static friction and coefficient of rolling friction between particle and between particle-wall and the particle size distribution, especially the model of the particle shape.

In future work, this method will be applied to the Australian Standard Dustiness Tester for different speeds of the rotating drum, duration of the test, different bulk materials and volume of the
materials for experiment and applied to other materials such iron ore, coal etc. Further work will also include CFD-DEM Coupling to model the air flow though the particles in the rotating drum.

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References