Experimental and numerical investigations of particle/air flows in dustiness testers

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Experimental and Numerical Investigations
of Particle/Air Flows in Dustiness Testers

A thesis submitted in fulfilment of the
requirements for the award of the degree

Doctor of Philosophy

from

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by

Sathaphon Wangchai

Faculty of Engineering and Information Sciences, School of
Mechanical, Materials & Mechatronic Engineering

2017
Certification

I, Sathaphon Wangchai, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical, Materials and Mechatronic Engineering, Faculty of Engineering and Information Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

(Signature)

Sathaphon Wangchai
February 2017
Abstract

Dust is generated from bulk materials during handling, free fall and through belt conveyor transfers, creating air pollutants which can affect human communities, industrial equipment and the environment. A greater understanding of the generation of dust from bulk material requires knowledge of the mechanisms of bulk material flows.

The purpose of this research was to investigate the mechanisms of bulk material flow in dustiness testers by using numerical simulations and by comparing these results with experimental data. The experiments were carried out using three types of bulk materials with different properties, namely, polyethylene pellets, iron ore and coal.

In these experiments, the flow of bulk materials are measured in rotating drums using two types of standard dustiness testers. The two standard dustiness testers that were chosen in this study are the International Standard (IS) dustiness tester and the Australian Standard (AS) dustiness tester. Even though both of these dustiness testers are very similar in their operations, they differ in terms of: (i) the air flow and velocity of the drum rotations and, (ii) the volume of materials used in the experiments. Four types of particle heaps were considered in this work, namely, particles that are: spread from the front to the back of the drum, in the middle, at the front and at the back of the drum. This study investigated the mechanisms of bulk materials movement in both dustiness testers by varying the types of materials, contact force, particle velocity and the collision of materials as the particles flow in both dustiness testers.

An experimental test programme was developed following the experimental data of the materials moving in both standard dustiness testers. This experimental work focussed on the material flow in both standard dustiness testers and trajectories of particle heaps on the wall of the rotating drums. The experimental data was obtained by using high-speed video capture and still photography to record the free-flow and movement of a range of bulk materials in the system. The initial effects on mechanisms of particle flow (velocity, force contact and others) were considered in these investigations. The capillary force - between particles and particles, and between particles and wall distribution among particles - were explicitly considered. The value of the parameters used in the numerical simulations were identified and validated by means of matching the experimental data with the simulation results. These comparisons, which involved investigating the effects of particle size, properties of materials and volume of materials test, showed that the simulation and experiment results were comparable in terms of flow patterns, maximum angle of particle flow and size of particle segregation. Simulation and prediction of the behaviour of materials lead to an understanding of the separation of particles of different sizes under various conditions of starting of particle heaps.

Bulk materials flow in the dustiness testers shows a variety of complex phenomena such as particle free-fall, surface flow, segregation, impact force and velocity of the particles. These are important in the mechanisms of dust generation by particle flow with different
particle size ratios. The segregation of particles was found to be minimal at low particle size ratios but increased significantly at higher particle size ratios. For axial segregation, the small particles moving to the middle of the drum and on the other hand, anomalous transport of particles of larger size was found during band formation along the drum axis. For the radial segregation occurring in the drum transverse plane, the interaction between particle size and density ratios was captured by an existing theory which successfully predicted the condition for optimum mixing performance. By separating the displacements caused by different interaction forces, a definite driving force responsible for segregation was identified for dry systems.

This project systematically investigated the bulk mechanisms flow in the dustiness tester through numerical simulations. The discrete element method (DEM) was used to generate three-dimensional simulations of material flows through rotating drums. These simulation results were compared to both standards of the experimental data and the data obtained from the analytical mechanisms models. The focus is on understanding particle movements. The driving forces are the force of gravity, particle velocity for each position and different simulation time step, contact or collision of particle affecting particle segregation in the axial and radial direction. The energy and the frequency of collisions between particles and others were also analysed.

Computational fluid dynamics (CFD) was used to produce the air flow interactions in the dustiness testers. The DEM-CFD coupling method was employed to develop simulations of particle flows with air flows in both rotating drums. This coupling method was used to study the particle mechanisms in more detail. It is capable of handling both particle-particle and particle-wall collisions. This is due to the method’s capability in capturing particle interactions and effects of the drag force on each particle falling in the drum. The Ensight software was used to present the results from the coupling method (CFD-DEM).

Numerical simulations of the particle motion in the dustiness testers showed particle flow mechanisms which compared favourably to those of the experimental testing. With respect to materials movement in both rotating drums, the simulation results agreed with the experimental results and also predicted movement of the same particle size ratio for the axial and radial directions and also when falling from the vanes. The importance of calibration and verification of the numerical simulations has also been demonstrated, which is an absolute necessity to accurately model industrial applications.
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### Nomenclature

- \(C_D\)  
  - drag coefficient

- \(CoR\)  
  - coefficient of restitution

- \(C_n\)  
  - normal damping coefficient

- \(C_t\)  
  - tangential damping coefficient

- \(D_{evd}\)  
  - equivalent volume diameter of a particle

- \(E\)  
  - Young’s modulus

- \(E'\)  
  - equivalent Young’s modulus

- \(E_{imp}\)  
  - impact energy

- \(F_r\)  
  - Froude number

- \(F_n\)  
  - normal force

- \(F_t\)  
  - tangential force

- \(F_f\)  
  - friction force of particle

- \(F_d\)  
  - particle drag force

- \(F^A\)  
  - total particle and fluid interaction forces in Model A

- \(F^B\)  
  - total particle and fluid interaction forces in Model B

- \(F_{pf}\)  
  - force interaction between particle and fluid

- \(F_c\)  
  - contact force

- \(F_d\)  
  - viscous damping force

- \(g\)  
  - gravitational acceleration

- \(G\)  
  - shear modulus

- \(G'\)  
  - equivalent shear modulus

- \(h_i\)  
  - initial height of material

- \(h_r\)  
  - rebound height of material

- \(h_p\)  
  - height of the pile

- \(I\)  
  - moment of inertia

- \(KE\)  
  - kinetic energy

- \(k_n\)  
  - normal spring stiffness

- \(k_t\)  
  - tangential spring stiffness

- \(k_c\)  
  - number of particles in contact with the particle

- \(M_t\)  
  - tangential force torque

- \(M_f\)  
  - rolling friction torque

- \(m\)  
  - mass of particle

- \(N\)  
  - number of test

- \(PE\)  
  - potential energy

- \(p\)  
  - pressure

- \(Re\)  
  - Reynolds Number

- \(R_0\)  
  - distance of the contact point from the centre of the mass

- \(R\)  
  - radius of particle sphere

- \(r\)  
  - inner radius of drum

- \(SF\)  
  - solid volume fraction

- \(T_k\)  
  - Rayleigh time step

- \(u_{p1}\)  
  - velocities of the first particle before impact

- \(u_{p2}\)  
  - velocities of the second particle before impact

- \(v_{p1}\)  
  - velocities of the first particle after impact

- \(v_{p2}\)  
  - velocities of the second particle after impact

- \(m/s\)  
  - metre per second

- \(J\)  
  - joule

- \(Pa\)  
  - pascal

- \(kg.m^2\)  
  - kilogram metre squared

- \(s\)  
  - second
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>( V )</td>
<td>volume of the particle</td>
<td>( m^3 )</td>
</tr>
<tr>
<td>( V_p )</td>
<td>particle volume</td>
<td>( m^3 )</td>
</tr>
<tr>
<td>( V_v )</td>
<td>volume of voids</td>
<td>( m^3 )</td>
</tr>
<tr>
<td>( V_s )</td>
<td>volume of the solids</td>
<td>( m^3 )</td>
</tr>
<tr>
<td>( V_r )</td>
<td>relative velocity</td>
<td>( m/s )</td>
</tr>
<tr>
<td>( v )</td>
<td>velocity of particle</td>
<td>( m/s )</td>
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<td>( v_n^{rel} )</td>
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<td>( v_t^{rel} )</td>
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<td>( \Delta V )</td>
<td>volume of a computational cell</td>
<td>( m^3 )</td>
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<tr>
<td>I.D</td>
<td>inner diameter</td>
<td>( m )</td>
</tr>
<tr>
<td>IS</td>
<td>International Standard dustiness tester</td>
<td>-</td>
</tr>
<tr>
<td>AS</td>
<td>Australian Standard dustiness tester</td>
<td>-</td>
</tr>
<tr>
<td>DEM</td>
<td>Discrete Element Method</td>
<td>-</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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</tr>
<tr>
<td>UDF</td>
<td>User Defined Function</td>
<td>-</td>
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<tr>
<td>PSD</td>
<td>particle size distribution</td>
<td>-</td>
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<tr>
<td>FVM</td>
<td>Finite Volume Method</td>
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<tr>
<td>COV</td>
<td>coefficient of variance</td>
<td>-</td>
</tr>
<tr>
<td>avg</td>
<td>average data</td>
<td>-</td>
</tr>
<tr>
<td>WPP</td>
<td>White Polyethylene Pellets</td>
<td>-</td>
</tr>
<tr>
<td>VOF</td>
<td>volume of fluid</td>
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**GREEK**

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<td>( \alpha_r )</td>
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<tr>
<td>( \nu_a )</td>
<td>air viscosity</td>
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<tr>
<td>( \mu_{s(p.w)} )</td>
<td>coefficient of static friction between particle–wall</td>
</tr>
<tr>
<td>( \mu_{s(p.p)} )</td>
<td>coefficient of static friction between particle–particle</td>
</tr>
<tr>
<td>( \mu_{r(p.w)} )</td>
<td>coefficient of rolling friction between particle–wall</td>
</tr>
<tr>
<td>( \mu_{r(p.p)} )</td>
<td>coefficient of rolling friction between particle–particle</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Poisson’s Ratio</td>
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<td>( \rho_b )</td>
<td>loose-poured bulk density of material</td>
</tr>
<tr>
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<td>air density</td>
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<tr>
<td>( \rho_p )</td>
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<td>( \varphi )</td>
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<tr>
<td>( e )</td>
<td>void ratio</td>
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<td>( \sigma_s )</td>
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<tr>
<td>( \sigma_t )</td>
<td>particle contact stress</td>
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<tr>
<td>( \delta_n )</td>
<td>normal overlap</td>
</tr>
<tr>
<td>( \delta_t )</td>
<td>tangential overlap</td>
</tr>
<tr>
<td>( \tau_i )</td>
<td>rolling friction torque</td>
</tr>
<tr>
<td>( \tau )</td>
<td>fluid viscous stress tensor</td>
</tr>
<tr>
<td>( \varepsilon_f )</td>
<td>porosity</td>
</tr>
</tbody>
</table>
\( k \)  
- turbulent kinetic energy

\( \epsilon \)  
- turbulent dissipation rate

\( \mu_t \)  
- turbulent viscosity

\( \alpha_1 \)  
- angle of the heap (left)

\( \alpha_2 \)  
- angle of the heap (right)

**SUBSCRIPTS**

i  
- particle i

j  
- particle j

p.p  
- interaction between particle and particle

p.w  
- interaction between particle and wall
Chapter 1

Introduction

1.1 Background

Bulk materials, such as granular materials or powders, have to be handled or stored by many handling and transportation systems in many industries. These include mining, cement, agriculture, and food processing. In Australia, mining is one of the most significant primary industries, and have the world’s leading coal exporters which contributes to the Australian economy. Mining has had a substantial environmental impact in some areas of Australia. In the United States (U.S.A.), agricultural infrastructure is one of the most efficient and productive systems in the world. Grain quality traits can be described in terms of their physical, sanitary and intrinsic quality characteristics according to Maier (1995).

Belt conveyors are widely used in the mining and process industries for the transport of product from one location to another which can often cause dust generation. Transporting materials through the equipment handling systems can affect their physical quality. Physical quality traits include moisture content, particle size, material properties, total damage of granular materials and granular breakage. Dust emission during transport and handling poses safety, health hazards and environmental concerns from nearby residents and also causes a loss of product being transported. The dust can cause maintenance problems in bearings and seals or other components of the conveyor system. The airborne dust could also be a fire or explosion risk, leading to a deteriorated condition of products in manufacturing processes and parts of machinery, a loss of product and economic loss (Hjemsted et al., 1996a; Hamelmann et al., 2005; Wypych et al., 2005). Figure 1.1 shows the dust emissions as a result of falling product in the bulk handling from a belt conveyor. Fugitive dust emissions from powders, granular materials, handling of powder materials, storage sites of bulk materials due to handling activities, transportation, wind erosion and loading or unloading of bulk materials all generate dust (Maier, 1995; EN15051, 2006). The formation and emission of dust during handling depends on the type of material being
handled, size distribution of generated particles and properties of the material (Wypych et al., 1995; Gill et al., 2006).

![Dust emission falling material from the conveyor](Liu, 2003).

**Figure 1.1** Dust emission falling material from the conveyor (Liu, 2003).

Understanding the dust generation helps to select a suitable dust prevention approach and is also useful to evaluate the environmental impact of dust emissions. Dustiness is defined as the propensity of material to emit dust during handling in the air flow and is an interesting phenomenon. Dust consists of small sized particles, usually having a diameter of lower than 50 microns. A measure of the dustiness of a material can be obtained from a dustiness testing mechanical dispersion (rotating drum methods) and it is also a key parameter for assessing the risk of dust explosions (Hjemsted et al., 1996b; Breum, 1999).

The test parameters such as sample mass, rotational speed, the air flow rate through the drum and the rotation time influence the amount of dust generated and subsequently captured in a test. The dustiness of dust contained in a bulk material is defined as the tendency to emit dust into the air during handling under specified conditions. The air flow and drag forces affect the resultant force acting on each particle, thus moving the particle to a new position.

Specifically relating to the dust emission field of this research, it is significant to be able to estimate the terminal velocity of particles as it can be used in studies for particle size reduction and suspension. In many phases of bulk handling, size reduction happens which might finally lead to the generation of micro-sized particles (see Figure 1.2).
Furthermore, it is important to understand the phenomenon of dust discharge under different circumstances. This understanding will help in selecting the right equipment for protection against dust and that method is also useful in assessing the environmental impact of dust emissions (Derakhshani et al., 2013). In these operations, granular materials tend to discharge a large amount of dust into the air. Three main dust liberating operations are: (1) when the material is falling, (2) when the falling stream of particles impacts on another bulk material and (3) when there is wind flow around the particles. Rotating drums are a fundamental research tool to study the granular matter. The movement of particles in a rotating drum shows a variety of complex phenomena: continuous surface flow, mixing and segregation. The rotating drum is based on the International Standard (IS) dustiness tester (EN15051, 2006) and the Australian Standard (AS) dustiness tester (AS4156.6, 2000). Each tester requires a total of 35 cm$^3$ and 1000 cm$^3$ of the product sample with the experiment running for 1 minute and 10 minutes with the drum rotation at 4 rpm and 29 rpm, respectively.

The discrete element method is a numerical method for computing the particle motion and particle interaction using Newton’s Second Law of Motion and the force-displacement law. The simulation is an analysis predicting the behaviour of bulk materials and visualisation of granular flow. The principle of DEM is to track in a time stepping simulation, the trajectory and rotation of each particle 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. DEM simulations are very sensitive to calibration parameters and before the model can be considered reliable the results must first be validated experimentally. Also, computational fluid dynamics (CFD) uses numerical analysis to solve the air flow interactions between particles such as pneumatic
conveying and cyclone dust collection where it largely contributes to the understanding of the particle movement under the air flow in the systems. Two popular combinations widely used in literature to describe particle and air flow are the continuum-discrete approach at a multiscale level mainly represented by combined DEM and CFD. The motion of particles is modelled as a discrete phase with DEM and the flow of fluid (gas or liquid) is treated as a continuum phase with CFD. The CFD is described by the local averaged Navier-Stokes equations on a computational cell scale while allowing the mutual interaction between particles and fluid phases. The method treats particles and air phases at different scales and has been recognised as an effective method to study the fundamentals of particle and air flow under various conditions by various investigators.

1.2 Phenomenology of the Dustiness Tester System

This research employs two approaches, experimental studies and simulation. The experimental studies consist of three materials: polyethylene pellets, iron ore and coal which were tested in both the IS dustiness tester and the AS dustiness tester. Each series of tests involves four initial loading positions of materials on the bottom of the drum. The simulation of this study proposes the principle of modelling shapes by the intersection of spheres and non-spherical particles that are applied in a 3D dustiness tester. The physical properties of each sample product investigate the volume, weight, solid density, loose-poured bulk density, angle of repose, coefficient of restitution, coefficient of static friction and coefficient of rolling friction. This thesis also illustrates a 3D DEM and DEM-CFD coupling simulation of particle flow in dustiness tester models and the test apparatus is again based on both standards (AS4156.6, 2000; EN15051, 2006). Simulation conditions are set to match those used in the experiments to validate at the same time the simulation method at a particle scale. In these simulations, cylindrical drums which rotate at a constant angular velocity are considered and the drums are partially filled with granular material. Particle heaps were placed at four different locations: front, middle, end and spread evenly along the bottom of the rotating drums. All the experimental results shown in this thesis have been compared to the DEM and DEM-CFD coupled simulations. The simulations have been completed after calibration against experimental results to validate the DEM models.
Chapter 1: Introduction

Also, taking advantage of the available CFD development, a DEM-CFD model has been extended with Ansys Fluent, achieved by incorporating EDEM and a coupling scheme between DEM and CFD through its User Defined Functions (UDF). In this method, Ansys Fluent solves the equations describing the fluid phase motion. EDEM solves the equations describing the solid phase motion. The coupling between DEM and CFD is written as a separate program that allows the mutual interactions between the particle and fluid phases.

1.3 Research Objectives and Scope of this Research

This study aims to improve the understanding of the underlying mechanisms of dust generation and to also investigate materials flow, velocity, segregation of materials, impact and collision between material and material or material and geometry in both the IS and AS dustiness testers. Experimental and numerical investigations will be carried out using the following three bulk materials; polyethylene pellets, iron ore and coal. For instance, the influence of physical properties and equipment characteristics on dust generation will be studied and some of the important parameters will be selected for use in the numerical modelling. The main objectives of this research are as follows:

1) To conduct particle scale investigations of the mechanisms of material flow in rotating drums using the DEM;
2) To develop an effective strategy to model the material flow using the DEM and CFD, and to identify the key parameters that affect the prediction of the particle mechanisms in the dustiness testers;
3) Develop and evaluate particle models to simulate the flow of the bulk material in the rotating drum and reduce computational time by using an adjusting domain frame for fine granular materials. In particular, modelling behaviour of bulk materials for dust generation with the DEM and CFD;
4) Study the effects of particle properties (size, shape, particle distribution, density, cohesion) with DEM, and on the particle segregation and flow pattern by modelling with the DEM-CFD couple, and characterise the dust generated during material flow in the rotating drum;
5) Model particle distributions and find effective parameters to control and minimise the dust generation in the rotating drum based on the modelling results.
1.4 Organisation of the Dissertation

This dissertation consists of 9 chapters and can be divided into four main sections. The first section, Chapters 1 and 2 builds the basis and background to the thesis. Chapter 2 reviews and discusses previous work relevant to this thesis, mainly focusing on fundamentals of material flow in the rotating drums different loading conditions of materials in the drum, previous research on the experimental verification simulation of DEM and DEM-CFD coupling. So these experiments can be designed and techniques can be optimised.

The second part, Chapters 3 and 4 focuses on experimental testing of the dustiness testers and validation parameters. Chapter 3 describes an experimental study of materials flow in the IS and the AS dustiness tester. It describes the granular behaviour in both drums under four different loading locations and different operation between two-dustiness testers. Chapter 4 describes the selection of the bench scale laboratory devices and the measured bulk response parameters that were used to calibrate the DEM models in the optimisation procedure. These include the particle size, particle shape, particle density and loose-poured bulk density. In addition, this chapter elaborates on the interaction between each particle and between particles and the wall which consists of coefficient of restitution, the coefficient of sliding friction and coefficient of rolling friction. All the parameters of the bulk materials are then used to calibrate the DEM models.

The third part, Chapter 5 to 7 contains the DEM and DEM-CFD coupling software analysis of the particle flow in both the IS and AS dustiness testers for the three material models. Chapter 5 focuses on the numerical DEM implementation used to simulate the polyethylene pellets models movement in both dustiness testers and the comparison with experimental data for the trends of particle flow. It also investigates the volume fraction of particle movement and particle velocity with the four initial locations of the mono-sized particles in both dustiness testers. Additionally, a binary particle size ratio was analysed for the effect of particle size and segregation of particles in the radial and axial directions in the drums. Furthermore, details of the couple simulation between DEM-CFD are presented, regarding the particles and air flow in both dustiness testers. Finally, the results of the non-air and air flow particle movement in both dustiness testers is analysed compared and presented. Chapter 6 focuses on the numerical DEM and DEM-CFD
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coupling analysis of iron ore models flow in both dustiness testers. The DEM simulations analyse the effects of contact particle forces between particle and particle static/rolling friction and between particle and wall static/rolling fraction and effect of the particle size flow in the both dustiness testers. In addition, the DEM-CFD coupling displays the particle movement and air flow in both dustiness testers. Three kinds of interaction were considered: particle and particle, particle and wall, and particle and air interaction force.

Chapter 7 focuses on the numerical DEM and DEM-CFD coupling analysis of coal models flow in both dustiness testers. The DEM simulations analyses the effects of particle on the particle flow in the dustiness testers. Particle velocity, particle flow, force structure and collision energy in each dustiness tester was also analysed. Moreover, the DEM-CFD coupling displays the particle and fluid dynamics, interaction between particle and particle and particle and wall collisions, particle velocity under different particle sizes and the effects of drag force occurring in the dustiness tester.

The last section consists of Chapters 8 and 9, containing the comparison of this study, conclusions and recommendations for future work. Chapter 8 focuses on the comparison of the results of the three materials used in this work, including air and particle velocity, energy dissipation and the mechanisms of dust generation from both dustiness testers. Chapter 9 summarises the general conclusions of the whole thesis and provides recommendations for further work.
Chapter 2

Literature Review

This chapter reviews the previous studies of dust generation presented in literature. The first section of this chapter explains how dust generation forms from industrial equipment and how to experimentally test the dust emissions from bulk materials in standard dustiness testers. In the next section, an overview of the properties of the materials and material interactions are given for the calibration of DEM simulations to match with experimental data. Following this, an overview of a proven method used to predict the granular flow from calculated operating conditions are presented. Finally, a computer simulation to predict the granular model of material flow in the dustiness tester will be presented. These simulations use DEM and CFD coupling for the mechanical interaction and air flow interaction with granules and the governing equations have been given.

2.1 Bulk Material Handling and Dust Generation

Many bulk materials are used in industry such as coal, iron ore, grain and other materials. Material is regularly transferred from one location to another and can generate dust as a result. Material is handled using equipment such as conveyor belts, screw conveyors, bucket elevators, truck transportation and pneumatic conveying. Conveyor belts mostly operate in open air, when materials move on the belt for loading and unloading of bulk material or flow from one conveyor to another dust can be generated (Chen et al., 2012). Small particles can be carried when wind flows past that zones, the fine particles are then emitted into the environment. The study was carried out to investigate the amount of dust generated by handling equipment. Belt conveyors are widely used in the mining and process industries. Witt et al. (2002) presented experimental results of ore material dust lift-off from belt conveyors at different wind velocity in a tunnel. Baker et al. (1986) found breakage of corn materials increased during handling in pneumatic conveying systems. The dimension of the pipe was 100 mm in diameter, total lengths were 31 to 60 m with 2 to 4 elbows (90 degree) with a 1.22 m radius of curvature. Foster et al. (1973)
investigated physical damage of agricultural products such as corn, wheat, soybeans, and dry edible peas by bucket elevator methods. In his study, the handling equipment method included dropping products by free fall, dropping products through a spout and handling the products in a bucket elevator. Variables involved in product damage caused by commercial handling such as height of free-fall, surface of particle impact, moisture content and temperature. The damage of material handled decreased at higher grain temperatures. Martin et al. (1977) experimentally transferred materials alternately between two bins repeatedly. During the repeated handling experiment, the percentage breakage of material increased linearly. Shaw et al. (1998) measured the corn material emission rate at the mills in cattle yards for unloading at 20 gram/tonne and 2.5 gram/tonne for loading feed.

**2.1.1 Size Distribution of Dust Particles**

Particle size distributions (PSD) for dust collected from the granular material have been reported in several studies. Calvert (1990) defined dust as the small dry granular materials moved into the air by natural forces (wind) and by mechanical process or manmade processes such as crushing, grinding, milling, demolition, conveying, screening and sweeping. Dust particles are usually in the size range from about 1 to 100 μm in diameter and they fall slowly under the force of gravity. Martin (1981) investigated the size of particles of dust from both cyclone separators and bag houses. The fraction of dust particles less than 10μm in size represented approximately 9% of dust from a cyclone and about 20% of dust from the bag house. Parnell et al. (1986) measured the percentage weight of dust less than 100μm in size for corn, wheat, sorghum, rice and soybeans products. Dust from these materials were collected by baghouses at the destination station of the elevators and obtained 54.1%, 34.3%, 34.3%, 44.2%, and 50.6% of the total mass, respectively. Parnell et al. (1986) reported the mean (and standard deviations) of particle size distributions of corn, wheat, sorghum, rice and soybean dusts at the particle size less than 100 μm using the Coulter Counter of 13.2 μm (1.80 μm), 13.4 μm (2.08 μm), 14.0μm(2.16μm), 10.7μm(2.24 μm) and 13.6μm(1.87μm), respectively. Martin et al. (1975) found the size of dust particles of corn and wheat products. The particle size of corn and wheat less than 125 μm in size accounted for an average of 80% and 43.5% of the total mass of dust collected at the cyclone. Dust particles less than 8μm averaged 7.5% for corn dust and 3.5% for wheat dust. Martin et al. (1977) observed the corn dust
at sizes lower than 125 $\mu m$ diameter increased the amount of dust emitted in the first eight transfers and was constant then after. Martin et al. (1978) cited the mean of mass at median diameters of residual dust of 13 $\mu m$ for wheat and 14 $\mu m$ for sorghum stuck to larger grains of the products. The percentages of sample mean of residual dust for sorghum, corn and wheat products with a diameter less than 11 $\mu m$ were approximately 34%, 33%, and 45%, respectively. They reported the percentage of dust size less than 125 $\mu m$ for corn, wheat and sorghum to be 85%, 78% and 60% of the total dust collected, respectively. Lai et al. (1984) reported the percentage weight of grain dust particles of diameters less than 105 $\mu m$ (size of sieve aperture) less than 84%, 100% and 70% for corn, wheat, and sorghum, respectively. The percentage of mass of dust particles of the mean diameter of the boundary sieve aperture less than 114 $\mu m$ (sieve aperture = 105 $\mu m$) were 34%, 32% and 72% for corn, wheat and sorghum, respectively. Baker et al. (1986) reported similar size distributions of dust collected during pneumatic conveying of shelled corn with that collected from grain handling by a bucket-elevator system. The percentage of mass of dust size less than 100 $\mu m$ was around 80%; less than 10 $\mu m$, 10%; less than 4 $\mu m$, 2% and less than 2.5 $\mu m$, 0.6%. Fairweather (1965) found the particle size distribution of settled dust on a 12-foot square plastic sheet for 20 samples. The results shown in two groups; the dust collected on the plate at 93.5% to 99.5% by weight of the sample of the size particles 30 $\mu m$ or greater in this size and 82.1% to 98.6% of the dust particle were 40 $\mu m$ or greater in diameter. Harper (2002) determined the particle size distribution of nineteen samples of wood dust collected by a personal air sampling with aerodynamic diameter greater than 100 $\mu m$. Kok (2011) investigated the size distribution of mineral dust aerosols depending on the velocity of wind at emission. Particularly, Gillette (1974) reported measurements of two fine sand soils and two loamy fine sand soils for wind friction speeds of 0.18–0.78 ms$^{-1}$. Shao (2011) measured the dust emission different size ranges of 0.3–8.4 $\mu m$ diameters at heights 1.0, 2.0 and 3.5 m. Gillette (1978) conducted on experiments six groups of soil particles $(d > 25 \mu m)$ with different surface texture in the wind tunnel. The fine particles were highly dependent on wind speed and surface crust of the soil was very important to prevent fine particle emission. Converse (1989) investigated the dust emission per handling transfer of six lots of corn at different moisture levels. The dust loss varies from 0.08% to 0.21% of the total mass with the higher temperatures of corn dried. Piacitelli et al. (1996) determined the size distribution of dust particles during sorghum grain handling operations in farms.
Their results indicated that about 2% of the grain had less than 3.5 \( \mu m \) diameter; 10% at less than 10 \( \mu m \), 24% at less than 15 \( \mu m \), 48% at less than 21 \( \mu m \) and 52% at more than 21 \( \mu m \).

### 2.1.2 Effect of Air Resistance

The velocity of particles is directly influenced by the air resistance of the particle. The ratio of air resistance to the force of gravity increases significantly with decreasing particle size. Thus, the steady-state velocity of particles in the gravity field decreases significantly with decreasing particle size (Table 2.1). This effect is low for particle sizes of 50 to 100 \( \mu m \) but becomes significant at particle sizes below 10 \( \mu m \). Therefore, small particles suspended in a gas cannot move with velocities relative to the gas and can be moved easily by a gas stream (Schulze, 2008).

<table>
<thead>
<tr>
<th>Particle diameter ( d (\mu m) )</th>
<th>Steady-state settling velocity ( w_g (mm/s) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ( \mu m )</td>
<td>0.082</td>
</tr>
<tr>
<td>10 ( \mu m )</td>
<td>8.2</td>
</tr>
<tr>
<td>25 ( \mu m )</td>
<td>51</td>
</tr>
</tbody>
</table>

*the air temperature at 20 \( \rho_s = 2700 kg/m^3 \)*

A stream of particles, when initially moving in a horizontal or an inclined direction, results in different trajectories as a function of particle size. The small particles are more affected by air resistance than larger particles, therefore, small particles do not travel as far as larger particles. The shape of particles may affect air resistance. Therefore, whenever there is a granular material moving with a component of horizontal velocity through a gas separation, different trajectories are likely to occur.

### 2.1.3 Numerical Simulation of Dust Emission

This includes all simulation methods that can replicate the processes of a system. It includes numerical methods including, the finite volume method (FVM) which is a common approach used in computational fluid dynamics (CFD) and the discrete element method (DEM), a numerical method to compute the motion of particles. Computational Fluid Dynamics (CFD) has been used to analyse the flow patterns of granular material to
predict air velocities and flow patterns obtained from simulations compared with the experimental data of the belt conveyor transfer chutes (Chen et al., 2012). Bielert et al. (1999) presented a numerical model through dust conveyors comparison with different experimental data for cone starch-air mixtures for different dust concentrations, flow velocities and tube lengths. Li et al. (2012) used a two-fluid model to simulate the dust integration rate and showed the influence of different parameters such as dust mass, temperature and bed mass. The dust integration rate depends linearly on the dust mass in the process. The dust integration decreases with increasing fluidisation air temperature due to faster evaporation of the film on the particle surface. Tóraño et al. (2007) studied pile formation to understand how wind direction can influence pile shape. Wakeham et al. (2014) analysed dust transfer around stockpiles of bulk material. Diego et al. (2009) predicted the wind flow around piles using CFD. Song et al. (2014) investigated the airflow structure around the pile, shear stress distribution on each surface determined according to the porosities, the maximum dust emission occurred at two-thirds the height of the windward side rather than at the top. Torno et al. (2011) used a CFD model to simulate dust generation in blasting local limestone quarries and decreased the dust via model simulations using physical barriers. Chen (2012) presented a model of dust emissions from belt conveyor transfer chutes. This experiment measured the quantity of fugitive dust and the velocity of air at the chutes using Particle Image Velocimetry compared with the simulation model by CFD. Chen et al. (2010) investigated the flow and particle properties for the different transfer chutes designs to decrease dust generation using CFD modelling. Witt et al. (2002) used CFD modelling to developed the velocity effect of wind direction and conveyor guarding on the dust loss from the conveyor. Experimental measurement of dust lift off from the surface of the bed of ore with different wind velocity in a wind tunnel was completed. Billate et al. (2004) measured dust emission rates during grain receiving operations from simulated hopper-bottom trucks. Silvester et al. (2004) investigated the influence on dust dispersion using a CFD model to simulation the movement of the dust generation in the unloading of the dump truck into a feeding hopper of a mill. Airflow over the stockpile and dust emission, erosion and surface deformation of sand material was simulated using the CFD and DEM coupled method. These results will be validated by experiment data of deformation of stockpile (Derakhshani et al., 2013). Katterfeld et al. (2010) investigated the design of transfer chutes using DEM. Sophisticated simulations were used to predict the material and air flow in such plants and analysis of the dust from conveyor transfer chutes (Donohue et
Hilton et al. (2013) simulated dust production from dynamic granular material dropped in a vertical direction from a set height and airflow over a granular stockpile.

2.2 Standard Dustiness Testing

There are two standards of dustiness testers; the International Standard (EN15051, 2006) and the Australian Standard (AS4156.6, 2000). Dustiness testing is used for bulk or granular materials in a rotating drum tester under standardised conditions. Similarities exist between the two standards and each involves the use of a rotating drum, both dustiness testers will be the focus of this research.

2.2.1 International Standard Dustiness Tester

This standard highlights areas of dust generation within the workplace. Materials were dropping on the wall inside of the rotating drum. The dust generated from the constant disturbance of material is then collected via vacuum by creating a horizontal flowing current of air. The IS dustiness tester consists of a 300 mm internal diameter stainless steel drum which is tapered at either end to aid in containment of the test material, as shown in Figure 2.1(a). Each test requires 35 cm$^3$ of material with known moisture content to be placed in the drum, after which the drum rotates at 4 rpm for 1 minute. There are eight longitudinal vanes evenly spaced around the circumference of the drum to promote the lifting of the test sample. The 230 mm long and 25 mm high stainless steel vanes are fixed longitudinally to the internal walls of the drum. As the drum rotates, the test sample is continuously disturbed by the internal vanes in the drums for the duration of the test causing the generation of dust and begins to move by the horizontal airflow of 38L/min transporting the dust through to the dust collection portion of the apparatus. The principle of the international standard tester consists of the following elements: dust generation section, dust transfer section, sampling section, size fractionator(s) and dust collection section.

Many researchers have used this machine for analysis of dust generation of bulk materials. The dustiness tester has been used to predict the level of that exposure potential of different materials (Pensis et al., 2010), nanopowders (Schneider et al., 2008; Tsai et
al., 2009; Tsai et al., 2011; Burdett et al., 2013) and compared the result with the heubach dustmeter and palas dustview (Bach et al., 2008; Evans et al., 2014).

![Figure 2.1](image)

**Figure 2.1** (a) Photo of International Standard dustiness tester (b) Schematic of rotating drum.

### 2.2.2 Australian Standard Dustiness Tester

The Australian dustiness tester consists of components similar to that of the international standard, comprising of a dust generation section, dust transfer section, dust sampling section and dust collection section. The primary objective of this tester is the determination of the dust extinction moisture of the bulk material by varying the moisture. This tester consists of a rotating drum and drive, a filter box including a filter bag, an air flow meter, flow controller and relevant piping. The drum is made of stainless steel and includes a front vertical plate, as shown in Figure 2.2. Specifically, the AS dustiness tester consists of a 300 mm internal diameter by 300 mm length which is tapered at the back of the drum (150 and 100 diameters, respectively) and an inlet of a 40 mm diameter for a vacuum airflow through the system. Each test requires 1000 grams of material to be placed in the drum, after which the drum rotated at 29 rpm for 10 minutes. There are eight longitudinal vanes evenly spaced around the circumference of the drum to promote the lifting of the test sample. The 300 mm long, 7 mm wide and 6 mm high vanes are made from stainless steel and are fixed longitudinally to the internal wall of the drum. Once the dust is generated, it is transported through the narrowing section of the drum to the filter bag via a required airflow of 175 l/min.

Frew et al. (2013) used this rotating drum for the determination of the dust extinction moisture content of a bulk material by testing a range of samples of the same bulk material with varying moisture contents and collecting the dust in a vacuum cleaner bag.
2.3 Rotating Drums

Previously, many researchers have been interested in understanding the dynamic behaviour of granular materials in rotating drums. Rotating drums and tumbling mills are a particular interest, as they are used in a variety of industry sectors, from agriculture to mining. They are used to reduce particle size, mixers, to produce segregation, dryers and reactors for the processing of granular materials. Many researchers from both the engineering and physics communities have analysed and explained the granular behaviour using numerical techniques and experimental investigations of the granular flow in rotating drums. The majority of research carried out in rotating drums has focused on: flow regimes at lower rotational speeds, segregation, mixing and granular breakage in industrial situations. The following sections will describe the flow properties of granular materials in the rotating drums and segregation of granular materials with different size.

2.3.1 Flow Properties

The particle motion in rotating drums has been linked to several particle properties such as sliding friction on the wall, particle fill volume in the drum, depth of the drum, shape and size of particles, particle density, the Froude number and rotational speed (Rutgers, 1965; Metcalfe et al., 1995a; Dury et al., 1998; Ding et al., 2001; Santomasso et al., 2003; Yang et al., 2008). Mellmann (2001) identified various flow motions in a rotating drum with three types of flow motion and seven subtypes of flow regimes identified when the rotating drum increases velocity from very low to very large values, see in Figure 2.3.
The particle slipping motion in a rotating drum occurs under unfavorable friction conditions between granular materials and the cylinder wall. There are principally two types of slipping motion; sliding and surging. Sliding may occur as a result of low rotational speeds, usually small angle of deflection (Rutgers, 1965) high degrees of filling or when the cylinder wall of the drum is very smooth and is characterised by the particles bed constantly sliding along the inner wall of the drum. A low surface profile is defined as the top layer of the particle and used to determine the surface inclination angle. As the drum increases rotational speed, filling degree and wall friction, sliding turns into surging. During surging, the material goes through periodic cycles of adhering to the inner wall of the drum until a certain inclination is reached and the material subsequently slides down. No mixing of the particles occurs in this slipping motion. For cascading motion, there is a continuous circulation of granular material and sufficient wall friction dependent on a rotational speed and particle size. This motion can be subdivided into slumping, rolling and cascading. During slumping, the material bed is carried along the inner wall of the drum and continuously levelled, as the highest particles intermittently roll along the surface profile. As rotational speed increases, the slumping regime transitions to a rolling regime, where a uniform static flow develops as particles are carried up the inner wall and a constant flow of particles is rolling along the surface. During this regime, a small flat surface profile of the particles with a constant inclination forms and also forms the dynamic angle of repose. Also, no more slippage along the inner wall is visible.

<table>
<thead>
<tr>
<th>Basic form</th>
<th>Slipping motion</th>
<th>Cascading (&quot;tumbling&quot;) motion</th>
<th>Cataracting motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtype</td>
<td>Sliding</td>
<td>Surging</td>
<td>Slumping</td>
</tr>
<tr>
<td>Schematic</td>
<td><img src="image1" alt="Sliding" /></td>
<td><img src="image2" alt="Surging" /></td>
<td><img src="image3" alt="Slumping" /></td>
</tr>
<tr>
<td>Physical process</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Froude number Fr [-]</td>
<td>$0 &lt; Fr &lt; 10^4$</td>
<td>$10^3 &lt; Fr &lt; 10^4$</td>
<td>$10^4 &lt; Fr &lt; 10^5$</td>
</tr>
<tr>
<td>Filling degree $f [-]$</td>
<td>$f &lt; 0.1$</td>
<td>$f \geq 0.1$</td>
<td>$f &lt; 0.1$</td>
</tr>
<tr>
<td>Wall friction coeff. $\mu [-]$</td>
<td>$\mu_w &lt; \mu_{w,x}$</td>
<td>$\mu_w \geq \mu_{w,x}$</td>
<td>$\mu_w &gt; \mu_{w,x}$</td>
</tr>
<tr>
<td>Application</td>
<td>no use</td>
<td>Rotary kilns and reactors;</td>
<td>Ball mills</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rotary dryers and coolers; mixing drums</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.3 Transverse flow regimes of solids in rotating drum (Mellmann, 2001).
Increasing the rotational speed further will see the transition to a cascading regime, where the surface profile arches slightly and an S-shape appears on the surface of the particles inside the rotating drum. The height of the S-shape is dependent on the particle size (Mellmann, 2001). Further increasing rotational speed results in the transition from cascading to cataracting, where particles will detach from the top of the surface profile and be thrown to the lower particle surface within the drum. Finally, for the centrifuging regime, increasing the speed further will cause the particles to line the inner wall of the drum with a uniform layer of particles, similar to the drying cycle of washing machine.

A characteristic criterion for the granular material motion in rotating drums is the Froude number \( F_r \), which represents the proportion between centrifugal force and gravitational force of a particle along the inner wall of the drum and can be calculated using equation 2.1

\[
F_r = \frac{r \cdot \omega^2}{g}
\]

where \( r \) is the inner radius of drum, \( g \) is the gravitational acceleration and \( \omega \) is the angular velocity of the drum. The particle movement in the drum (see Figure 2.3) was described by different particle motion in the transverse direction depending on the rotational speed of the rotating drum. Walton et al. (1993) investigated the effects of rotation rate in horizontal rotating drums and friction on the bulk materials flow using particle dynamic simulation. Dury et al. (1998) investigated the effect between particle and boundary interaction on the particle dynamic.

### 2.3.2 Particle Segregation

Powders and other bulk solids materials have a tendency to segregate during handling, transportation, storage of particulate solids when the particles are different properties (size, shape, surface roughness or density of particle) (Enstad, 2001). Most segregating materials are free-flowing or slightly cohesive so that the particles can easily separate from each other. In contrast, the behaviour of poorly flowing bulk solids (fine particles with moisture) is dominated by adhesion forces between particles, thus reducing the movement of individual particles and thus the tendency to separate (Schulze, 2008).
Segregation is hard to totally prevent altogether, but once the underlying mechanisms are understood, it is possible to diminish the adverse effects of the phenomena to tolerable levels. Granular materials often segregate when they flow under external disturbance such as shearing (Drahun et al., 1983), shaking (Rosato et al., 1987), vibration (Mobius et al., 2001), or undergo motion in rotating drums (Rapaport, 2007). Two types of particle segregation are radial segregation and axial banding in rotating cylindrical drums (Ottino et al., 2000) detailed in Sections 2.3.2.2 and 2.3.2.3.

2.3.2.1 Segregation Mechanisms

The processes of segregation are complex and hard to predict quantitatively. Bulk solids segregate mostly due to differences in particle size, particle density, particle shape, and/or particle surface roughness. Nevertheless, it is significant for the interpretation of segregation processes to know the principles of the segregation mechanisms. Some of the observed effects have been investigated scientifically (Williams, 1976; Johanson, 1978; Arnold, 1991). There are four main segregation mechanisms of particles that have been extensively studied such as trajectory segregation, percolation/sieving segregation, segregation convection and segregation by fluidization (see Figure 2.4), although many more segregation mechanisms have been identified in the literature (de Silva et al., 2000).

Trajectory segregation is caused by the difference between small and large particles in the air drag forces of the body and body forces such as gravity and acceleration. The air drag is proportional to the diameter squared of the particle while the body forces are proportional to the mass or the volume of the particle. For a spherical particle, the volume is proportional to the diameter cubed of the particle, which means that the body forces will dominate for large particles whereas the air drag will dominate for small particles. This difference causes the particles to follow different paths depending on their size when they are subjected to a horizontal velocity component through air or gas when it is moved with a velocity ($v$) in a fluid of viscosity ($\mu_f$). Smaller particles will be slowed down much faster than the larger particles. This mechanism can cause segregation where particles are caused to move through the air (Figure 2.4(a)). Percolation segregation is included in a multi-size component mixture and occurs when smaller particles pass freely through the voids between the larger particles to accumulate beneath the large particle in the direction of gravitational acceleration. This occurs during stirring, shaking, vibration,
pouring, tumbling and drum rotation, the smaller particles can fall between the large particles and reach a heap the bottom of the container. Figure 2.4(b) shows the mechanism of percolation. Segregation by convection is observed when a mixture of small and large particles is subjected to a vibration movement (Knight et al., 1993). The large sized particles have the tendency of moving up as the small particles move down. This effect occurs even when the large particles are denser than the small particles. This behaviour can be attributed to the fact that the region around below the larger particles causes increased pressure. This compacts the particles and stops large particles moving down. Therefore, any upward movement will allow the small particles to move under the large particles and lock in position (Williams, 1976), as shown in Figure 2.4(c). Segregation by fluidization can occur in a air-fluidized bed, where the velocity needs to be averagely above the minimum fluidization velocity then the bed can separate by fluidization (Hoffmann et al., 1993). The larger particles (and/or heavier) move to the lower part of the bed while the smaller particles (and/or lighter) move to the upper part of the bed.

The segregation of particles can occur in both the axial and radial directions of a cylindrical drum. Axial segregation proceeds slowly (usually more than a hundred drum revolutions) while radial segregation takes place rapidly (often within several drum revolutions) (Heinein, 1987; Pollard et al., 1989; Wightman et al., 1998a; Wightman et al., 1998b).
2.3.2.2 Radial Segregation

Radial segregation refers to the phenomena that smaller particles are transferred towards the central region of the drum and the larger particles that move to the periphery of the drum transverse plane (Khakhar et al., 1997a). As shown in Figure 2.5, two major mechanisms have been proposed for radial segregation: “percolation” and “buoyancy”. Nityanand et al. (1986) demonstrated the typical behaviour of systems with size segregation and the effects governing the size segregation from his experimental work. Gaps between particles will occur and under gravity the small particles are more likely to fall through whereas for large particles the gaps are too narrow (Gray, 2001; Haron et al., 2012). Particle dynamics simulations of segregation due to density differences were investigated by Ristow (1994) and size differences (Dury & Ristow 1997) between a two-dimensional system in the rolling regime. Experimental studies of particle size segregation were completed in two dimensions in the avalanching regime (Clément et al., 1995) and rolling regime (Cantelaube et al., 1995). In both cases, the smaller particle size formed a central core of the drum. Cantelaube et al. (1995) performed trapping the small
particle size at different locations in each layer of material. Baumann et al. (1995) suggested a similar trapping mechanism for small particle size segregation between a two-dimensional piling algorithm based on computations and Prigozhin & Kalman (1998) proposed a method for evaluating the radial segregation on the basis of measurements taken in the pile formation. Khakhar et al. (1997b) presented mixtures of equal-sized particles of different density for mixing and segregation of particle from experiments and analysis of simultaneous. Alonzos et al. (1991) illustrated how a combination of particle size and density differences can be used to minimise segregation.

Experimental tests performed by Cantelaube et al. (1995) determined the radial segregation of a mixture containing disks of two sizes in a 2D rotating drum. Segregation was found to occur both in avalanche and in continuous flow regimes after less than one drum revolution. By tracking the trajectory of a single small particle, they observed that percolation primarily happens in the rapid flow surface and the probability for a small particle to percolate is dependent on the location of the particle entering the flow layer. Thus, they concluded that radial segregation is accounted for by single particle percolation and the description of collective particle motion is not necessary. The radial segregation caused by density difference was studied by Ristow (1994) who obtained the trajectory of a heavier particle in an equal-size binary system through DEM simulation.

![Figure 2.5 Segregation mechanisms is driven by (a) percolation (b) buoyancy (Jain et al., 2005).](image)

2.3.2.3 Axial Segregation

Experimental investigation of the rotating drums using mixtures of particles has previously revealed alternating bands separated along the axial direction in a rotating drum, observed under different operational conditions and physical properties of the particles, including different particle sizes, density, shape and roughness (Hill et al., 1997) and also in some numerical simulations (Taberlet et al., 2006; Rapaport, 2007). Gupta et al. (1991) found that the axial segregation was preceded by radial segregation, which
generated cores of small particles inside the bed, depending on filling level and rotational speed. Hill et al. (1995) observed bands formed at higher rotation speed but became well mixed again when rotation dropped to a lower speed. They suggested that reversible segregation happens depending on the particle size ratio. The effect of interstitial fluids on axial segregation was studied by Jain et al. (2001), who found that segregation occurred much faster in a drum completely submerged in liquids compared with systems surrounded by air.

After the initial segregation of particles into alternating bands, the segregation can be stable over a relatively long period (Gupta et al., 1991). For mono-sized binary mixtures, surface roughness difference was found not able to cause axial segregation when one type of particle has a friction coefficient up to 5 times of the other type (Pohlman et al., 2006). However, different from radial segregation that can be triggered by density difference, Kuo et al. (2006) found that mono-sized particles of steel and glass beads did not form axial segregation. More recently, Sanfratello et al. (2009) also found no axial segregation in mono-sized mixtures up to a density ratio of 4.9. These studies suggested that density difference alone may not lead to axial segregation.

### 2.3.3 Particle Breakage

The main breakage mechanism is due to particle impact on other particle or the wall of the drum. The particles broken to smaller particle size are a result of the particle impact stress being larger than the particle strength acting on the particles and were calculated based on Griffith’s theory and Hertz’s theory. The mechanics of size reduction processes in a typical mode of breakage are present: body breakage and surface breakage. Body breakage is a high-energy impact and surface breakage is a low energy impact. The importance of surface breakage has been confirmed as the mechanism of coarse particles in the numerical modelling (Yahyaei et al., 2013; Powell et al., 2008; Morrison et al., 2004). The particle movement in the rotating drum is sliding and rolling that provide to breakage environment (Gao et al., 1995). Particle contact strength ($\sigma_s$) is determined by the Griffith’s theory (Smagorinsky, 1963). In preliminary investigations, it was found that the particle strengths can be predicted experimentally by measuring the distribution of crack length. Particle contact stress ($\sigma_1$) is the measure of particle impacts on the drum wall or the other particles.
2.3.4 Applications of DEM and CFD

In this section, the investigation of dispersion is briefly reviewed focusing on the previous application of numerical studies on them. The extensive experimental works on them are not reviewed due to the scope of this study but provides a good overview of the application of DEM to many large scale industrial applications.

2.3.4.1 Application of DEM in Rotating Drums

Particle flow in a partially filled rotating drum has been simulated with DEM and makes a significant contribution to a better understanding of particle dynamics. DEM simulations have been performed for various values of parameters and primary operating conditions, i.e., mechanical properties, physical properties, the rotational speed and the filling degree. The results from validation of numerical models shows comparison between simulation results and those measured from experiments. (Cleary et al., 2003; Yang et al., 2003), more detailed mixing of particles in rotary drums (Kwapinska et al., 2006), the angle of repose (Yamane et al., 1998; Yang et al., 2003), velocity field (Yamane et al., 1998), particle and particle interactions (Favier, 2007), large scale industrial applications (Cleary, 2004), modelling of SAG mills (Cleary et al., 2003) and mixing of solids in the transverse direction of a rotating kiln (Van Puyvelde, 2006). Finnie et al. (2005) used three-dimensional DEM simulations to investigate mixing in horizontal rotary kilns. Yang et al. (2003) have analysed the flow structure in terms of porosity and coordination number and force structure such as collision frequency of particles, collision velocity of particles and interaction forces between particles.

Currently, there are several concerted research efforts directed towards understanding charge dynamics in tumbling mills (Rajamani et al., 2000; Venugopal et al., 2001; Djordjevic, 2003), contact in tumbling mills (Mishra, 2003), mechanism of centrifugal mills (Inoue et al., 1996), model breakage in mills (Powell et al., 2006), influence of lifters in tumbling mills (Djordjevic, 2003), mixing and segregation in a tumbling mills (Shinbrot et al., 2001; Chaudhuri et al., 2006) and particle breakage in tumbling ball mills (Wang et al., 2012). These and other investigations are summarised in Table 2.2.
Table 2.2 Summary of application of DEM.

<table>
<thead>
<tr>
<th>Application</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating Cylinders</td>
<td>(Walton et al., 1993; Wightman et al., 1998a; Wightman et al., 1998b; Chakraborty et al., 2000; Arntz et al., 2008; Yang et al., 2008; Freireich et al., 2009)</td>
</tr>
<tr>
<td>A range of mills (ball, grinding, centrifugal, SAG and AG)</td>
<td>(Shoji et al., 1973; Cleary, 1998; Watanabe, 1999; Cleary, 2000; Cleary et al., 2000; Rajamani et al., 2000; Govender et al., 2004; Chibwana et al., 2006; Djordjevic et al., 2006; Khanal et al., 2009; Maleki-Moghaddam et al., 2012)</td>
</tr>
<tr>
<td>Mixers (tumbling, blade and V-blender, double-cone blender and related)</td>
<td>(Agrawala et al., 1997; Brone et al., 1997; Chester et al., 1999; Moakher et al., 2000; Rajamani et al., 2000; Alexander et al., 2001; Khanal et al., 2009; Manickam et al., 2010; Mendez et al., 2011)</td>
</tr>
<tr>
<td>Particle Breakage in the drum or related</td>
<td>(Austin, 2004; Morrison et al., 2004; Metzger et al., 2009; Lee et al., 2010)</td>
</tr>
</tbody>
</table>

2.3.4.2 Application on CFD-DEM in Rotating Drum

More realistic process simulation should be possible with a realistic shape, high number of particles and realistic geometry of particles and boundaries. Modelling the breakage of particles and fully coupled simulations with fluid flow should also be incorporated to improve the optimization process and equipment design. Hence, in the future simulation should be capable of predicting real industrial processes. As DEM has developed and become more widely known, there has been an ever-increasing number of applications to which DEM has been successfully applied, several studies of dispersion in air flow have been reported. There are many researchers use coupling software to analyse granular flow in rotary drums (Liu et al., 2008), analysis of fluid energy in mills (Teng et al., 2011), particle drying in a flighted rotary dryer (Hobbs, 2009), dry powders (Tong et al., 2012), modelling of particle flow in Isa-Mills (Jayasundara et al., 2011), novel rotating fluidised beds (Nakamura et al., 2006), the fluid and particle dynamics in a rotor granular rotor system (Neuwirth et al., 2013), simulation of spouting of corn (Ren et al., 2012), the behaviour of fluid-particle interaction in geomechanics (Zhao et al., 2013), the gas-solid flow in an air and screen cleaning shoe (Li et al., 2012), simulation behaviour of particles in centrifugal field (Romaní Fernández et al., 2013), numerical dust emissions from soil surfaces in a wind tunnel (Roney et al., 2010), temperature distribution and heat transfer in fluidized bed (Sae-Heng et al., 2011). A more detailed summary can be found in Table 2.3
Table 2.3 Summary of application of CFD and DEM coupling.

<table>
<thead>
<tr>
<th>Application</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluidization</td>
<td>(Tsuji et al., 1993; Hoomans B. P. B. et al., 1996; Nakamura et al., 2007; Di Maio et al., 2009; Zhao et al., 2009; Fries et al., 2011; Zhao et al., 2011; Fries et al., 2013)</td>
</tr>
<tr>
<td>Cyclone separator</td>
<td>(Chu et al., 2009; Chu et al., 2011; Chu et al., 2012; Varga et al., 2014)</td>
</tr>
<tr>
<td>Die filling</td>
<td>(Guo et al., 2009; Guo et al., 2011; Nwose et al., 2012)</td>
</tr>
<tr>
<td>Blast Furnace</td>
<td>(Adema et al., 2010; Yu et al., 2010)</td>
</tr>
<tr>
<td>spray</td>
<td>(Fries et al., 2011)</td>
</tr>
<tr>
<td>Centrifugal separation</td>
<td>(Romani Fernández et al., 2013)</td>
</tr>
<tr>
<td>IS-Mill and Jet mill</td>
<td>(Jayasundara et al., 2011; Brosh et al., 2014)</td>
</tr>
<tr>
<td>Screen cleaning</td>
<td>(Li et al., 2012)</td>
</tr>
<tr>
<td>Pneumatic conveying</td>
<td>(Li et al., 2000; Feng Y. Q., 2004; Feng et al., 2004; Golz et al., 2006; Xiang et al., 2010; Brosh et al., 2011; Hilton et al., 2011; Stratton et al., 2011; Guo et al., 2013)</td>
</tr>
</tbody>
</table>

2.4 Materials Interaction Properties Relevant for DEM Modelling

In this section, the specific methods used for the direct measurement of the material properties will be explained; stainless steel (the wall) and various test products. DEM models require a range of parameters for simulation modelling. There are two groups of parameters consisting of properties of materials and properties of interactions (Mohsenin, 1986; Vu-Quoc et al., 2000; Raji et al., 2004a; 2004b). In the first group, particle models are defined using the characteristics of the material to create realistic modelling. The properties of material as inputs in DEM modelling are particle shape, particle size distribution, particle density, particle Poisson’s ratio and particle shear modulus. The second group is the interaction properties, which are the characteristics of the particle contacts with other particles, wall surfaces and other boundaries. Interaction properties important in DEM modelling are coefficient of restitution, coefficient of static friction and coefficient of rolling friction (LoCurto et al., 1997; Chung et al., 2004).

2.4.1 Particle Size and Shape

Particle shape and particle size are not separated the physical properties in a granular material. In determining the shape, the dimensions of the particle must be measured. There are many different types of particle shapes (Gonzalez-Montellano et al., 2012) and measuring the PSD of materials fall into four general methods: sieving, microscope counting techniques, sedimentation and stream scanning (Ortega-Rivas, 2009). Sacilik et
al. (2003) investigated granular size by picking 100 particles and Markauskas et al. (2011) represented rice grains by selecting 20 particles randomly and measuring with a micrometer with an accuracy of 0.01 mm. Boac et al. (2010) and Hastie et al. (2009) selected 50 particles at random from the bulk material to determine particle shape and particle size. Three key dimensions of 50 particles were taken for each particle corresponding roughly to the particle length and two perpendicular diameters (Mohsenin, 1986; Nelson, 2002; Ortega-Rivas, 2009). The equivalent volume diameter of a non-spherical particle is equal to diameter of a spherical particle that exhibits identical volume to that of the investigated non-spherical particle. Hastie et al. (2009) described the equivalent volume diameter of materials for 50 particles. The shape of individual polyethylene pellets was approximately cylindrical so the length and diameter of the particle were measured and the shape of corn was approximately a trapezoidal prism so the maximum and minimum widths, height and depth were measured. The shape of iron ore particles were submerged in a known quantity of water, and then the change in volume recorded. This change in volume was equivalent to the total volume of the 50 iron ore particles and average size for one iron ore particle was determined. The average equivalent volume diameter ($D_{evd}$) of a particle is determined using equation 2.2 (Hastie, 2010).

\[
D_{evd} = \left(\frac{6V_p}{\pi}\right)^{1/3} = 1.241(V_p)^{1/3}
\]

2.4.2 Density

Density is the ratio of the mass of a granular material sample to the volume of the system. The following sections detail the two types of density relevant in this thesis.

2.4.2.1 Particle Density

The particle density ($\rho_p$) of a material is defined as the ratio of the solid mass to the solid volume occupied by the sample. Gupta et al. (1997) and Nelson (2002) proposed the measured material volume of by Beckman air-comparison pycnometer, model 930. Aydin (2003) determined the volume and density of grain using the liquid displacement method. Sacilik et al. (2003) used the toluene displacement method to determine the ratio between
mass of hemp materials and solid volume of materials. Karababa (2006) measured solid density using the water displacement method. Five hundred millilitres of water were placed in a 1000 cm\(^3\) measuring cylinder and 25 grams of material were immersed in that water. Gonzalez-Montellano et al. (2012) investigated particle density based on the pycnometer method (ASTM D584-10), five samples of 20 – 40 particles of the materials were tested to determine the volume of a set of particles via the volume of water they displaced when introduced into a vessel containing a known volume of the liquid.

2.4.2.2 Loose-Poured Bulk Density

The loose-poured bulk density (\(\rho_b\)) is the weight of granules per unit volume of a granular material sample including the voids between each grain. Many researchers used a different method for determined bulk density. Hastie (2010) and several researchers determined bulk density as the mass per unit volume of the material sample carefully poured freely into a cylindrical container without causing any compaction or consolidation (Molenda et al., 2005) with a constant volume of 500 cm\(^3\) and 1000 cm\(^3\) diameter and 15 cm high container and the excess amount was removed, and then the contents weighed (Gupta et al., 1997; Sacilik et al., 2003; Karababa, 2006). Aydin (2003) and Deshpande et al. (1993) determined the bulk density with a weight per hectolitre tester and experimental \(\rho_b\) values for granular were found in the literature (Mohsenin, 1986; LoCurto et al., 1997).

2.4.3 Particle Poisson’s Ratio and Shear Modulus

Poisson's ratio (\(\nu\)) is the absolute value of the ratio of decrease in the thickness (lateral contraction or perpendicular to the axis) of the body material being pulled (under the tensile load) to its increase in length (longitudinal extension or parallel to the longitudinal axis) resulting from uniformly distributed axial stress below the proportional limit of the material (Mohsenin, 1986). The shear modulus (\(G\)) for measuring the stiffness of materials and defined in terms of Poisson’s ratio (\(\nu\)) and Young’s modulus (\(E\)) is given by

\[
G = \frac{E}{2 + 2\nu}
\]
Poisson’s ratio and shear modulus are also required in the setup of the discrete element modelling using EDEM. No equipment was available to conduct tests to determine these two variables. Therefore, estimates of these two parameters will be made based on other research.

2.4.4 Interaction of Particles

The interaction of a particle can be divided into two groups consisting of the interaction between each particle and interaction between a particle with a boundary (wall or surface). The following sections describe three interaction properties of particles including particle coefficient of restitution, coefficient of static friction and coefficient of rolling friction.

2.4.4.1 Particle Coefficient of Restitution

The coefficient of restitution (CoR) of two colliding objects is a positive number between 0.0 and 1.0. The value is 1.0 (maximum value) for perfectly elastic collisions and value is zero (minimum) for perfectly inelastic (plastic) collisions. This represents the ratio of the difference in relative normal velocities or height of particles after and before the collision and for particles without rotation (Gonzalez-Montellano et al., 2011; Gonzalez-Montellano et al., 2012), the determination of CoR was based on drop tests similar to those described by (Gorham et al., 2000; Dong et al., 2003; Chung et al., 2004; Wu et al., 2007; Wong et al., 2009). When the particles involved in a collision are not subject to rotation, the coefficient of restitution (for any type of collision) are calculated by

\[ CoR = -\frac{(v_{p1} - v_{p2})}{(u_{p1} - u_{p2})} \]  

where \( u_p \) and \( v_p \) is the velocities just before and just after impact and subindices 1 and 2 identify the first element and second element in the collision (Dong et al., 2006; Haron et al., 2012). LoCurto et al. (1997) described CoR as the square root of the total kinetic energy \( (KE = \frac{1}{2}mv^2) \) or gravitational potential energy \( (PE = mgh) \) before and after collisions are calculated by
\[ \text{CoR} = \left( \frac{KE_{\text{after collision}}}{KE_{\text{before collision}}} \right)^{0.5} \]

Using the energy principles, the velocity of a particle before and after impact also relate to the drop height. The CoR value can be computed as the ratio of the square root of the initial height of drop \((h_i)\) and the height of rebound \((h_r)\) (LoCurto et al., 1997; Zhang et al., 2002) as in equation 2.6

\[ \text{CoR} = \frac{\sqrt{h_{\text{rebound of height}}}}{\sqrt{h_{\text{initial height}}}} \]

2.4.4.2 Particle Coefficient of Static Friction

The coefficient of friction is a measure of the resistance of two bodies sliding over one another. This value can be obtained analytically from the relationship between the tangential force that appears between the sliding force and the normal force. This value must be obtained from the particle and wall coefficient of friction \((\mu_{p,w})\) or the particle and particle coefficient of friction \((\mu_{p,p})\) (Li et al., 2005; Gonzalez-Montellano et al., 2012). There are various methods used for determining the coefficient of friction between the particles and walls, such as Aydin (2003) investigated coefficient of friction by measuring the torque obtained as a disc starts to rotate on the surface of the granular material. The value of torque occurring at the start of rotation of the disc was used to calculate the static coefficient of friction. While the value of torque during the rotation of the disc was used to calculate the dynamic coefficient of friction. Mohsenin (1986) investigated the coefficient of friction between two solid surfaces and is defined as the ratio of the friction force \((F_f)\) and the normal force between the surface contact \((F_n)\). Karababa (2006) measured the coefficient of static friction by placing material on an adjustable tilting table and the tilting surface was raised gradually until the material just started to slide down. The coefficient of friction with the surface was taken as the tangent of this angle. Many researchers used this method to measure the angle of a wall material. Particles were placed on a wall material sample and the inclination angle was slowly increased until the particles began to roll or slide. At this point, the inclination angle was recorded and equation 2.7 was used to calculated the coefficient of static friction \((\mu_s)\) (Dutta et al., 1988; Joshi et al., 1993; Singh et al., 1996; Suthar et al., 1996; Chung et al., 2004; Hastie, 2010; Gonzalez-Montellano et al., 2012).
The maximum value of friction force was obtained when the sample material started moving and this was used to calculate the static coefficient of friction. While the sample material continued to slide over the test surface at a constant velocity, the dynamic coefficient of friction was measured. This coefficient is selected where the conical pile experiment (Grima et al., 2011) matches the pile modelled using the DEM with regards to the angle of repose (AoR) and the height of the pile (h_p). This is achieved by DEM sensitivity analysis. The results of the DEM calibration tests are used to determine the ideal \( \mu_s \) for particle-to-particle interactions by comparing AoR determined in the DEM simulations to the experimental data.

### 2.4.4.3 Particle Coefficient of Rolling Friction

The coefficient of rolling friction or rolling resistance (\( \mu_r \)) is defined as the ratio of the force resisting the motion when the material rolls on the wall surface or on another material. Rolling friction directly affects the angular motion of each particle and not the translational motion of particles. Jiang et al. (2005) presented the concept of rolling friction at particle contacts as an alternative approach in DEM modelling to establish contact laws related to particle rotation. Zhou et al. (2002) examined the effect of rolling friction on particle and particle contact and particle and wall contact of the angle of repose simulation. The concept of rolling friction was probably first introduced into DEM modelling by Sakaguchi et al. (1993) conducting a comparison study of experimental and numerical modelling of plugging of granular flow during silo discharge. Ai et al. (2011) studied the assessment of rolling resistance in DEM models of the piles with coarse spheres to describe particle to particle and particle to boundary interactions. The results from simulation were compared with experimental measurements of torque in the rotational direction of the rolling resistance or rolling friction. Zhou et al. (1999) represent the rotational motion of spheres as a large resistance force on the particle and is an effective mechanism in kinetic energy consumption when the particle stops the rotational motion and leads to the formation of a pile with high potential energy.
2.4.5 Void Ratio and Porosity

The mechanical properties of granular materials compression were affected by a change in the primary particle size. It is also possible to find a balance between size ratio and density difference to avoid segregation (Drahun et al., 1983). However, reducing the particle size can also affect the flowability properties of the materials (Mosby et al., 1996). The porosity ($\varphi$) and void ratio ($e$) of a particulate solid has an important role in defining the mechanical response under various loading conditions such as compression or direct shear. The void ratio given by equation 2.8 can be defined as the ratio of the volume of voids to the volume of solids.

\[ e = \frac{V_v}{V_s} = \frac{V - V_s}{V_s} \quad 2.8 \]

where $V$ is the total volume of the sample, $V_v$ is the volume of voids and $V_s$ is the volume of the solids in the sample. Porosity is calculated by $\varphi = e/(1 + e)$ of describing the packing of a granular solid and the value will always be between 0 and 1. The porosity can also be related to the particle density and the bulk density by equation 2.9 when the material is dry or with negligible moisture content.

\[ \varphi = 1 - \frac{\rho_b}{\rho_p} \quad 2.9 \]

The packing can also be expressed in terms of the solid volume fraction ($SF$) which is a measure of the amount of solids in a volume rather than a number of voids as described by the porosity. The solid volume fraction is related to the porosity by equation 2.10.

\[ SF = 1 - \varphi \quad 2.10 \]

2.5 Fundamentals of the Discrete Element Modelling

The discrete element method (DEM) is to be used in this work as a numerical analysis tool which was initiated and developed by Cundall et al. (1979). This method considers particles are interacting using continuous contact and non-contact forces. Any particle in a system, which can move translationally and rotationally is described by Newton’s
Second Law of Motion and the force-displacement law. The main advantage of DEM is that highly complex systems can be analysed. The interactions between individual particles, surrounding fluid and wall are quite complex, which makes the dynamic behaviour of material complicated and difficult to understand (Zhu et al., 2008). DEM can be used for dispersed systems in which the particle and particle interactions are collisional and compact systems of particles with multiple enduring contacts. However, the calculation of collision forces increases the computational complexity of the calculation and makes this method computationally expensive. DEM is an approved method to model particles and should be coupled with computational fluid dynamic (CFD) methods to model multiphase flow.

The basic methodology of DEM for all particle dynamics can be determined, firstly by the total force acting on each particle and then by applying Newton’s second law of motion to determine the positions of each particle. From these, the interaction of particles is determined and then the subsequent position changes are evaluated. The position of particles and particle velocities are determined at regular time intervals and calculations are event-driven, e.g. contact force calculation is recorded during a contact. This numerical method considers every particle in a system along with the interaction forces, acceleration and movement of each particle, which are calculated individually at each time step.

**2.5.1 Hard-Sphere and Soft-Sphere Approaches**

In DEM, the individual particle trajectories are tracked of such a nature that the translational and rotational displacements of each particle are incremented at fixed time steps by integrating the equations of motion, which are governed by Newton’s second law. Normally the particles are accelerated by interparticle and gravitational forces. If the particle has been dealt a strong presence in the fluid, the fluid-particle interaction force can also have a significant affect on the movement of the particles. Two types of DEM have been proposed: the hard-sphere and the soft-sphere approaches, as shown in Figure 2.6. In a hard-sphere simulation, the particle collisions are assumed to be binary and instantaneous, the velocities of the particle after a collision are related to the velocities before the particle collision and depend on the coefficients of restitution and particle friction (Li et al., 2002; 2003). Deformation of particles and forces occur between
individual particles and are not considered explicitly. Thus, the hard-sphere method is typically applicable to rapid particle flow. The hard-sphere particle model considers in the Newtonian equations of particle motion in the integral form of the force acting on a particle versus time. The equations and more details of hard-sphere particle model can be found in Campbell C.S. (1982), Devahastin (1998) and Crowe et al. (1998). In contrast, the soft-sphere particle model considers the deformation of particles in contact and the inter-particle forces can be calculated from the deformations based on the given force models. As indicated in previous work (Zhu et al., 2007; Crowe et al., 1998) the soft-sphere method is capable of handling multiple long duration particle contacts. Therefore, the soft-sphere method is believed to be superior to the hard-sphere method and has been extensively used to study various particle-handling processes.

![Figure 2.6 Particle and particle collision (a) in a hard-sphere model (b) in a soft-sphere model.](image)

There are numerous contact force models available to simulate particle and particle and particle and wall interactions. These are all classified as soft-sphere contact models where contact mechanics is used to quantifying the displacements, velocities and forces of the particles. The time step used is only a fraction of an actual collision and more than one collision is possible at each time step. Also, it is assumed that the particles which collide do not undergo any deformation but instead overlap to a small degree (Di Renzo et al., 2005). The other type of contact model is the hard-sphere model where a collision is seen to be instantaneous. The conservation of energy, momentum and surface sliding are applied to quantify the velocity of the particles, which are colliding before and after the impact (Di Renzo et al., 2005). However, the soft-sphere particle model requires more computational power than the hard-sphere particle model, the inter-particle force obtained in the soft-sphere particle model and cannot be obtained in the hard-sphere particle model. Also, the hard-sphere particle model breaks down in systems with long inter-particle contact durations. In this thesis, multiple particle contacts are present in the system, therefore, the soft-sphere approach is used.
2.5.2 Equations of Motion

In a short time, there has been a rapid advancement in the understanding of rotating drums through computer simulations. The DEM software has helped the design and optimisation of rotating drums to improve industrial practice further. Numerical simulations have been able to capture the various flow regimes that may exist within drum modelling for calculation of size distribution, distribution of contact forces and energies between collisions and wear qualitatively. The flow of granules in a rotating drum can be divided into two types of particle motion; particle translation and particle rotation, both governed by Newton’s laws of motion. The movement of particles affects the interaction with adjacent particles, the wall and interacts with the surrounding fluid during the motion. This yields the velocity and displacement of each particle and after balancing the angular momentum of each particle the rotation can be determined. The governing equations for the rotational and translational motions of particle \((i)\) with mass \((m_i)\) and moment of inertia \((I_i)\) can be written as

\[
\begin{align*}
    m_i \frac{dv_i}{dt} &= F_{pf,i} + F_{c,ij} + m_i g \\
    I_i \frac{d\omega_i}{dt} &= \sum_{j=1}^{k_c} (M_{t,ij} + M_{r,ij})
\end{align*}
\]

where \(v_i\) and \(\omega_i\) are the transitional and rotational velocities of particle \(i\), respectively. \(k_c\) is the number of particles in contact with the particle. \(F_{pf,i}\) is the force interaction between particle and fluid occur on particle \(i\). \(F_{c,ij}\) is the particle and particle contact force acting on particle \(i\) by particle \(j\) or the walls. \(m_i g\) is the gravitational force. \(M_{t,ij}\) is the tangential force torque and \(M_{r,ij}\) is the rolling friction torque acting on the particle \(i\) by particle \(j\) or the walls. Figure 2.7 displays the forces and torques on the particle in DEM simulation. The forces and torques can be solved by equation 2.11 and 2.12.
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![Figure 2.7 Schematic show the forces acting on particle i and particle j (Zhu et al., 2007).](image)

2.5.3 Contact Models

In the soft particle model during contact, two rigid bodies are allowed to overlap slightly due to deformation of the particles. The contact forces considered in the model are elastic, cohesion, friction and damping forces. These forces are divided into normal and tangential components based on the contact plane, as shown in Figure 2.7. The resulting force on each particle is the summation of all these forces in addition to any external forces acting on the particle. The normal contact between two particles is modelled as a linear spring in parallel with a dashpot element, as shown in Figure 2.8. It is difficult to be accurate and describe a contact distribution at the contact point. There is a torque and force acting on the surface of a particle and relates to physical and geometrical factors such as the particle shape, particle size, properties of material and particles movement.

The most simple model is the linear spring and dashpot model presented by Cundall et al. (1979). The spring model describes the deformation of elastic bodies and the dashpot model describes the viscous dissipation in shear flows. The complex model was developed by the Hertz-Mindlin model. Hertz (1882) proposed the normal contact force between two particles include the normal force and normal displacement in the normal direction and Mindlin et al. (1953) proposed a generally tangential force model. They illustrate that the normal force and tangential force displacement are based on the history of all load and instantaneous rate change. The force-displacement relative with the tangential force and normal force of the Hertz’s theory has been popular to investigate the mechanisms of granular matter (Langston et al., 1995; Zhou et al., 1999; Cleary et al.,
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2000; Hoomans et al., 2000; Arntz et al., 2008; Yang et al., 2008). For the plastic deformation, the contact force has been studied (Vu-Quoc et al., 1999a; 1999b). The inter-particle forces act at the contact point between two particles and create a torque when the particles rotate (Iwashita et al., 1998; Zhou et al., 1999; Papanicolopulos et al., 2011). Theoretically, the non-linear model of Hertz and Mindlin-Deresiewicz will provide better results than linear models. On the other hand, Di Renzo et al. (2004) presented that sometimes a simple linear model gives more accurate results than the nonlinear models. Such particles are not perfect in practical applications, the correct results are based on the particle models and the selection of appropriate parameters. Also, the complex models will also take extra computational time for the DEM simulations.

The most commonly used contact model is the Hertz-Mindlin no-slip contact model (Mindlin, 1949; Mindlin et al., 1953; Tsuji Y. et al., 1992; Di Renzo et al., 2004; 2005). Forces on the particles at contact points include the contact force and viscous damping force (Stewart et al., 2001). These contact forces have normal and tangential components and have spring stiffness and damping coefficients (dashpot), related to the coefficient of restitution as described in Tsuji Y. et al. (1992). The Hertz-Mindlin no-slip contact model with damping and a frictional slider in the tangential direction (Tsuji Y. et al., 1992) is shown in Figure 2.8 spring-dashpot contact model.

![Spring-dashpot contact model](image)

**Figure 2.8** Spring-dashpot contact model.

In Figure 2.8, particle $i$ is contacting with particle $j$, the normal component of the contact force ($F_n$), acting on particle sphere $i$. Resulting total force $F_n$ is the sum of elastic and damping force (Tsuji Y. et al., 1992; Cleary, 1998; Chu et al., 2009; Remy et al., 2009) and is given as:

$$F_n = -k_n \delta_n + C_n \nu^r_{et}$$  \hspace{1cm} 2.13
The total tangential force $F_t$ is limited by Coulomb friction (Cleary, 1998; Chu et al., 2009) and is given as:

$$F_t = \min[\mu F_n, k_t \delta_t + C_t v_{t}^{rel}]$$ \hspace{1cm} (2.14)

where $k_n$ and $k_t$ are the normal stiffness and tangential stiffness respectively, $\delta_n$ and $\delta_t$ is the normal overlap and the tangential overlap respectively, $v_n^{rel}$ and $v_t^{rel}$ are relative normal velocity and relative tangential velocity respectively, $C_n$ and $C_t$ are the normal damping coefficient and the tangential damping coefficient respectively. The spring stiffness and damping coefficient are described in Table 2.4. The tangential overlap is calculated by Remy et al. (2009), as given in equation 2.15.

$$\delta_t = \int v_t^{rel} dt$$ \hspace{1cm} (2.15)

The relative tangential velocity of colliding particles is defined by Remy et al. (2009), as given in equation 2.16.

$$v_t^{rel} = (v_i - v_j) \cdot s + \omega_i R_i + \omega_j R_j$$ \hspace{1cm} (2.16)

where $s$ is the tangential decomposition of the unit vector connecting the centre of the particle. Additionally, there is a tangential force limited by Coulomb friction $\mu_s F_n$, where $\mu_s$ is the coefficient of static friction ($F_t < \mu_s F_n$). The rolling friction can be accounted for by applying a torque to the contacting surface. The rolling friction torque $\tau_i$ is given by Remy et al. (2009) and EDEMSolutions (2013), shown in equation 2.17.

$$\tau_i = -\mu_r F_n R_o \omega_0$$ \hspace{1cm} (2.17)

where $\mu_r$ is the coefficient of rolling friction, $R_o$ is the distance from the contact point to the centre of the mass and $\omega_0$ is the unit angular velocity vector of the object at the contact point (Tsuji Y. et al., 1992; Di Renzo et al., 2004; Li et al., 2005; Remy et al., 2009; EDEMSolutions, 2013).
Table 2.4 Spring stiffness and damping coefficient used in the contact model (EDEMSolutions, 2013).

<table>
<thead>
<tr>
<th></th>
<th>Spring stiffness constant (k)</th>
<th>Damping coefficient (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal force</td>
<td>( k_n = \frac{4}{3} E^* \sqrt{R^* \delta_n} )</td>
<td>( C_n = 2 \sqrt{\frac{5}{6} \beta S_n m^*} )</td>
</tr>
<tr>
<td>Tangential force</td>
<td>( k_t = 8 G^* \sqrt{R^* \delta_n} )</td>
<td>( C_t = 2 \sqrt{\frac{5}{6} \beta k_t m^*} )</td>
</tr>
</tbody>
</table>

Note: \( S_n = 2 E^* \sqrt{R^* \delta_n} \); \( \beta = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}} \); \( m^* = \left( \frac{1}{m_i} + \frac{1}{m_j} \right)^{-1} \frac{1}{R_i} \); \( \frac{1}{R_i} + \frac{1}{R_j} : \frac{1}{R} = \frac{(1- \nu_i^2)}{E_i} + \frac{(1- \nu_j^2)}{E_j} \)

where: \( E^* \) is the equivalent Young’s modulus; \( E_i, E_j \) is the Young’s modulus; \( \nu_i, \nu_j \) is the Poisson’s ratio; \( R_i, R_j \) is the radius of each sphere in contact; \( G^* \) is the equivalent shear modulus; \( m^* \) is the equivalent mass and \( CoR \) is the coefficient of restitution.

2.5.4 Geometry of Particle

Walton et al. (1993) investigated the effect of particle shape on the dynamic angle of repose and on the bulk flow behaviour in horizontal rotating cylinders using dynamic particle simulations. They performed simulations using single spheres and a cluster of spheres (tetrahedral and eight sphere cube). They concluded that dynamic angle of repose and particle flows in the rotating drum, illustrating the importance friction between particles on the heap and the slipping flow of particles in the rotating drum.

Particle shape representation is an important aspect of DEM simulation. Creating a more accurate representation of irregular shapes such as agricultural grains (Kremmer et al., 2000; Tijskens et al., 2003; Chung et al., 2006; Härtl et al., 2008) requires more spheres per particle and will increase the computational time. It has been suggested (Chung et al., 2006; Härtl et al., 2008) that an accurate geometrical representation of a granular material does not necessarily lead to a more accurate prediction of the bulk behaviour and that often quite crude representations of fewer numbers of spheres can produce similar results, thereby reducing the computational time.

2.5.4.1 Spherical Shape Particles

Traditionally, two-dimensional discs and three-dimensional spherical particles have been used to represent particles within DEM simulations but with the ever-increasing computational power comes the ability to generate more realistic particle shapes, in turn
producing even more outcomes that are realistic, where every sphere can be described by a centre point and a radius (Li et al., 2005; Gui et al., 2009). Fernandez et al. (2011) used the DEM to predict spherical particle movement in a horizontal screw feeder for a range of designs including a variable screw flight, core diameters and screw pitch. Mindlin (1949) analysed the elastic friction contact between spheres and showed the maximum tangential force was limited by the coefficient of friction.

2.5.4.2 Non-Spherical Particles

Non-spherical particles are more difficult to roll and rotate within an assembly to a greater degree than spherical particles. The most commonly used DEM method is to create non-spherical particles with a number of original elements (3D spheres) that are reciprocally connected in a rigid model (Kremmer et al., 2000; Favier et al., 2001; Matsushima, 2003). This method has been adopted by both PFC3D and EDEM to represent particles of any shape. Using a multi-spherical method, it is possible to create a cluster of spheres (a particle consisting of many spheres) with different sizes and positions or can overlap to create the desired shape and is rigidly linked. Contacts internal to the cluster are skipped during the calculations and reducing the computational simulation time. However, contacts with spheres external to the particles are not affected and the contact detection method is the same as for spherical particles except that translation and rotation of element spheres are calculated with respect to the motion of the whole particle. With the multi-spherical shape method, any particle shape can be created which acts as a rigid unbreakable body that will not break apart, regardless of the forces acting upon it. The motion of a non-spherical particle is determined by the resultant force and the moment vector acting on the particle. Since such particles are treated as rigid bodies, particle motion can be described in terms of the translational and rotational motion of a point on the entire particle. Chung et al. (2006) conducted a careful validation study where DEM was used to model the confined compression and rod penetration test of spherical and non-spherical particles.

2.6 Fundamentals of Computational Fluid Dynamics

Computational fluid dynamics (CFD) is a common numerical analysis method for fluid mechanics and prediction of the fluid flow in a range of domains. The CFD simulations
calculate the interaction of fluids (air or gases) and surfaces of the models as defined by boundary conditions such as in the automotive, aerospace industries and air flow around the particles. CFD is based on the use of applied mathematics and physics is based on the Navier-Stokes equations. These equations propose the relation of the fluid velocity, pressure, temperature and density in the system. CFD has been used to model various applications such as particle flow in rotary drums (Liu et al., 2008). Christakis et al. (2002) used CFD to simulate a process of binary material in bulk solids handling through pneumatic conveying. Arntzen (1998) used a CFD simulation of gas to analyse and present models of turbulent reactive flows of gas explosions in complex geometries like offshore modules. Chang et al. (2012) presented a CFD method investigation of heat transfer between different sizes of a particle in a dense air-solid fluidised bed of binary particle. CFD has been used investigate mechanisms of the bulk materials flow in a horizontal rotating fluidized bed was analysing the bed thickness and pressure drop (Ahmadzadeh et al., 2008).

Basic equations in all mathematical models for CFD are balanced for momentum and total mass in determining velocity, pressure and density field. In addition, each model is required to describe turbulence and multiphase flows. In the case of fluid and solid interaction modelling, CFD can take advantage of both Eulerian-Lagrangian and Eulerian-Eulerian approaches.

In the Eulerian-Lagrangian method, the air phase is still described as a continuum by solving the time-averaged Navier-Stokes equations, while the motion of the particle phase is solved by tracking a particle through the calculation by a CFD simulation of the fluid (Morsi et al., 2004). This method can exchange momentum, mass, and energy between the air and particle phases. The particle motion is as a result of the effect of all the forces acting on the particles (Zhang et al., 2002). The behaviour of particles in the fluid flow can be considered a source term in a governing equation of the fluid for each sample particle (Crowe et al., 1996).

The Eulerian-Eulerian method takes the solid particles as a continuum interpenetrating and interacting with continuous gas (Deng et al., 2013). This model allows momentum exchange between the air phase and particle phase, but also considers the effect of the particle solid fraction on the air phase. In Fluent software, there are three different
Eulerian-Eulerian multiphase models consisting of mixture model, volume of fluid (VOF) model and Eulerian model. The mixture model is designed for two phase or more phases (fluid or particulate). The mixture model solves the mixture momentum equation and determine the relative velocity to describe the distribution of phases. Several applications of this model such as bubbly flows and cyclone separators. The VOF model is a free surface modelling technique, the numerical technique for tracking and locating of the interface between the fluids is of interest in the model through the domain in the volume fraction of each fluid in each computational cell. The applications for this model such as free-surface flows, filling, sloshing and the steady or transient tracking of any liquid-gas interface. The Eulerian model solves a set of $n$ momentum and continuity equations for each phase. Coupling is achieved through the pressure and interphase exchange coefficients. This coupling is depends on the type of phases; granular (fluid-solid) flows are differently than non-granular (fluid-fluid) flows. For granular flows, the properties are obtained from application of kinetic theory. Momentum exchange between the phases is also dependent upon the type of mixture being modelled. For applications of this model include bubble columns and fluidised beds (ANSYS Fluent 14.5, 2013).

The turbulence modelling of the air phase and particle phase are difficult because of the velocity of air and particle fluctuations and are strongly linked together. The particles start to affect the turbulent behaviour of the air phase and in dense regions. One of the most common turbulence models is the standard $k-\varepsilon$ model, the methods of calculating turbulent viscosity. This model has two transport equations which are solved simultaneously with the continuity and momentum equations. The model has base on the model transport equation for the turbulent kinetic energy ($k$) and the turbulent dissipation rate ($\varepsilon$) but the approach to solve these equations are different for all of them (ANSYS Fluent 14.5, 2013). In this thesis the standard $k-\varepsilon$ model will be used, proposed by Launder and Spalding (Choobari et al., 2014).

\[ \mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \]

where $C_\mu$ is a constant, $k$ is the turbulence kinetic energy, $\varepsilon$ is the rate of dissipation are obtained from the following transport equations:
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\[
\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \tag{2.19}
\]

\[
\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_1 \frac{\varepsilon}{k} (G_k + C_3 \varepsilon G_b) - C_2 \rho \frac{\varepsilon^2}{k} + S_\varepsilon \tag{2.20}
\]

The model constants have the following default values: 
\[C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, C_\mu = 0.09, \sigma_K = 1.0, \sigma_\varepsilon = 1.3\] (Choobari et al., 2014).

### 2.7 Combined DEM and CFD Model

For a particle movement and fluid flow combined method of Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) is also developed to study the particle-particle and particle-fluid interactions in complex industrial applications.

Coupling involves the modelling of the individual particle movement by DEM and the fluid flow by CFD in each computational cell. Xu et al. (2001) described the coupling method between CFD and DEM as follows in Figure 2.9. DEM will provide information for every time step, namely position and velocity of each particle. CFD then uses this information to calculate fluid volume and drag force in a cell to determine the air flow field acting on each particle. The combination of forces resulting from the DEM will produce data on the movement of each particle for the next time step.

This coupling method has been used in numerous investigations. Feng et al. (2004) proposed three groups; Group 1: the interaction force transfer from the air phase to each
particle is calculated by the velocity of individual particles. In contrast, the interaction force transfer from the particle phase to the air phase is calculated by an average local method. Group 2: the interaction force transfer from the particles phase to the air phase is calculated using the average as used in group 1 and then this value distributed to each particle. Group 3: at each time step, in the first step is calculated by the interaction forces on the individual particle in each computational cell and summed the values of the interaction force to produce in each cell. The interaction force on the individual particle phase is equal in magnitude to the air phase but opposite direction of the force, as described in the Newton’s third law of motion. Group 1 does not guarantee the results of this condition will be satisfied, because of this group was used only in the first stage of DEM-CFD development Group 2 can satisfy the third law of Newton. The interaction force between each particle evenly distributes in a computational cell, without regard to the different behaviour of these particles in the cell. This group cannot represent the reality of a particle and fluid interaction force for each particle in the computational cell. The calculation of the interaction force \((F)\) used the mean particle velocity. Group 3 can solve the problems in group 1 and group 2. This group has been widely accepted and applied by Xu et al. (1997).

DEM is a method that can provide details of the granular-dynamic information of each particle such as the velocity of individual particles and the forces between particles. Computational Fluid Dynamics (CFD) is numerical methods and algorithms to solve and analyse problems that involve fluid flow. As pointed out by Yu et al. (2003), there are difficulties in modelling the flow of fluid and solid particles that are mostly particle phase rather than a fluid phase. These problems can be resolved by coupling DEM and CFD, which has the ability to capture particle physics.

In DEM-CFD, the motion of individual particles is modelled as a discrete particle phase based on Newton’s laws of motion and the air flow is created as a continuum air phase present by the Navier-Stokes equations on a computational cell of the CFD. These coupling models are based on the initial conditions and boundary condition will be determined by solids mechanics and fluid mechanics. However, in the solid phase, there are often a lot of number of particles. Therefore, the model requires many equations to be solved the movement of each particle and to resolve the air flow closely spaced with particles in the mesh cell. The consequences, depending on the simulation time and
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dimension of geometry are interesting. The main advantage of DEM-CFD is that detailed particle-scale information is obtained, including particle trajectories and forces acting on each particle.

One of the advantages of this model compared with CFD is that in the DEM-CFD coupling method, the effects of particle solid fraction on the fluid phase that can be considered. The computational efforts needed for the calculations in this process are quite high because the governing equations need to be corrected for each particle and computational cell and information of coupling needs to be exchanged several times (depending on the time interval of coupling) during the simulation. The method treats particle and fluid interaction of the fluidized bed at a different scale in DEM-CFD simulation under different conditions, as briefly reviewed by various investigators spherical particle conveyed in a horizontal pipe (Tsuji Y. et al., 1992), gas and fluid flow in a fluidisation of vertical pipe (Xu et al., 1997), homogeneous and bubbling fluidisation (Di Renzo A. et al., 2007) and discrete particle model simulation of gas-solid flow (Feng Y. Q., 2004; Deen N. G. et al., 2007; Zhu et al., 2007; 2008).

The CFD simulations will be iterated to converge for the procedure over time-step. The drag force is calculated for the particles in DEM contained in the mesh cell of the conditions of fluid phase. The DEM solver then takes control of the simulation and performs one (or several) iterations. This process then repeats until the simulation is complete.

2.7.1 Particle Flow Modelling

Many research papers published on the air and particle Eulerian-Lagrangian approach use coupling between CFD and DEM. There are many groups applying the CFD-DEM method (Zhu et al., 2007; Chu et al., 2011). Zhao et al. (2010) has implemented the CFD-DEM method to simulate fluid and solid flow. The Eulerian simulation method described a fluid phase and the Lagrangian simulation method described a particle motion. The equations relating the turbulent flow of the fluid to the forces on each solid bubble in a one-way coupled by Mattson et al. (2012), two-way coupling method (Hu et al., 2008) and developed a four-way method (Gruber et al., 2013). The fluid effects in fluidised beds were also investigated (Tsuji et al., 1993).
The Eulerian-Eulerian approach has become popular in practical engineering multiphase flow simulations. As the computational domain is divided into control volumes between solid phase and fluid phase, this is assigned as the ratio of volume fraction in each phase, especially the solid phase in each control volume. Both the fluid phase and the solid phase are modelled as continuums and generalised Navier-Stokes equations are used for both phases. This model most widely referred in the kinetic theory applied to granular flow (Gidaspow, 1994). The particle slip velocity (Liu et al., 2008) has been use in in cyclone modelling (Chu et al., 2009). At each time step, analysis of the forces affecting the particle motion and particle size distribution is completed.

2.7.2 Governing Equations

The DEM-CFD coupling method was presented by Tsuji Y. et al. (1992), Tsuji et al. (1993) and many others. The approach was improved by (Xu et al., 1997). In this approach, the motion of particles is explained by DEM based on Newton’s laws applied to the particle and the air flow by the CFD based on the basis of local averaged Navier-Stokes equations. There are two formulations, Gidaspow (1994) presented the formulation in Model A is shared the pressure drop between the particle phase and air phase, Model B in the air phase only. Both formulations can be used in the DEM-CFD coupling (Chu, 2010), given by

For model A:

\[
\frac{\partial \varepsilon_f}{\partial t} + \nabla \cdot (\varepsilon_f \mu_f) = 0 \tag{2.21}
\]

\[
\frac{\partial (\rho_f \varepsilon_f \mu_f)}{\partial t} + \nabla \cdot (\rho_f \varepsilon_f \mu_f) = -\varepsilon_f \nabla p - F^A + \nabla \cdot (\varepsilon_f \tau) + \rho_f \varepsilon_f g \tag{2.22}
\]

For model B:

\[
\frac{\partial \varepsilon_f}{\partial t} + \nabla \cdot (\varepsilon_f \mu_f) = 0 \tag{2.23}
\]

\[
\frac{\partial (\rho_f \varepsilon_f \mu_f)}{\partial t} + \nabla \cdot (\rho_f \varepsilon_f \mu_f) = -\nabla p - F^B + \nabla \cdot (\varepsilon_f \tau) + \rho_f \varepsilon_f g \tag{2.24}
\]

where \(\varepsilon_f\) is the porosity, \(\mu_f\) is the fluid velocity, \(p\) is the pressure, \(\tau\) is the fluid viscous stress tensor and \(\Delta V\) is the volume of a computational cell. \(F^A\) and \(F^B\) are the total volumetric particle and air interaction forces for the Model A and Model B. However,
different results may arise due to the difference of numerical treatments between the two models. An example of this was the investigation of particle and fluid flow in pneumatic conveying, particle fluidisation and hydrocyclones (Zhou Z. Y. et al., 2010).

2.7.3 Particle–Particle Interaction

The particle and particle interactions have two basic methods generally used to model the particle collisions, consisting of the hard-sphere and soft-sphere models, as described in Section 2.5.1.

The force acting on individual particles is calculated using Newton’s second law in terms of the velocity and position of the particle in the system. DEM used to form simple models and the equation to determine the effect of the forces and torque from the interaction between individual particles. For the frictional elastic contact of spherical particles, the theory of Hertz (1881; see also Johnson, 1985) is used to describe the normal force-displacement relationship while the theory of Mindlin et al. (1953) is used to describe the tangential force-displacement calculations. The normal force contact between two particles is modelled as a dashpot element in parallel with a linear spring, where the dashpot element is used for the viscous dissipation while the spring element is used for the elastic deformation of energy during contact. As a result, the effective coefficient of restitution is less than one. In the tangential model, the spring is in series with a Coulombic friction sliding element. The spring allows the particle to respond elastically while the sliding friction element allows particles to slide against each other. The magnitude of the tangential force is limited by the sliding element.

2.7.4 Particle–Wall Collisions

The physical models are important for the particle and wall interactions in numerical simulations, since the particles impact on the wall and rebound into the air flow (Sommerfeld et al., 1999). If the particle velocity is below a certain value, called the capture (or critical) speed, it may remain attached to the wall (Brach et al., 1998). If the particle velocity is higher than the capture speed, the particle rebounds with a loss of momentum. Many parameters control the process of particle and wall collisions such as particle velocity, initial angular velocity, the angle of particle impact, dimension and
shape of the particle as well as its material properties. Other parameters such as the surface characteristics of the particles and the roughness of particles influence the impacting and rebounding of the particles on the wall surface (Sommerfeld, 1992; Li et al., 2000). Many other experimental and computational investigations have been conducted by Brach et al. (1992), Brach et al. (1998), Sommerfeld (1992) and Sommerfeld et al. (1999), with success in accurately modelling the collision of particles and walls remaining elusive because of the complex nature of the motion.

Particles in a fluid flow will collide with other particles or walls, as shown in Figure 2.10, depending upon their inertia. As expected, if the stress induced by an impact is greater than the strength of the loose aggregates they will deform, break or disintegrate, aiding dispersion (Calvert et al., 2009).

![Figure 2.10 Particle and particle, and particle and wall collisions (Calvert et al., 2009).](image)

Particle and wall interaction force in a system relates to many researcher efforts since it closely relates to the wearing of the wall, where the particle undergoes breakage to smaller particles and the degrading of the conveyed product (Mills et al., 1977; Converse, 1989). For example, for a given bend of pipe, the extent of erosion of the wall and a mixing, the product will break into smaller particles when it impacts on the wall or another particle and depends on three factors: operational conditions, nature of target materials and properties of impact particles. The information on the magnitude force of particle and wall interaction is a significant factor in the modelling of air and particle flow in a cyclone separator. The collision between the particles and fluid is the lowest interaction force, the particle and particle interaction forces are higher than the particle and wall interaction forces (Chu et al., 2011). These factors, in terms of operations conditions such as the velocity of the impact, an angle of impact, the density of the particles impact and affect the properties of the fluid are the most important (Converse, 1989; Salman et al., 2002). For dilute flow, the Stokes number can be used in assessing the impact ability of particles on the wall. For dense flow, the situation is more complicated because of the collision
between the particles can be in the form of a barrier to shield against particles-wall collision (Mahowald et al., 2014). Current simulations have shown that collisions between particles can cause some particles to collide with the wall several times but at the same time some particles do not collide directly with the wall.

2.7.5 Particle–Air Interaction

Particles will interact with the surrounding fluid and the particle and fluid interaction forces will generate shear stress in the fluid acting on the surface of the particle, causing motion of the particles. Therefore, the interaction forces between particle and fluid must be considered. There are a number of forces in the DEM-CFD coupling, including pressure gradient force, drag force, lift forces, virtual mass force and Basset force (Potic B. et al., 2005; Xiong Y. Q. et al., 2005). For a particle in a air phase, the drag resistance force is explained by the equations of Newton. The air-particle drag coefficient ($C_D$) is based on Reynold's number ($R_e$) and air properties. The increasing number of particles reduces the gap for air between particles and as a result generates air velocity, thus there is increasing shear stress on the particle surface. The drag force is influenced by a combination of the air-particle configuration, air and particle slip velocity and the properties of air and the particles. Li et al. (1996) started to understand the structure heterogeneity, various regimes and the non-linear behaviour of particle and fluid systems which gave rise to difficulties in their modelling and scale-up.

There are two methods used to determine drag force from the air and particle interaction. The first method is based on empirical correlations represented by Ergun (1952) and Wen et al. (1966). The effect of the increase in the number of particles is considered in terms of porosity, flow regimes or Reynolds number of particle, as represented by Di Felice (1994). The second method is based on numerical simulations (Choi H. G. et al., 2001). While simulations are limited by the ability of computational power in the present day, numerical methods have been used for simple systems. Li et al. (2003) studied the amount of difference between these correlations and concluded that these correlations have a similar ability to predict, although their accuracy may differ.
2.7.5.1 Drag Force Model

Every particle surrounded by liquid or gas with relative motion between particle and liquid (fluid or gas) is subjected to a force that applies in the same direction as the relative velocity; it is called drag force and is proportional to the square of the relative velocity of the object and the fluid. There are different drag models that describe the proportionality coefficient as a function of the object size, shape and characteristics of the surrounding medium. The drag force depends on the properties of the fluid and on the size, shape and speed of the particle. The air particle drag force $F_d$ is determined on the basis of an individual particle depending on the air voidage and on the relative velocity between air and particles.

In the CFD-EDEM Coupling Interface, Fluent uses modified spherical particles and non-spherical particles is the bounding of many spheres and free-stream flow through the particles is used to calculate the drag force acting on the particles. All fluid parameters are taken from the CFD mesh element, which contains the centre of the DEM particle. This model is only valid for particles of the same size or smaller than the computational mesh cell or when there is a change to the fluid parameters (velocity, density, viscosity, etc.) over the extent of the particles remaining constant.

The drag force depends on the drag coefficient ($C_D$) on the particle and is given by

$$F_D = \frac{1}{2} C_D \rho A v^2$$

where $A$ is the cross-sectional area of the particle in the plane perpendicular to the air flow direction, $v$ is the speed of the particle relative to the fluid, $\rho$ is the density of the fluid and $C_D$ is the drag coefficient. The drag coefficient ($C_D$) depends on the Reynolds number using the equation as;

$$R_e = \frac{\varepsilon_f \rho_d |v_f - v_p|}{\mu_f}$$

$$C_D = \begin{cases} \frac{24}{R_e} & R_e \leq 0.5 \\ (24/R_e)(1.0 + 0.15R_e^{0.687}) & 0.5 < R_e \leq 1000 \\ 0.44 & R_e > 1000 \end{cases}$$
where $D$ is some characteristic diameter or linear dimension and $d_p$, $\mu_f$ is the particle diameter and dynamic viscosity, respectively.

The influence of surrounding particles is usually taken into the drag model to the particle loading characteristics. Zhu et al. (2007) reviewed the models for the computing of the interaction force occur between particle and particle and between particle and fluid, the DEM and CFD coupling to describe the flow of particle and fluid in the domain and determine the drag force between particle and fluid (Ergun, 1952; Wen et al., 1966). The pressure loss during the flow through a packed bed of granular material is given a viscous energy loss and an inertia loss (kinetic energy) term (Niven, 2002). This is not suitable to apply to dilute systems. The Di Felice (1994) model is more applicable to dilute suspensions and corrects the free-stream equation for the presence of other particles by including a multiplying term, called voidage function to the drag coefficient that depends on the local porosity and flow regimes (i.e. Reynolds number). Both models require the local volume fraction around the particle to be known. Many correlations have been well established (Ergun, 1952; Wen et al., 1966; Di Felice, 1994).

The freestream drag model is the freestream drag ($F_{free stream}$) for a sphere is calculated according to:

$$F_{free stream} = 0.5 C_D \rho_f A_p (v_f - v_p) |v_f - v_p|$$  \hspace{1cm} 2.28

where $A_p$ is the cross section area of the particle. The Ergun and Wen & Yu drag model is the freestream drag equation and can be modified as follows:

$$F_D = \frac{\beta V|v||v|}{1-\epsilon}$$  \hspace{1cm} 2.29

where $V$ is the particle volume and

$$\beta = \begin{cases} \frac{150(1-\epsilon)^2}{eL^2} + \frac{1.75(1-\epsilon)\rho|v|}{L} & \text{for } \epsilon < 0.8 \\ \frac{3}{4} C_D \rho e^{-1.65}(1-\epsilon)|v| & \text{for } \epsilon \geq 0.8 \end{cases}$$  \hspace{1cm} 2.30

where $\epsilon$ is the voidage/porosity.
The Di Felice drag model adds a porosity correction term to the freestream drag model to take into account the effect on drag of neighbouring particles. The model is formulated as:

\[ F_d = F_{\text{freestream}} \varepsilon^{-(\chi+1)} \]  \hspace{1cm} 2.31

where \( F_{\text{freestream}} \), \( \chi \) and \( \varepsilon \) is the air drag force on the particle in the absence of the other particle, empirical coefficient and the porosity of the computational fluid cell, respectively and is given by

\[ \chi = 3.7 - 0.65\exp\left[-\left(\frac{1.5-\log_{10}\text{Re}_p}{2}\right)^2\right] \]  \hspace{1cm} 2.32

The fluid drag coefficient is expressed as

\[ C_d = \left(0.63 + \frac{4.8}{\text{Re}_p^{0.5}}\right)^2 \]  \hspace{1cm} 2.33

where \( C_d \) and \( \text{Re}_p \) are the fluid drag coefficient and particle Reynolds number, respectively. The fluid drag coefficient depends on geometrical properties like particle size and shape as well as dynamical properties, especially on the particle Reynolds number is calculated by the fluid density \( \rho_f \), the particle diameter \( d_p \), the relative velocity and the dynamic viscosity \( \mu_f \).

2.7.5.2 Lift Force Model

It is very difficult to study lift forces experimentally because they are governed by the instantaneous and local flow structures, as well as the boundary properties of the immersed object, represented by Pang et al. (2011). As a simplifying assumption, it is customary to consider colloidal particles as perfectly spherical and the vast majority of both experimental and modelling work considers spherical particles for which lift forces have been well studied. For spherical particles, droplets and bubbles (Dijkhuizen et al., 2010) there are two sources of lift forces consisting of the Saffman lift force (Saffman,
1965) and the Magnus lift force (Rubinow et al., 1961), which are due to the particle falling or the particle as it rotates.

Saffman (1965) indicated that for high air velocity flows around a particle, a lift force will be generated due to the velocity difference between the top and bottom of the particle. The direction of this lift force is vertical to the direction of the relative velocity of the particle and fluid. The Saffman force occurs when the particle is placed in a flow with local shear and when the particle Reynolds number is smaller than unity, which generally applies to micron-size particles represented by Ookawara (2007). It has been demonstrated by Wang (1997) and Lataste (2000) that wall effects on the Saffman lift are significant in aerosols where turbulent shear stresses are modulated near a boundary represented by Hall (1988), however it is not a concern in this work as for hydraulic suspensions the wall effect on lift is negligible (Drew, 1988). The Saffman lift force is given by:

\[
F_{LS} = 1.615(u - v_p)(\rho g\mu_g)^{0.5}d_p^2C_{LS}\sqrt{|\frac{\partial u}{\partial n}|} sgn\left(\frac{\partial u}{\partial n}\right), \quad (n = x, y, z) \tag{2.34}
\]

where \(C_{LS}\) is the Saffman lift coefficient in this study developed by Mei (1992) and calculated from the equation 2.35 is given as

\[
C_{LS} = \begin{cases} 
(1 - 0.3314\gamma^{0.5})\exp(-0.1Re_p) + 0.3314\gamma^{0.5}, & (Re_p \leq 40) \\
0.0524\gamma^{0.5}(Re_p)^{0.5}, & (Re_p > 40) 
\end{cases} \tag{2.35}
\]

where, \(\gamma = \frac{0.5d_p}{|u-v_p|}\left|\frac{\partial u}{\partial n}\right|\)

The Magnus force (Rubinow et al., 1961) accounts for the lift generated by the rotation of the particle itself, influencing the pressure and velocity differential on the surface of the particle (particle spin), which mostly applies to fluids of low viscosity that do not prevent particle spinning freely, typically gases. When the air flow is not uniform at various locations in the domain, the particle will rotate due to the velocity gradient. For the low Reynolds number, the rotation of particles will bring the fluid near the surface moving around the particle, which leads to the increasing of fluid velocity on the same side as the flow direction and the decreasing of fluid velocity on the opposite side. The
particle rotation results in an increase in the velocity on one side and a decrease on the other side. The Magnus lift force can be calculate by the following correlation (Lun et al., 1997; Lun, 2000)

$$F_{LM} = \frac{1}{8} \rho_g v_r^2 \pi d_p^2 C_{LM} \frac{\omega_r \times v_r}{|\omega_r| \cdot |v_r|}$$  \hspace{1cm} (2.36)

where $v_r$ is relative velocity between air and particle, $v_r = u - v_p$, $\omega_r$ is the rotation angular velocity between air and particle, $\omega_r = \omega_g - \omega_p$ and $\omega_g = 0.5\nabla \times u$. $C_{LM}$ is the Magnus lift coefficient. $C_{LS}$ in this study is calculated from correlation developed by Lun et al. (1997), which is expressed as

$$C_{LM} = \begin{cases} \left| \frac{\omega_r}{v_r} \right| d_p & (Re_p \leq 1), \\ \left| \frac{\omega_r}{v_r} \right| d_p (0.178 + 0.822 Re_p^{0.522}) & (1 < Re_p < 1000), \end{cases}$$  \hspace{1cm} (2.37)

The pressure gradient force in the fluid includes the buoyancy force and lift force was presented by Crowe et al. (1977) and Devahastin (1998). The pressure gradient force is given by equation 2.38.

$$F_p = -V_p \frac{dp}{dx} = -V_p \left( \rho_f g + \rho_f u \frac{du}{dx} \right)$$  \hspace{1cm} (2.38)

where $V_p$ is the Volume of the particle (m$^3$), $\rho_f$ is the fluid density (kgm$^{-3}$), $g$ is the gravitational acceleration ($ms^{-2}$) and $u$ is the velocity ($ms^{-1}$). The virtual mass force relates to the force required to accelerate the mass of the surrounding continuous phase and Basset force describes the force due to the lagging boundary layer. According to Hjelmfelt Jr et al. (1966), the small density ratios ($\frac{\rho_f}{\rho_s} \sim 10^{-3}$) are unimportant for the Basset term and virtual mass term.

### 2.7.5.3 Void Fraction Calculation

In the simulation coupling, three drag models are available: the free-stream model, the Di Felice model and the Ergun and Wen & Yu model. Each point is checked to determine which CFD mesh cell it lies within. For the drag force to be calculated on the particles in
Chapter 2: Literature Review

each mesh cell, the void fraction in the computational cell must be known and every time step of the particles entering and leaving a mesh cell. The particle (from DEM) volume fraction is the sum of all particle volumes in the mesh cell. It is useful to look for the values of particles volume fraction and velocity of a particle by each size. This requires the computation of several particles volume fractions per mesh cell. The particle volume fraction within a particular mesh cell, therefore, is the percentage of the number sample points that lie within that mesh cell, as given by:

$$\varepsilon_s = 1 - \varepsilon = \sum_{\text{particles}} \frac{n_c}{N} V_p$$  \hspace{1cm} 2.39

where $n_c$ is the number of sample points contained within the mesh cell of particle $p$ and $N$ the total number of sample points of the particle and $V_p$ is the volume of the particle.

2.7.6 Simulation Time Matching

There are several factors which closely dictate the time required to complete a DEM simulation. As computer power increases (e.g. processor speed, the number of CPU cores and RAM), faster DEM simulation outputs will result. The simulation time step used in DEM simulation is the period between two particle interactions for calculating the increasing forces and displacements for the minimum size particle within the group of particles. At all times the forces acting on any particles are determined specifically by the particle interaction with particles with which it is in contact. Small time-steps must be used in the simulation. Although the explicit numerical scheme is more computationally efficient than the implicit numerical scheme, there is a limitation that it is only conditionally stable. If the used time step is greater than a critical time step, the scheme becomes unstable and the simulation outcomes are unreliable. If the defined time step is very small, the particles will be calculated in very small intervals resulting in a very accurate calculation that will take a very long time to simulation complete. If the time step is too large, considerable particle movement can occur between two interactions causing significant particle overlap in densely packed systems resulting in erratic particle movement.
EDEM implements a fixed time-step which is a fraction of the Rayleigh time \( T_R \). The critical time step is based on the average particle size and the Rayleigh time is based on the smallest particle and is calculated using equation 2.40 (Li et al., 2005; EDEMSolutions, 2013).

\[
T_R = \frac{\pi r_p \left( \frac{\rho_p}{G} \right)^{1/2}}{(0.1631 \nu + 0.8766)^2}
\]

where \( r \) is the radius of the smallest particle in the system, \( \rho_p \) is the particle density, \( G \) the shear modulus and \( \nu \) is the Poisson’s ratio. For a system with materials of different properties, the smallest critical time step for the various materials should be chosen.

Selecting a suitable time step for running the numerical simulation is crucial for increasing the computational efficiency. DEM Solutions recommend a time step of 20% for densely packed systems and 40% for looser packed assemblies when using their DEM simulation software (EDEMSolutions, 2013). Chung et al. (2006) found that 20% of the critical time step was sufficient for the majority of systems which were predominantly quasi-static. Additionally, particle scaling can reduce the time required to complete a DEM simulation. There is a twofold way in which this can help by having a larger particle diameter, the Rayleigh time step will decrease the time needed for each simulation step and also by having larger particles, there will be fewer particles in the simulation overall, also reducing the time required. Some researchers have documented investigations in this area with positive results (Ji et al., 2006; Grima et al., 2009).

For a DEM-CFD coupling method, normally the DEM time steps are smaller than CFD time steps. Therefore, the ratios for DEM-CFD time steps vary from 1 : 10 to 1 : 100. The DEM-CFD Coupling will automatically adjust the number of DEM iterations carried out in order to match the CFD time step, \( \tau_{FLUID} \) such that:

\[
\tau_{FLUID} = \sum_{\text{iterations}} \tau_{DEM}
\]

2.8 Summary

The related literature regarding this thesis has been reviewed in this chapter. The literature reviews have shown previous studies of dust generation mechanisms using coupled
DEM-CFD, dustiness testing presented using the International Standard and Australian Standard dustiness tester, a review of DEM, parameter input to DEM and CFD coupling, granular materials of properties, the various flow regimes that may exist in a rotating drum, a review of the experimental validation of DEM simulations and experimental design methods and optimisation techniques. There are two groups of parameters input to DEM simulations consisting of material properties and interaction properties, consisting of particle shape, particle size distribution, particle density, Poisson’s ratio, shear modulus, coefficients of restitution, the coefficient of static friction and coefficient of rolling friction. In DEM-CFD coupling, the movement of particles is modelled as a discrete phase, described by Newton’s laws of motion on an individual particle and the flow of air is treated as a continuum phase.

In the next section, the calibration of DEM and experimental testing of the materials directly measured in the laboratory will be covered. All methods described in these sections will be applied to the polyethylene pellets, iron ore and coal materials considered in this work.
Chapter 3

Materials Flow in Dustiness Testers

3.1 Introduction

The previous chapter contained the literature review and presented previous works and theory related to this research. The dust generation occurring during the handling, transportation, loading and unloading of bulk materials, in free fall or impact on conveyor transfers can pose a detrimental effect to human health, communities, the environment and can also be an air pollutant. Dustiness testers are used to experimentally measure the amount of dust occurring for each material. Two standards exist, the International Standard (IS) dustiness tester (EN15051, 2006) and the Australian Standard (AS) dustiness tester (AS4156.6, 2000) and will be the methods of focus for this research. While similar in concept, there are different variables present in both standards. The dust from the IS dustiness tester is captured and evaluated as a health hazard by means of filtration whereas the AS dustiness tester records the total amount of dust captured and via calculation this mass is converted to a dust number serving the needs of materials handling, processing and manufacturing industries in an attempt to reduce losses by improving efficiency.

This chapter reports on an experimental investigation of the flow pattern of bulk material in the IS and the AS dustiness testers. The experimental component of this research consists of two sections; first, the vacuum flow in the dustiness test was excluded and the second was the air flow was allowed to interact with the materials moving in the dustiness tester. Both sections investigate four initial loading locations of material in the drums.

3.2 Methodology Analysis

The IS and the AS dustiness testers operate under different operating conditions to adhere to their respective intended purpose, see Section 2.2. These conditions have been
followed for the non-air flow and air flow methods for both dustiness testers. In the experiments, focus is on the materials flow in the dustiness tester section of each tester. The IS dustiness tester was operated only with no air flow because to successfully visualise the flow of material the rear dust collection components (see Figure 2.1(b)) had to be removed to allow light to enter the drum for video recording. The AS dustiness tester was operated with and without air flow because a light source was used from the front of the drum. Both dustiness testers were operated at their specified rotational speeds and specified volume of test sample. However, the location of the initial sample was also investigated to determine the influence of the material movement in the dustiness testers as they rotate. Four locations were trialled in each tester;

- location 1: an even spread of material from front to back of the drum,
- location 2: a heap at the front of the drum,
- location 3: a heap in the middle of the drum,
- location 4: a heap at the back of the drum.

**Note:** the distance between the top of the material heap and the end wall of the drum for the bin2 and bin4 is 40 mm for the IS dustiness tester and 75 mm for the AS dustiness tester.

In this work three materials were used in the experiments, each products sample employed in the test with four different locations, focusing on the flow pattern of materials in the IS and the AS dustiness tester when the size and shape of the material are different. The particles are difficult to observe separately in dustiness testers, therefore, this process used digital video recording to show the flow pattern of material in the two dustiness testers for three material samples based on the experimental standards.

Reviewing of both standard tests related to the dustiness testers allows for a greater understanding and overall analysis of the particles moving in both dustiness testers. This will allow insights into the equipment used to verify the theoretical background and understanding of the results obtained. Both dustiness testers have varying attributes in each standard, those including different applications for the dustiness testing, airflow, material size and test duration, as explained in Table 3.1.
Table 3.1 Dustiness tester specifications.

<table>
<thead>
<tr>
<th>Description</th>
<th>IS dustiness tester</th>
<th>AS dustiness tester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk sample size</td>
<td>35 cm³ (35 ml)</td>
<td>1 kg (coal) – or equiv. bulk volume (1 litre)</td>
</tr>
<tr>
<td>Max. Particle size</td>
<td>Not specified</td>
<td>6.3 mm</td>
</tr>
<tr>
<td>Drum Diameter</td>
<td>300 mm</td>
<td>300 mm</td>
</tr>
<tr>
<td>“Vanes” inside drum</td>
<td>25 mm high (8 off)</td>
<td>7 mm wide × 6 mm high (8 off)</td>
</tr>
<tr>
<td>Drum speed</td>
<td>4 rpm</td>
<td>29 rpm</td>
</tr>
<tr>
<td>Test duration</td>
<td>1 min</td>
<td>10 min</td>
</tr>
<tr>
<td>Drum air inlet dia.</td>
<td>150 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Air flow</td>
<td>38 litres/min</td>
<td>175 litres/min</td>
</tr>
<tr>
<td>Drum inlet air velocity</td>
<td>0.036 m/s</td>
<td>2.25 m/s</td>
</tr>
<tr>
<td>Superficial air velocity</td>
<td>0.009 m/s</td>
<td>0.04 m/s</td>
</tr>
</tbody>
</table>

To provide a direct comparison of the results of the two standardised tests, a particle size of lower than 6.3 mm as noted in the Australian Standard test is also used for the International Standard testing.

3.3 Particle Sizing Sieve Machine

Particle sizing involves the separation of the desired testing sized particles from the larger particles within bulk materials including polyethylene pellets, iron ore and coal. This separation is completed utilising a piece of equipment known as a sieve shaker and will be discussed in further detail throughout this section. The fine particles of the desired size pass through the sieve leaving the particles larger than required above the sieve. The particle size distribution (PSD) of the bulk material selected for the experimental work was of a granular nature and sieves were used to determine the PSD of each material, as shown in Table 3.2. The sieves were selected by spanning the size range of the material, as shown in Figure 3.1(a). The material sample is placed in the top sieve and all were shaken for a standard time in the sieve shaker (coarse at the top and fine at the bottom), as in Figure 3.1(b). The sieves were removed and each one weighed to determine the retained sample mass for each particle size fraction. The percentage of the material sample retained on each sieve was then used to represent the particle size distribution.

The Australian Standard requires a maximum particle size of 6.3 mm and due to practical limitations of particle sizes used in DEM Simulations. 2.0 mm was chosen as the smallest particle size. To ensure a valid comparison of the IS and AS dustiness testers, material to be tested by both standards was sieved to the same sized particles. The sieve sizes used were 5.6 mm, 4.0 mm, 3.35 mm and 2.36 mm for polyethylene pellets, and 6.3 mm, 5.6
mm, 4.0 mm, 2.0 mm and 1.0 mm for iron ore and coal materials. The sieve test was used to measure the size distribution of the material and the results are shown in Figure 3.2.

Figure 3.1 (a) Sample of sieves, (b) sieves in mechanical sieve shaker.

Figure 3.2 Particle size distribution of materials (smoothed fitted).
Table 3.2 Particle size distribution of materials.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Size Sieve (mm)</th>
<th>Avg. ∑ Mass (%)</th>
<th>% of mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene Pellets</td>
<td>4.00</td>
<td>81.83</td>
<td>81.83</td>
</tr>
<tr>
<td></td>
<td>3.35</td>
<td>97.64</td>
<td>15.81</td>
</tr>
<tr>
<td></td>
<td>2.36</td>
<td>99.84</td>
<td>2.20</td>
</tr>
<tr>
<td></td>
<td>&lt; 2.35</td>
<td>100.00</td>
<td>0.16</td>
</tr>
<tr>
<td>Iron Ore</td>
<td>6.30</td>
<td>3.38</td>
<td>3.38</td>
</tr>
<tr>
<td></td>
<td>5.60</td>
<td>18.91</td>
<td>15.53</td>
</tr>
<tr>
<td></td>
<td>4.00</td>
<td>76.75</td>
<td>57.83</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>99.78</td>
<td>23.03</td>
</tr>
<tr>
<td></td>
<td>&lt; 1.99</td>
<td>100.00</td>
<td>0.22</td>
</tr>
<tr>
<td>Coal</td>
<td>6.30</td>
<td>13.15</td>
<td>13.15</td>
</tr>
<tr>
<td></td>
<td>5.60</td>
<td>39.57</td>
<td>26.42</td>
</tr>
<tr>
<td></td>
<td>4.00</td>
<td>89.21</td>
<td>49.64</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>99.86</td>
<td>10.65</td>
</tr>
<tr>
<td></td>
<td>&lt; 1.99</td>
<td>100.00</td>
<td>0.14</td>
</tr>
</tbody>
</table>

3.4 International Standard Experiments

The testing of dustiness focuses on the flow pattern of particle movement in the International Standard dustiness tester with no air flow. The results as shown in the following sections are for the three materials tested, in four different loading locations.

3.4.1 Setup and Experiments for the IS Dustiness Tester

The material sample is placed on the bottom of the dustiness tester, rotating at 4 rpm for a period of 60 seconds. Each material is tested at all four different loading locations, as shown in Figure 3.3 and Figure 3.4 for the polyethylene pellets, iron ore and coal material samples flowing in the dustiness tester at different time steps.

3.4.2 IS Dustiness Test Procedures

The dustiness tester used in this test is based on the IS dustiness tester (EN15051, 2006), as shown in Figure 2.1. The test procedure is as follows:

1) Prepare tester setting, material samples of approximately 35cm³ by volume.
2) Place product sample in the bottom of drum.
3) Press ON/OFF button and press start button for the drum to rotate at 4 rpm.
4) After 1-minute of rotation the drum will stop automatically.
5) Clean the sample from tester.
6) Repeat the process for another material location.
3.4.3 Material Flow in the IS Dustiness Tester

All three materials tested in the IS dustiness tester were video recorded and the results for all four loading locations were captured at different time steps.

3.4.3.1 Polyethylene Pellets

The polyethylene pellets were the first material used in the IS dustiness tester, as shown in Figure 3.3. The results display all four locations of material loading and three time steps during the test. The first row shows the initial loading position of material at time 0 sec before the drum rotates. The particles start moving out from the vanes after the drum has rotated for 5 sec, which is equivalent to the vane having an angle of 7.5 degrees above the horizontal plane, as shown in Figure B3 (Appendix B). It can be seen that the material on the top of the heap is falling to the next vane in the same section and spreads on the vane. Some material drops to the top edge of the vane and rebounds to the other vanes as the drum rotates. The drum continues to rotate and the remaining material drops to the other vanes until to the end of the test (60 sec). Figure 3.3 shows the polyethylene pellets starting injection at an even spread from the front to back (the first column), at the front (second column), at the middle (third column) and at the back (fourth column) of the drum. The experiment runs for 60 sec, after 5 sec the material flows every 2 sec from the vanes. For material loading at the middle, the particles spread evenly along the full length of the vanes after one revolution, while for the front and the back heap, the particles spread after 3 revs of drum rotation.
3.4.3.2 Iron Ore and Coal

The experimental iron ore and coal results in the IS dustiness tester are shown in Figure 3.4. Both materials were tested at four loading locations and results captured at two time steps. The first time step shows the material sample beginning to fall from the vanes and continue this process until the end time (4 revs). The iron ore material flow in the IS dustiness tester, is shown in Figure 3.4(a). The material is moving out from the vanes at 19.5 degrees above the horizontal plane (after the drum rotates 5.5 sec) for the front, back and middle heaps, while for the even spread, material moves out from the vanes after the drum rotates 5.7 sec (the vane being 24.3 degrees above the horizontal plane). The irregular shape of material interlocked with other particles, which reduced the rolling and sliding friction. Therefore, the angle of the vanes is higher than the polyethylene pellets of 15 degrees, approximately. It can be seen that the material at the top of the heap falls to the next vane in the same section and spreads on the vane. Some material falls to the top edge of the vanes and rebound to free space and as the dustiness tester continues rotate, the remaining material drops to the lowest vane. The material continues to flow for 4 revs (60 sec), then the material stays on the three vanes without the material falling to the bottom of the drum. Figure 3.4(b) displays the coal material flow in the IS dustiness
The material sample moves out from the vanes at a lower angle than the iron ore material by 5 degrees, approximately. Both materials showed very similar trends of material flow in the dustiness tester after the drum had rotated 3 revs. It can be seen that for all material loading positions, the continuous motion of particle samples show a very similar trend of particle flow after 4 revs (t = 60 sec).

3.5 Australian Standard Experiments

The testing of dustiness focuses on the flow pattern of particles in the Australian Standard dustiness tester with non-air flow and air flow. The result as shown in this section are for the three materials with four loading locations.

3.5.1 Setup and Experiment for the AS Dustiness Tester

The AS dustiness tester has been constructed from stainless steel, the drum has a vertical front wall and tapered at the back, the front stainless steel plate has been replaced with an equivalent dimension Perspex plate to allow visual inspection of the particle rotation within the dustiness tester. Material sample of 1000 cm$^3$ is placed on the bottom of the drum and is rotated at 29 rpm for a period of 10 minutes. Each material has been tested with four different loading locations, as shown in Figure 3.5 and Figure 3.6 for three materials flow with non-airflow and Figure 3.7 for the material samples moving with air flow in the dust generation section.
Chapter 3: Material Flow in Dustiness Testers

Figure 3.4 Materials flow in the IS dustiness tester with four loading locations and two time steps for (a) iron ore and (b) coal.

3.5.2 AS Dustiness Test Procedures

The dustiness tester used in this test is based on the AS dustiness tester (AS4156.6, 2000) as shown in Figure 2.2. The test procedure is as follows:

1) Prepare tester settings, material samples of approximately 1000 cm³ by volume.
2) Ensure the drum is clean, the rotation speed is correct, using the tachometer and adjusting motor speed if necessary. The required drum speed is 29 rpm.
3) Place product sample in the bottom drum.
4) Press ON/OFF button and start fan for the tests with air flow.
5) Press start button to rotate the drum and record the time with a stopwatch.
6) After 10 minutes, stop drum motor and stop fan 13 sec later.
7) Empty sample and clean inside the drum.
8) Repeat the process for another material and location.

Note: For the test with non-air flow in the AS dustiness tester, ignore step 4.
3.5.3 Material Flow in the AS Dustiness Tester: Non-Air Flow

There are three materials were tested in the AS dustiness tester with non-air flow, the results for four material loading locations were analysed and results captured at two different times.

3.5.3.1 Polyethylene Pellets

The polyethylene pellets moving in the AS dustiness tester are shown in Figure 3.5. The initial heap (time = 0 sec) of material sample at the four initial locations is demonstrated in the first column. The next columns show the drum rotation at 10 sec and 60 sec. The particles are sliding on the free surface when the drum rotates from the bottom to 90 degrees. Also, the materials drop from the vanes after the drum has rotated 10 degrees to 55 degrees from the horizontal plane. The observation from the captured image consists three sections. The broad zone is the top free surface of the material sample moving in the opposite direction to the drum rotation, the velocity of the particles depend on the density, especially the coefficient of friction and the shape of the material sample. Also, materials close to the wall surface is a small zone where product samples moving in the same direction as the drum rotates. Finally, in the middle is the smallest zone, the particle velocity is very close to 0 m/s, the material in this zone is close to stationary.

3.5.3.2 Iron Ore and Coal Flow in the AS Dustiness Tester

The iron ore and coal material flow in the AS dustiness tester is shown in Figure 3.6. There are two different time steps shown, the materials dropping from the vanes to the free surface at time $t = 0.5$ sec and at time $t = 10$ sec the materials continue to separate evenly along the full drum for both two materials. Both materials were tested at four loading locations, the same as for the polyethylene pellets. The particles start moving out from the vanes after the drum rotates 20 degrees from the horizontal plane ($at \ t = 0.5$ sec). It can be seen that the material moves on the free surface to the bottom of the heap in the same section. The material heap rises with the lifting vanes and then tumbles back to the bottom and repeats process for the entire test. As the drum continues to rotate to 55 degrees (from the horizontal), approximately, the material moves out from the vane dropping to the free surface, as shown at 10 sec of the drum rotation. The experimental
results for all four material loading locations and both materials showed very similar trends in the AS dustiness tester after 10 sec of drum rotation.

3.5.4 Materials Flow in the AS Dustiness Tester: With Air Flow

Three materials were used in the AS dustiness tester, investigating the materials moving and air flow pattern in the dustiness tester. To generate dust in the AS dustiness tester there must be an airflow within the system. Figure 3.7 illustrates the three materials moving with airflow in the dustiness tester, with four different loading locations and different time steps. The material falling from the vanes dispersed and moved to the back section of the drum, particularly, the small materials of the iron ore and coal as the drum rotated. The velocity of particles is based on the velocity of air from the inlet section of the drum (front) to the back section. The polyethylene pellets are very close to monosized, it is very hard to look at the materials moving with the air effect. However, the iron
ore and coal have several shapes and sizes and segregation was seen in the drum and impacts during rotation produced small particles and dust. At the start of the test, the smaller particles percolate through the larger particles and as the drum rotates the material moving by vanes and falling to the free surface, these small particles end up on the top of the material and are captured by the airflow.

Figure 3.6 Materials flow in the AS dustiness tester with four loading locations and two time steps for (a) iron ore and (b) coal.
3.5.5 Material Segregation in the Dustiness Tester

Differences of particle size, density, and shape of the particles moving in the drums all contribute in causing segregation in the rotating drum (Williams, 1976). The coefficient of friction affects particle movement by particle size and particle shape. Bulk density has
more influence on the motion of particles, as the forces vary with different particle masses (Hogg, 2009).

Experiments were conducted for iron ore and coal placed in the IS and AS dustiness testers containing particles of differing size and shape and revealed alternating axial bands. The size segregation appears to be an important prerequisite of axial segregation. On a long time scale, in the dustiness tester, travelling wave patterns are obtained. For the dustiness test, all sizes of particles mix and pour on the bottom wall of the dustiness tester. As the drum rotates, the basic mechanism of flow of the particle size difference between small and large are segregation in the axial direction. The small particles flow on the free surface and they move to the void between large particle size until to the wall surface of the drum. In the axial direction it was found that the smaller particle size segregates to the middle of the dustiness tester. The surface angle of repose reduces for the small particles in the cylinder and near the middle of the drum shows the smaller surface angle. Particle shape also affects particle movement and is a cause of segregation.

Figure 3.8 shows material segregation in the axial direction for the iron ore and coal materials at three time steps as well as with and without air flow in the AS dustiness tester. The IS tester was not used due to the relatively small material samples used. The size segregation after the drum had rotated 60 sec to the end time it show is three bands (large-small-large) for both materials and both the non-airflow (see Figure 3.8(a)) and airflow (see Figure 3.8(b)).
Figure 3.8 Material segregation in the axial direction for iron ore and coal flow in the AS dustiness tester (a) non-air flow (b) with air flow.
After testing, the product was removed from the drum in five equal sections in the axial direction, shown in Figure B2 (Appendix B) and equivalent to the bins used in the numerical simulations presented later. The material samples were mechanically sieved to identify the quantity of small particles in each section of the drum. Figure 3.9 shows the influence of the movement of iron ore and coal in the dustiness tester with and without airflow. Both materials have similar material shape and size but have different density. Therefore, the percentage of small particle segregation in the AS drum is different. Both materials flow in the AS drum, as shown in Figure 3.8, sieve the small size fraction of materials (≤ 2.0 mm) for the five bin sections, as shown in Figure B2 (Appendix B) and shown in the results in Figure 3.9. It can be seen that the small material moves to the middle section of the drum (bin3) after 3 mins and begins to level towards the end time (10 mins) of the drum rotation. Also, the number of small sized particles at the back section (bin4) is higher than the front (bin2) section. There are two issues present causing this result, the percentage of small sized particles is uneven on the heap as the drum rotates and the drum has slight wobble due to method of manufacture. This causes a non-symmetrical movement of particles in the drum. The percentage of the small size of iron ore movement to the middle section with air flow is faster than without air flow in the dustiness tester as shown in Figure 3.9(a). For the coal material flow in the AS dustiness tester, as shown in Figure 3.9(b) most small particles move to bin3 for the drum with non air flow while the drum rotating with air flow causes the small material to move to bin4. The results are an effect of the materials properties (especially density) and the amount of each material size fraction in the experimental tests.

Figure 3.9 Material segregation in axial direction of the AS dustiness tester (a) iron ore (b) coal.
3.6 Conclusion

Both dustiness testers were used to investigate the particle flow mechanisms of three different granular materials. Three materials were tested in the IS and the AS dustiness testers and the results compared for the particle flows pattern in the dustiness tester at several time steps. The flow pattern of the three materials is very similar for the experiments without airflow. The coefficient of friction (sliding and rolling), especially, the particle shape and size of materials had the most effect on the material flow in the dustiness testers. The polyethylene pellets are faster than other materials falling from the vanes due to their shape. The iron ore and coal materials have very similar results for the particle flow pattern, as they have very similar shape, but different density. The lower density materials fall faster from the vanes than the higher density material; observed from the two materials with four locations of the particle heap. The material from the front and back initial loading positions spread along both drums during the test and the results are very similar. Material at the top of the initial middle heap moved down to the bottom in both axial directions and in the radial direction as the drum rotated.

For the IS dustiness tester, the polyethylene pellets loaded at the front and the back of the dustiness tester, spread along the full vanes by the end of the test. On the other hand, for iron and coal, there was not enough time for the materials to spread along the vanes in the dustiness tester by the end of the test. The result were affected by the friction between material-material and material-wall in the drum, and the material shape is the most different between polyethylene pellets and the other two materials. For the AS dustiness tester, steady-state had been reached after 10 sec and all the material continued to spread evenly along the full drum and showed similar results for three materials. The small size segregation of the materials movement to the middle section of the AS dustiness tester after 180 secs.
Chapter 4

Material Characterisation for DEM Calibration

4.1 Introduction

This chapter presents the experimental methods used for the DEM calibration process to develop the parameter values for the calibrated DEM particle models. The accuracy of DEM models depends on the mechanical and physical parameters, hence, the calibration of the DEM parameters is critical in obtaining realistic simulation results. The parameters that are required in the DEM simulations are particle shape and particle size, Poisson’s ratio, shear modulus and particle density are possible with available tests. The interactions between particle and particle and between particle and geometry consist of; coefficient of restitution, coefficient of static friction and coefficient of rolling friction. The tests used to characterise a granular material and the experiments developed to create representative granular material flow behaviours to match against DEM models will be calibrated using experimental results. Four laboratory devices were previously developed to provide a range of calibration data for the proposed calibration methodology. The inclination shear tester, angle of repose tester, drop test and loose poured bulk density were used to determine the material internal friction angle, interaction between the material and geometry and interaction between the material and material. The inclination tester results were found to be dependent on both the coefficients of static friction and rolling friction between particle and wall surface. In addition, the angle of repose of the particle heap depends on the coefficient of static and rolling friction occurring between each particle. Moreover, the drop test of particles found the coefficient of restitution between particle and particle, and particle and wall interaction. The loose poured bulk density to confirm of the particle shape model. The particle size was the same as the real material, and the particle shape was modelled using both a single sphere and spherical clusters rigidly fastened together to form a shaped particle representation. The following sections also
describe in detail various interaction properties for different particle shapes and sizes as well as the loose poured bulk density, coefficient of static friction, coefficient of rolling friction, concentrating on the inclination tester, swing arm slump tester and other devices. Regarding the properties of materials of the polyethylene pellets, iron ore and coal, they will be explained in terms of material physical and mechanical properties as well as each materials’ characterisation. The validation of the three materials was performed by DEM, where the DEM output matched with the experimental results. As a results, the particle size, shape, material properties and material interactions between the particle and between particle and geometry have been determined.

4.2 Material Properties

This section describes and summarises the laboratory measurements of the three materials used in this thesis. The material properties were either determined through a set of laboratory tests or referenced from the literature. The material properties included; Poisson’s ratio, solid density, shear modulus, particle size, particle shape, the coefficient of restitution, the coefficient of static friction and coefficient of rolling friction.

The granular materials used in this thesis include polyethylene pellets, iron ore and coal. Polyethylene pellets are widely used in DEM research (Boateng et al., 1996; Ding et al., 2001; Hastie et al., 2010; Grima et al., 2011) as they are relatively easy to model in DEM simulations that use spheres and spherical clusters to represent the material sample. The polyethylene pellets used in this thesis are nearly mono-sized with an average equivalent diameter of 4.54 mm that has been determined by experimental averaging. The measured widths were 3.84 mm, 3.62 mm diameter (max and min) and particle length was 4.56 mm of 50 random particles. Iron ore and coal have been chosen as they are representative of industrial products where DEM simulation is becoming more common to determine handling characteristics. Granular materials such as iron ore and coal can fracture and abrade during handling, loading and unloading and transportation generating fine material and dust as a result. This is especially important for this research focusing on dustiness testers.

Understanding the details of a granular system is important when trying to simulate the system model, that it is on the micro (particle) or macro (bulk) sizes. One thing that is
especially important is to correctly represent the properties of granular materials. The material properties of a typical granular material may be grouped into two categories; physical and mechanical. Physical properties refer to properties of a material that can be determined without altering its size and shape or density, for example; geometric shape descriptors, mass and density of materials. Mechanical properties refer to the material properties and their plastic and elastic behaviour when a force is applied, such as; shear modulus, Poisson’s ratio and contact friction.

The optimisation procedure developed to calibrate DEM models described in this chapter was developed to apply to a wide range of materials, thus polyethylene pellets, iron ore and coal materials were chosen, as shown in Figure 4.1.

Figure 4.1 Images of various granular materials (a) polyethylene pellets (b) iron ore and (c) coal material.
4.2.1 Particle Physical Properties

Three material samples were available for conducting the experiments used to investigate particle volume, particle weight, particle shape, solid density and bulk density. A series of bench-scale tests were required to determine the particle and bulk properties. The test data was then used in the analytical modelling and discrete element modelling simulations as well as being used to create the beginnings of the particle database.

![Material samples](image)

**Figure 4.2** Material samples (a) polyethylene pellets (b) iron ore (c) coal.

Polyethylene pellets were selected as the first test material due to their consistency. This material is highly free-flowing, non-cohesive, non-adhesive and has a sphere-cylindrical shape and are non-dusty, as seen in Figure 4.2(a) with size of 4.5 mm approximately. Iron ore and coal have more dust generation in the experiments for the two standard dustiness testers. The samples of these materials were randomly selected from the large granular samples. The material samples were taken in the size range 2.0 – 6.3 mm to investigate the possible material flow of different size fractions (see Figure 4.2b and c). Also, the measurement of particle size, particle shape, particle weight, particle volume, particle density and loose-poured bulk characteristics are presented in the following section.

4.2.1.1 Particle Sizing Sieve Machine

Particle sizing of the material used in this work including polyethylene pellets, iron ore and coal are described more detail in Section 3.3 for the size range from 5.6 mm, 4.0 mm, 3.35 mm, 2.36 mm for polyethylene pellets and 6.3 mm, 5.6 mm, 4.0 mm, 2.0 mm and 1.0 mm for iron ore and coal materials.
4.2.1.2 Particle Shape Descriptors

The shape of three individual material samples (polyethylene pellets, iron ore and coal) was approximated by measuring 50 particles (Hastie et al., 2009) randomly selected from the bulk material to determine particle shape. Subsequently, the average volume for one particle was determined for each material based on averaging. Iron ore and coal materials are quite irregular in shape and do not match any of the geometric primitives easily. A significant number of shape parameters may be required to describe them accurately. Practical measurements show that the various shapes may broadly be characterised by specifying selected orthogonal axes. Figure 4.3 can be characterised by using the linear dimensions along the three orthogonal axes; length, width and thickness. These dimensions usually range in size from the largest to the smallest. Therefore, it is proposed to refer to the length, width and thickness as the major, intermediate and minor dimensions respectively.

![Image](image.png)

**Figure 4.3** Definitions of particle length, width and thickness dimension using with (a) polyethylene pellets (b) iron ore (c) coal material.

Measurement of the three key dimensions was taken for each particle corresponding to the particles major axis and two perpendicular diameters (intermediate and minor diameter) for the polyethylene pellets, iron ore and coal. The mean particle diameters were taken as the average of all the recorded dimensions. The equivalent volume diameter is the diameter ($D_{evd}$) of a sphere having the same volume as the particle being measured and calculated via equation 4.1, where 50 particle volumes were measured to achieve a representative value.

$$D_{evd} = \left( \frac{6V_p}{\pi} \right)^{1/3} = 1.241(V_p)^{1/3} \quad 4.1$$

The particle dimensions for the various materials were measured with a Vernier caliper and are summarised in Table 4.1. The aspect ratio $a_r$ of a particle is defined as the ratio
between major and minor dimensions. The coefficient of variance (COV) is defined as
the ratio of the standard deviation to the mean in this study.

### Table 4.1 Dimensions of material samples.

<table>
<thead>
<tr>
<th>Material</th>
<th>Major (mm)</th>
<th>Intermediate (mm)</th>
<th>Minor (mm)</th>
<th>$D_{evd}$ (mm)</th>
<th>$a_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene Pellets</td>
<td>avg 4.54 COV 6.75 %</td>
<td>3.85</td>
<td>2.66 %</td>
<td>3.62</td>
<td>4.56</td>
</tr>
<tr>
<td>Iron Ore</td>
<td>avg 7.40 COV 12.65 %</td>
<td>5.16</td>
<td>7.88%</td>
<td>4.99</td>
<td>6.58</td>
</tr>
<tr>
<td>Coal</td>
<td>avg 7.97 COV 6.98 %</td>
<td>4.82</td>
<td>7.39%</td>
<td>4.43</td>
<td>6.34</td>
</tr>
</tbody>
</table>

avg: Average, COV: coefficient of variance, $a_r$: aspect ratio, $D_{evd}$: equivalent volume diameter

#### 4.2.1.3 Individual Particle Weight and Particle Volume

A total of 50 particles were randomly selected and weighed using a scale with an accuracy of ±0.01g. The particle volume of the polyethylene pellets was calculated from the equivalent volume diameter. In the case of iron ore and coal, their shapes were more irregular and dimensions hard to determine in the same way as the polyethylene pellets, therefore 50 particles were submerged in a known volume of water. This method also assumes the particles are non-porous. The volume of solids is determined by using the volume of the water change. This change in volume was equivalent to the total volume of 50 particles of each material samples. The average mass and volume for one particle could then be determined and is summarised in Table 4.2.

### Table 4.2 Average individual particle mass and volume.

<table>
<thead>
<tr>
<th>Material</th>
<th>avg Mass (g)</th>
<th>avg Volume (cm$^3$)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene pellets</td>
<td>0.04</td>
<td>0.047</td>
<td>50</td>
</tr>
<tr>
<td>Iron ore</td>
<td>0.15 - 0.60 (0.276)</td>
<td>0.101</td>
<td>50</td>
</tr>
<tr>
<td>Coal</td>
<td>0.06 - 0.24 (0.132)</td>
<td>0.107</td>
<td>50</td>
</tr>
</tbody>
</table>

The individual weight distributions of the materials are presented as a point in Figure 4.4. The individual masses for the polyethylene pellets appear to follow a normal distribution from 0.02 to 0.06 g, and the frequency of more than 30% occurs at 0.04 and 0.05 g. In addition, the iron ore material distribution is from 0.15 g to 0.6 g, 3% higher frequency close to 0.3 g, as seen in Figure 4.4(b). Furthermore, the coal has a height frequency in the range 0.1 g to 0.2 g (see Figure 4.4(c)).
4.2.1.4 Particle Density ($\rho_p$)

Density is the ratio of mass per unit volume and can be divided into two groups. The determination of particle density does not include the void space between particles. The density of the geometry material used in this study has been sourced from the literature, with a solid density of 1200 $kg/m^3$ (3DCAM, 2014) for the perspex acrylic and 8000 $kg/m^3$ (Harris et al., 1999) for stainless steel.

The solid particle density of a granular material is determined by measuring the material volume and known material sample mass, randomly taken from the bulk material. The mean granular density of the material sample is determined by using a manually controlled stereo pycnometer tester (see Figure 4.5) and the result is shown in Table 4.3. The material sample is placed in the pycnometer and subjected to known gas pressures, then the density is derived from the evaluated volume and mass. The change of the gas volume inside the pycnometer was determined by the position of the movable frictionless mercury plug. Thus, the volume of the gas was determined and subtracted from the volume of the pycnometer, the result was the volume of the sample.

Figure 4.5 Stereo pycnometer machine.
Table 4.3 Various granular material solid densities.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \rho_s ) (avg), (kg/m(^3))</th>
<th>COV</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene pellets</td>
<td>907.6</td>
<td>0.22 %</td>
<td>6</td>
</tr>
<tr>
<td>Iron ore</td>
<td>3867.8</td>
<td>0.26 %</td>
<td>8</td>
</tr>
<tr>
<td>Coal</td>
<td>1422.4</td>
<td>0.41 %</td>
<td>8</td>
</tr>
</tbody>
</table>

avg : Average, COV: coefficient of variance, n: number of tests, \( \rho_s \); solid density

4.2.1.5 Loose-Poured Bulk Density (\( \rho_b \))

The loose-poured bulk density is calculated as the mass of the granular material sample divided by the total volume of the granular material sample including the void between each particle of material. In this thesis, the mass and volume of the materials sample was investigated by weighing a container of known volume without the material and then gently pouring material into the container until it is full. The material was poured through a conical hopper and allowed to fall a fixed height of 50 mm approximately to 1000 cm\(^3\) cylindrical container. Excess material was removed using a ruler to scrape slowly across the top of the cylindrical container, without disturbing the particles settled loosely in the container. This known mass of material in the container is then determined by mass scale. The loose-poured bulk density is then calculated as the mass of the material sample divided by the volume, using the following equation 4.2. This procedure was repeated numerous times to obtain an average loose-poured bulk density.

\[
\rho_b = \frac{\text{Mass}_{\text{solid}}}{\text{Volume}_{\text{total}}} \tag{4.2}
\]

The average loose-poured bulk densities and void ratios for the three materials are summarised in Table 4.4. The void ratios is defined as the ratio of the volume of voids to the volume of solids, gives another form of mass balance for a volume of solids, can be calculated from \( e = (\rho_p - \rho_b)/\rho_b \).

Table 4.4 Bulk density and void ratios for various granular materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \rho_b ) (avg), (kg/m(^3))</th>
<th>COV</th>
<th>e</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene pellets</td>
<td>531 – 533 (532)</td>
<td>0.15%</td>
<td>0.57</td>
<td>7</td>
</tr>
<tr>
<td>Iron Ore</td>
<td>1465 - 1489 (1475)</td>
<td>0.60%</td>
<td>0.36</td>
<td>7</td>
</tr>
<tr>
<td>Coal</td>
<td>689 – 706 (697)</td>
<td>1.03%</td>
<td>0.48</td>
<td>5</td>
</tr>
</tbody>
</table>

avg: Average, COV: coefficient of variance, e: void ratio, n : number of tests
The low coefficient of variance highlights the test’s repeatability. However, the limited range of particle size from 2.36 mm to 4.00 mm for the polyethylene pellets and 5.60 mm to 6.30 mm for the iron ore and coal materials are also taken into consideration.

4.2.2 Particle Mechanical Properties

The mechanical properties for the polyethylene pellets, iron ore and coal materials were acquired through a combination of laboratory tests and from literature.

4.2.2.1 Poisson’s Ratio ($\nu$) and Material Shear Modulus ($G$)

Poisson’s ratio and shear modulus are parameters required in DEM simulations. Poisson’s ratio ($\nu$) is a measure of the ratio of lateral to axial strain provided they both fall in the range of Hooke’s law (Shigley, 1986), see equation 4.3.

$$\nu = -\frac{\text{lateral strain}}{\text{axial strain}}$$  \hspace{1cm} 4.3

The shear modulus ($G$) is an indication of the stiffness of a material. The shear modulus is represented by equation 4.4, where $E$ is Young’s modulus and $\nu$ is Poisson’s ratio.

$$G = \frac{E}{2(1+\nu)}$$  \hspace{1cm} 4.4

The values for the shear modulus and Poisson’s ratio for the materials being used in this thesis were unable to be determined due to a lack of suitable test equipment. Approximate shear modulus values and values of Poisson’s ratio for the test materials were sourced from various locations, as referenced in Table 4.5.

<table>
<thead>
<tr>
<th>Material</th>
<th>Shear modulus, $G$ (GPa)</th>
<th>Poisson’s ratio, $\nu$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene pellets</td>
<td>0.117</td>
<td>0.45</td>
<td>(Lardner, 1972)</td>
</tr>
<tr>
<td>Iron ore</td>
<td>1.926</td>
<td>0.41\textsuperscript 1</td>
<td>(Garg, 1973)</td>
</tr>
<tr>
<td>Coal</td>
<td>0.9</td>
<td>0.35</td>
<td>(Greenhalgh et al., 1986; Khandelwal et al., 2009)</td>
</tr>
<tr>
<td>Acrylic (Perspex)</td>
<td>1.4</td>
<td>0.37 – 0.39\textsuperscript 2</td>
<td>(3DCAM)</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>193</td>
<td>0.29</td>
<td>(Harris et al., 1999)</td>
</tr>
</tbody>
</table>

\textsuperscript 1 unfrozen permafrost containing iron ore, \textsuperscript 2 at room temperature
4.2.2.2 Coefficient of Restitution (CoR)

The simplest method to estimate the coefficient of restitution (CoR) is dropping a particle from a specified height onto another particle or wall surface material and measuring the height of rebound. The experimental procedure used to test the coefficient of restitution consisted of dropping 25 particles from a height of 150 mm, 200 mm and 250 mm onto a sample wall surface. Material sheets are 150 mm square sheets made of polyethylene pellets, iron ore, coal, stainless steel and acrylic perspex, as seen in Figure 4.6. Each examined particle was held in position by a vacuum pump then released at the initial height \( h_i \) above the wall surface. The particles fell freely until impacting the wall surface and bounced to a height \( h_r \), as shown in Figure 4.7. The results were extracted from images taken during the experiment using a high-speed digital video camera to record particles falling and rebounding on each wall surface. The value of coefficient of restitution (CoR) was computed as the ratio of the square root of the height of rebound \( h_r \) trajectories that were vertical (particles not rotating) and the initial height of drop \( h_i \) and can be obtained using equation (4.5).

\[
CoR = \sqrt{\frac{h_r}{h_i}}
\]  

\[4.5\]

Figure 4.6 Coefficient of restitution test (a) drop test machine (b) plate sheet of test material (1) polyethylene pellets (2) iron ore (3) coal (4) stainless steel (5) acrylic perspex sheet.
A potential issue with the measurement of the coefficient of restitution results from the irregular shape of materials. Spherical particles would rebound vertically, providing an accurate measurement of height, but irregularly shaped particles would potentially rebound with a varied angular component (Hastie, D.B., 2013; Wang L et al., 2015). In this thesis, 25 particles that rebounded close to vertical (within 10 degree of vertical) were used in this analysis. The document can be divided into two groups of coefficient of restitution included the particle–particle \((\text{CoR}_{p,p})\) and the particle–wall or environment \((\text{CoR}_{p,w})\). The experimental results for the three test materials are presented in the Table 4.6.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>(\text{CoR})</th>
<th>avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene pellets - Polyethylene pellets plate (Figure 4.6(b1))</td>
<td>0.617 – 0.690</td>
<td>0.654</td>
</tr>
<tr>
<td>Polyethylene pellets - Stainless steel plate (Figure 4.6(b4))</td>
<td>0.655 – 0.674</td>
<td>0.664</td>
</tr>
<tr>
<td>Polyethylene pellets - Perspex Acrylic plate (Figure 4.6(b5))</td>
<td>0.665 – 0.670</td>
<td>0.668</td>
</tr>
<tr>
<td>Iron ore - Iron ore plate (Figure 4.6(b2))</td>
<td>0.220 – 0.295</td>
<td>0.258</td>
</tr>
<tr>
<td>Iron ore - Stainless steel plate (Figure 4.6(b4))</td>
<td>0.192 - 0.346</td>
<td>0.269</td>
</tr>
<tr>
<td>Iron ore - Perspex Acrylic plate (Figure 4.6(b5))</td>
<td>0.423 – 0.475</td>
<td>0.449</td>
</tr>
<tr>
<td>Coal - Coal plate (Figure 4.6(b3))</td>
<td>0.525 – 0.575</td>
<td>0.55</td>
</tr>
<tr>
<td>Coal - Stainless steel plate (Figure 4.6(b4))</td>
<td>0.590 – 0.610</td>
<td>0.60</td>
</tr>
<tr>
<td>Coal - Perspex Acrylic plate (Figure 4.6(b5))</td>
<td>0.550 – 0.610</td>
<td>0.58</td>
</tr>
</tbody>
</table>

\(\text{CoR}\) : Coefficient of Restitution, avg : Average of coefficient of restitution

### 4.2.2.3 Coefficient of Sliding Friction \((\mu_s)\)

Many researchers have attempted to measure the coefficient of friction between particle and particle and particle and boundary (Lorenz et al., 1997). However, the granular material previously tested is almost all limited to spherical or nearly spherical particles.
and may not be suitable for irregularly shaped particles. Therefore, the literature on the measurement of friction coefficient for irregularly shaped particles is scarce. In this thesis, the sliding friction angle between the granular material and boundary was determined using a sliding friction tester (see Figure 4.8). The inclination test rig is used to find the coefficient of friction between the granular material sample and the wall surface material. Three material samples and five plates were used in this section and can be divided into two interaction groups such as friction that occurs between particle to particle \( \mu_s(p,p) \) and particle to the wall \( \mu_s(p,w) \).

Particle samples were placed on the inclined surface of the test plate material sample, as illustrated in Figure 4.8. The inclination of the test plate is slowly increased around the hinge using the motor drive at a constant speed until the particles begin to slip or sliding occurs. At this point, the inclination angle was recorded and the test was repeated numerous times with different particles of random size and shape to obtain an average angle of slip \( \theta \) and then the coefficient of sliding friction, \( \mu_s \) was calculated by equation 4.6.

\[
\mu_s = \tan(\theta)
\]  

To approximate the static friction between two particles material \( \mu_s(p,p) \), a simple inclination test used the test plate for the polyethylene pellets, iron ore and coal. Meanwhile, the static friction between particles and a boundary or wall \( \mu_s(p,w) \) has been estimated by conducting a wall friction test using the test plate for acrylic Perspex and stainless steel. The five plates for the various wall materials, shown in Figure 4.6(b) were secured to the test rig. The results of these experiments are presented as an average from five tests as show in Table 4.7.
Table 4.7 Coefficient of static friction values of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \mu ) (low – high)</th>
<th>( \mu ) (Average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene pellets - Polyethylene pellets plate</td>
<td>0.275 – 0.420</td>
<td>0.347</td>
</tr>
<tr>
<td>Polyethylene pellets - Stainless steel plate</td>
<td>0.274 – 0.317</td>
<td>0.277</td>
</tr>
<tr>
<td>Polyethylene pellets - Perspex plate</td>
<td>0.280 – 0.410</td>
<td>0.300</td>
</tr>
<tr>
<td>Iron ore - Iron ore plate</td>
<td>0.540 – 0.620</td>
<td>0.580</td>
</tr>
<tr>
<td>Iron ore - Stainless steel plate</td>
<td>0.300 – 0.370</td>
<td>0.330</td>
</tr>
<tr>
<td>Iron ore - Perspex plate</td>
<td>0.300 – 0.400</td>
<td>0.348</td>
</tr>
<tr>
<td>Coal - Coal plate</td>
<td>0.520 – 0.715</td>
<td>0.600</td>
</tr>
<tr>
<td>Coal - Stainless steel plate</td>
<td>0.360 – 0.450</td>
<td>0.400</td>
</tr>
<tr>
<td>Coal - Perspex plate</td>
<td>0.410 – 0.460</td>
<td>0.430</td>
</tr>
</tbody>
</table>

Note: the parameter average from the 5 tests

4.2.2.4 Angle of Repose (AoR)

The angle of repose is the steepest angle at which a sloping surface is formed of loose material when stable (Grima et al., 2011; Nakashima et al., 2011). The angle of repose (AoR) for the conical deposition of granular material is assumed to be an average of two angles (\( \alpha_1 \)) at left and (\( \alpha_2 \)) at right will be calculated by equation 4.7, as shown in Figure 4.9.

\[
AoR = \frac{1}{2} (\alpha_1 + \alpha_2) = \frac{1}{2} \left[ tan^{-1} \left( \frac{BD}{AB} \right) + tan^{-1} \left( \frac{BD}{BC} \right) \right]
\]

4.7

The angle of repose of material is poured onto the flat horizontal wall a heap formed in the range 0°–90°. The internal angle between the surface of the particle heap and the flat horizontal wall is related to the particle density, particle surface area, particle shapes of the material sample, the coefficient of friction and coefficient of rolling friction. This angle is equal to the arctangent of the coefficient of static friction (\( \mu_s \)) between the surfaces.

![Figure 4.9 Definition of angle of repose.](image-url)
4.2.2.4.1 Translating Slump Tube Tester

A simple test to study the influence of the static friction and rolling friction between each particle on the formation of granular heap is a translating slump tube test, where particles are loosely poured into a cylindrical tube with 60 mm inner diameter, 185 mm high and is then lifted up in the vertical direction at 7 mm/s via a pneumatic cylinder to allow the particle to form a heap under gravitational forces. A ring of 150mm inner diameter is placed beneath the tube and filled with same material to form an initial bed of particles below the tube. Figure 4.10(a) shows the experimental setup of the translating tube in the laboratory, which consists of a pneumatic cylinder with a long stroke connected to an acrylic tube.

4.2.2.4.2 Swing Arm Slump Test

The swing arm slump test provides information regarding the internal flow mechanisms of a granular material such as inter-particle rolling friction, sliding friction and cohesion. Interaction between particles including sliding and rolling friction is a good indicator of the inter-particle friction by the swing arm slump test. The ability to separate the effects of rolling friction in a physical test is very useful in the calibration of particle properties in DEM simulations. Figure 4.10(b) shows the experimental setup of the swing-arm tester that consists of a split tube attached to a swing arm mechanism. The swing arms rotate around a fixed connection using a simple linkage connected to a pneumatic cylinder where the cylinder rod retracts controlled by a pressure regulator and speed controllers. The split acrylic tube has dimensions of 60 mm I.D. and 185 mm height and a 150 mm I.D. ring is placed beneath the split tube and filled with particles to form a bed of particles below the tube. The tester is designed so that the swing-arms pull away from the granular material rapidly to minimise the interaction between the material sample and tube. In this test, the material sample in the split tube cylinder is 180 mm high, with the split tube rotating around the fix point at 15 rpm and materials form a heap on the base ring, after which the angle of repose can be measured.
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![Experimental setups](image)

**Figure 4.10** Experimental setups (a) translating slump tube tester (b) swing-arm slump tester (Grima, 2011).

Five tests for each granular material were conducted. Each test was captured by a digital camera at four sides including front, back, right and left side of the granular heap. The average results from the four sides of the granular heap are shown in Table 4.8, showing the angle of repose ($\text{AoR}$) and height of the granular heap ($h_p$). Only the swing arm tester was used to measure the angle of repose for iron ore and coal.

<table>
<thead>
<tr>
<th>material</th>
<th>translating slump tube tester</th>
<th>swing arm slump tester</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$h_p$(mm)</td>
<td>$\text{AoR}$ (degree)</td>
</tr>
<tr>
<td>polyethylene</td>
<td>48.1</td>
<td>35.61</td>
</tr>
<tr>
<td>pellets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iron ore</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coal</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$h_p$: height of the particle heap, $\text{AoR}$: angle of repose

The angle of the granular material heap on the ring from the two test rigs used in this section; the translating slump tube tester and the swing arm slump tester have been averaged and a graph of the surface are shown in Figure 4.11(a). It can be seen that the results from the translating slump tube tester are higher than for the swing arm slump tester. The height of the heap depended on the condition of the experiment. As the tube is lifted up directly vertical, these materials gradually move out of the tube and slide down to the bottom. The materials are arranged in the void formed between the availability of materials and build a material heap. Likewise, for the swing arm test, materials fall from the outside of the tube quickly in a short period of time. The material above impacts on the surface of the material below and slides to the bottom to build a heap. Therefore, the angle of repose and height of the heap for the three test materials were compared and shown in Figure 4.11(b), for the experimental results from the swing arm slump test rig. It can be seen that the results from the polyethylene pellets is the lowest and the results
for iron ore and coal were very similar, the angle of repose increases with increasing departure from the spherical shape (Riley et al., 1972). The size and shape of the polyethylene pellets are very close to mono-size, while iron ore and coal are very different. The non-spherical particle shape and the surface roughness effect to the coefficient of friction, as show for the iron ore and coal are affect to the angle of repose (Zhou et al., 2002).

![Figure 4.11](image_url) Experimental angle of repose (a) polyethylene pellets (b) iron ore, coal and polyethylene pellets (WPP) for the swing arm slump testers.

### 4.3 DEM Calibration Modelling

This section examines the development of calibrated DEM material models using the Hertz-Mindlin no-slip contact model. This procedure is to examine all the parameters by comparing the simulation results with the previously measured experimental data. Four experimental tests have been used, consisting of; loose-poured bulk density, inclination test, swing-arm slump tester and translating slump tube tester with three materials; polyethylene pellets, iron ore and coal. This method is used to calibrate the particle loose-poured bulk density ($\rho_b$), coefficient of static friction ($\mu_s$) and coefficient of rolling friction ($\mu_r$). This procedure to investigate the interaction of particles model as shown in Figure 4.12.
4.3.1 Particle Shape Model

The effects of particle shape representation are investigated, as well as the variation of $\mu_s$ and $\mu_r$ of the interaction between each particle and between the particle and wall surface. To explore the effects of particle shape, spherical and non-spherical (shaped) particles were used to model the polyethylene pellets. This material has a sphere-cylindrical shape and a relatively narrow particle size distribution. Section 4.2 presented the solid density, particle dimensions and an average diameter of particles, which are required to build the model. The spherical and non-spherical particles were represented by overlapping two, three and four spheres, as shown in Figure 4.13. A one-sphere particle which is shown in Figure 4.13(b) was built in the EDEM software, which is 4.54 mm diameter, equal to the equivalent volume diameter from experimental data. The non-spherical particles which are shown in Figure 4.13(c, d and e) do not look identical to the polyethylene pellets, which are shown in Figure 4.13(a). However, the mechanical difference between the spherical particle (Figure 4.13(b)) is remarkable with the possible approximation of the real particles. A multi-sphere approximation of an elliptical particle would provide a better correlation to the spherical particle but requires a larger number of smaller spherical
elements of varying diameter to model adequately the particle shape which needs high-performance computing (Markauskas et al., 2010).

**Figure 4.13** Representation of the polyethylene pellets (a) photo of polyethylene pellets, and DEM of the polyethylene pellets b) 1-sphere and overlapping spherical (c) 2-sphere (d) 3-sphere and (e) 4-sphere.

The mechanical properties and interaction properties of the polyethylene pellets that were used for this investigation are listed in Section 4.2 and have been estimated from available literature or laboratory tests. DEM simulations of the loose-poured bulk density, inclination tester, translating slump tube test and swing-arm slump test were set up. All geometry models in the simulations have been setup as per the experiments presented in Section 4.2.

### 4.3.2 Void Ratio

The particle density can have a significant influence on an arrangement of particle packing in the system. Therefore, the particle size and shape of a particle in the packing arrangement can have a large influence on the void ratio of the system. The bulk density and initial void ratio is dependent on various parameters including the particle size, shape, filling method, the container dimensions and the coefficient of the interaction of particle contact parameters. To perform a comparative study, it was essential to limit the amount of variables (e.g. height, the diameter of the container and filling method). In each simulation, a particle factory was placed just above the required sample height and the particles were generated dynamically in 2.5 sec. The predicted sample height was based on the volume of the container, the volume of particles and the initial void ratio of the full-scale experiment. The granular systems described in this thesis are comprised entirely of solids and air voids between the particles.
4.3.3 Loose-Poured Bulk Density using DEM

Loosed-poured bulk density ($\rho_b$) is defined as the material mass per unit volume of a granular material including the voids between each particle and internal pore volume. To confirm the accuracy of the particle shape model, comparison with experimental data of the bulk density was investigated. In this thesis, the CAD model used in EDEM is shown in Figure 4.14. Dimensions of the model are the same with the experiment at the laboratory, 117.5 mm I.D. and 101.5 mm height of the cylindrical container. The distance between the hopper and container is 50 mm. The primary parameters are shown in Section 4.2 and then the processing of each particle shape will be varied by changing the coefficient of rolling friction in the range of 0.01 to 0.20 in 0.05 increments and changing the coefficient of static friction in the range of 0 to 1.0 in 0.2 increments. The particle model of each shape was poured through a conical hopper to the cylindrical container. The boundary geometry according to the size of the container is 1000 cm$^3$ and is selected with the option to display the mass of materials within the container. In this way, the volume of material and the mass of materials is known. Bulk density ($\rho_b$) in kg/m$^3$ is calculated by the total mass of materials filling the cylindrical container (kg) divided by the volume of the cylindrical container in m$^3$. The mass of the material heap on the top and outside of the cylindrical container was excluded in the calculation. The next step is to select the desired particle size for DEM then simulate the exact experimental procedure using an estimated particle density. Once completed, the simulated bulk density is compared to the experimental and the DEM particle density is adjusted accordingly. This process is iterated until identical results are achieved. This method is referred to by many researchers (Deshpande et al., 1993; Gupta et al., 1997; Aydin, 2003; Sacilik et al., 2003; Karababa, 2006; Boac et al., 2010; Hastie, 2010).

![Figure 4.14 Loosed-poured bulk density tests in simulation.](image_url)
The time of this simulation was determined by the dynamics of particles stabilising on the top and kinetic energy of particles in the system being close to zero. The mean bulk density for each simulation was computed by equation 4.2. Figure 4.15 demonstrates the effect of four particle shapes on the loosed-poured bulk density varying the coefficient of rolling friction between particle and particle and particle and wall in the range 0.01 and 0.2, constant coefficient of static friction at 0.2 compared with the experiment data. It can be seen that loose-poured bulk density decreased with the increase of coefficient of rolling friction and shows that the cluster spherical particles are very close to experiment data for \( \mu_r = 0.1 \), and \( \mu_r = 0.05 \) for spherical particles.

![Figure 4.15](image-url)  
**Figure 4.15** Effect of the loose-poured bulk density and coefficient of rolling friction by the particle shape (Figure 4.13) and fixed \( \mu_s = 0.2 \) (polyethylene pellets materials).

### 4.3.4 Coefficient of Friction

The coefficient of friction is a measure of the friction between two objects. This section validates the coefficient of static friction with different particle shapes. This includes two interactions between a particle and a drum wall surface for the friction force resisting the motion of the particle and friction between particles use DEM simulations.

#### 4.3.4.1 Interaction Between Particle and Wall

The determined coefficient of friction between particle and wall surface was based on the particle models beginning to roll or slide on a tilting flat plate. The walls of the plate are either the Perspex acrylic or Stainless steel 304 plate (150 mm square sheet). The Perspex acrylic was used to make the cover at the front of the AS dustiness tester and the wall of two dustiness testers was made from stainless steel. The simulation model is the same geometry as the experimental setup explained in Section 4.2.2.3. The particles in the ring
on the test plate totalled 1000 particles (approximately), the dimension of the ring is 95 mm diameter and 15 mm height and once full of material the ring was lifted vertically at a rate of 0.25 m/s. After the particle heap on the plate no longer moved, then the test plate was tilted at 0.25 rpm. The preliminary definition of the primary particle parameters was given in Table 4.7 for the test materials, where each particle shape will be simulated with the coefficient of static friction ($\mu_{s(p,p)}$) of 0.347 and $\mu_{s(p,w)}$ is 0.277 and the coefficient of rolling friction ($\mu_{r(p,p)}$) of 0.1. The interaction between the four particle shape models and the wall surface (stainless steel) plate is shown in Figure 4.16. The effect of coefficient of rolling friction ($\mu_{r(p,w)}$) vs inclination angle and the results are compared with experiment data. The coefficient of static friction has confirmed the accuracy of particle shape and coefficient of static friction resulting by DEM modelling to match the inclination experiment.

![Figure 4.16](image)

**Figure 4.16** The relation between angle of incline and coefficient of rolling friction (polyethylene pellets materials).

It can be seen that the results for two and four sphere clustered particles are similar and match the experimental results between 0.01 to 0.05 for the $\mu_{r(p,w)}$. However, the 3-sphere clustered shape can use the $\mu_{r(p,w)}$ of 0.01, which is very close to the highest angle of incline from the experiment data. Moreover, the single sphere particle requires a higher $\mu_{r(p,w)}$ at 0.15 to 0.2 to match with experiment data. In addition, for the $\mu_{r(p,w)}$ of the polyethylene pellets on the Perspex wall surface, as shown in Appendix A.

### 4.3.4.2 Interaction Between Particle and Particle

The coefficient of friction occurring between each particle consists of the coefficient of static friction between particle and particle ($\mu_{s(p,p)}$) and the coefficient of rolling friction...
between particle and particle ($\mu_{r(pp)}$). It is important to accurately model the interactions between the granular material flowing in the rotating drum. In this thesis, the coefficient of friction is approximated via the angle of repose by DEM modelling to match with the experimental data. The experiments investigated the effect of coefficient of static and rolling friction on the particle heap forming the angle of repose using 2 tests; the translating slump tube test and the swing arm slump test, represented by (Grima, 2011; Grima et al., 2011). DEM Simulations were completed with the coefficients of rolling friction varied in the range of 0.01 - 0.2 with steps of 0.05. The coefficient of static friction was varied in the range of 0 to 1.0 on the particle and particle contact to determine the combination of parameters where the DEM modelling matched the experimental data (Grima et al., 2011; Wangchai et al., 2013).

4.3.5 Angle of Repose

4.3.5.1 Translating Slump Tube Test

The tester has been explained in Section 4.2.2.4.1. A 3D CAD model was developed as shown in Figure 4.17. Particle rolling resistance occurring between each particle from the experiments has been compared to the results from the DEM Simulations. This test investigated the effect of coefficient of rolling friction on the angle of repose and the height of the heap by varying the coefficient of rolling friction in the range 0.01 to 0.2 in step of 0.05 in the DEM Simulations. The angle of repose ($AoR$) and pile height ($h_p$), as shown in Figure 4.17(b), were examined. The translating slump tube test DEM simulation is automated to lift the tube at a constant vertical velocity along a defined axis to replicate the experimental tests.

![Figure 4.17 Schematic of the translating tube slump test to calibrate particle-to-particle interactions (Grima, 2011) (a) setup and slumping, (b) pile formed.](image-url)
The parameters used in the DEM simulations are listed in Section 4.2. These simulations were performed to investigate an appropriate $\mu_r(p,p), \mu_s(p,p)$ and the influence of particle shape to model the translating tube slump tests. Only a velocity of 7mm.s$^{-1}$ was examined in the laboratory experiments and also used in the DEM simulations. Figure 4.18 shows the pile profiles formed using spherical and non-spherical particles respectively (see Figure 4.13), where $\mu_r(p,p)$ was varied between 0.05 and 0.1 and $\mu_s(p,p)$ between 0.2 and 0.4. When particle clusters were used in the simulations, it can be observed that when using low values of particle angular and translational velocity, the coefficient of rolling friction in the DEM model is not as critical. The pile profile from DEM results at the $\mu_r(p,p) = 0.1$ with a $\mu_s(p,p) = 0.2$ or $\mu_r(p,p) = 0.05$ with a $\mu_s(p,p) = 0.4$ is a good match to the experimental results. Figure 4.18 shows that the spherical particle model required the $\mu_r(p,p) = 0.10$ and $\mu_s(p,p) = 0.20$, which were sufficient to achieve the correct angle of repose. Especially, the spherical shape saves simulation time compared to the cluster model.

![Figure 4.18 DEM and experiment comparison of translating tube slump tester](image)  
(a) 1-sphere (b) 2-sphere (c) 3-sphere (d) 4-sphere.
4.3.5.2 Swing Arm Slump Test

Grima (2011) used a swing-arm slump tester in his research, which is a testing device to study the influence of particle friction and rolling resistance on the formation of granular piles. It is mainly focused on the particle and particle interactions while the particle boundary interactions are found negligible. The schematic of the swing-arm slump tester is shown in Figure 4.19. Particle rolling resistance occurs between each particle from the swing arm slump tester with dimensions the same as the experimental test rig. This test was compared to modelling in DEM, investigating the effect of particle rolling friction on the angle of repose and height of the heap by varying the coefficient of rolling friction in the range of 0.01 to 0.2 on particle - to - particle contact and the coefficient of static friction in the range 0 to 1.0.

![Schematic of the swing-arm slump test](image)

**Figure 4.19** Schematic of the swing-arm slump test to calibrate particle-to-particle interactions (Grima, 2011) (a) setup and slumping, (b) pile formed.

Figure 4.20 shows the results of the DEM simulations of the swing-arm slump test where the $\mu_{s(p,p)}$ was varied between 0.2 and 0.4, the $\mu_{r(p,p)}$ was varied between 0.05 and 0.1 and particle shape was varied using spherical and non-spherical particles. The DEM results were then compared to the experimental results. It can be seen that $\mu_{s(p,p)} = 0.2$ and $\mu_{r(p,p)} = 0.1$ or $\mu_{s(p,w)} = 0.4$ and $\mu_{r(p,w)} = 0.05$ closely match the DEM pile profile for the spherical and non-spherical model. However, for the $\mu_{s(p,p)} = 0.2$ and $\mu_{r(p,p)} = 0.1$, the result from the swing arm slump test matches to the translating tube slump test results.
4.3.5.3 Material Properties of Polyethylene Pellets

The aim of the experimental validation undertaken was to determine whether the DEM material models were able to reliably predict particle flow in the rotating drum. The experimental validation of any numerical model requires comparisons to be made between predicted variables and those measured in laboratory-scale experiments. The particle model depends on particle shape and coefficient of sliding and rolling friction. The result from the two test rigs show very close results with the coefficient of rolling friction \( \mu_{r(p,p)} \) being 0.1 and the coefficient of static friction \( \mu_{s(p,p)} \) being 0.2 between each polyethylene pellet model. Therefore, calibration of the coefficient of rolling friction \( \mu_{r(p,p)} \) varied in the range 0.01 to 0.20 and the coefficient of static friction \( \mu_{s(p,p)} \) varied in the range 0.1 to 1.0 between polyethylene pellets model on the angle of repose, as shown in Figure 4.21 under different particle shape. It can be seen that the angle of repose increases when both coefficient of friction (sliding and rolling) increase. The third colour from the bottom were present in the range 15 – 20 degree of the four different particle models. This angle is similar to the results from the experimental tests.
4.3.6 Develop of a DEM Material Model for Iron Ore and Coal

Similar to the investigation for polyethylene pellets, particle shape and the size of the material model representation are used to investigate and the variation of $\mu_s$ and $\mu_r$ between each particle, and particle and wall surface.

4.3.6.1 Particle Size Distribution and Particle Shape Representation

To explore the effects of particle shape, spherical and non-spherical particles were used to model the particles. The properties of the bulk material, solid density, particle dimension and particle interaction are presented in Section 4.2. The dimensions of the iron ore and coal particle models were represented in Figure 4.22. The raw material of iron ore is shown in Figure 4.22(1). A one-sphere particle is shown in Figure 4.22(2) where the defined size is from the equivalent volume diameter (see Table 4.1). A pyramid shaped and two spherical cluster shaped particle are shown in Figure 4.22(3) and (4) based on the average volume and mass of each particle (avg. 50 particles), as shown in Table 4.2.
Figure 4.22 Material model (a) iron ore (1) photo of iron ore (2) 1-sphere (3) pyramid shape (4) 2-sphere and (b) coal material (5) photo of coal (6) 1-sphere (7) pyramids shape (8) 4-spheres.

Figure 4.22(b) shows the dimensions of the coal particle model including the raw material and three particle shape models. Figure 4.22(5) is the coal material and one sphere particle, as shown in Figure 4.22(6) where the defined size of the particle model is equivalent volume diameter (see Table 4.1) and Figure 4.22(7) and (8) were the same volume and mass of the coal material (see Table 4.2). The particle size of the both materials in the range 2.00 – 6.3mm and the material properties were presented in Table 4.1 to Table 4.4.

4.3.6.2 Loose-Poured Bulk Density of Iron Ore and Coal

The loose-poured bulk density DEM simulations are based on the test method used in Section 4.3.3. Particles are released from the hopper and dropped into a cylindrical container. The excess material was allowed to overflow, as see Figure 4.14. Simulation time was determined by the materials stabilising on top of the materials and the kinetic energy of the complete system approaching zero. The mean bulk density for each simulation combination (particle shape, $\mu_s$ and $\mu_r$) was computed by equation 4.2. The resulting mass in each simulation varied with the coefficient of rolling friction. As presented in Figure 4.23, the effect of three particle shapes on the loosed-poured bulk density for various coefficient of rolling friction values between 0.01 and 0.2 and with a fixed coefficient of sliding friction ($\mu_{s(p.w)}$) at 0.6 have been compared with the experimental data. It can be seen that loose-poured bulk density decreased with the increase of coefficient of rolling friction for both iron ore and coal simulations. The 2-sphere clustered particles and pyramid clusters are very close to the experiment data when
\( \mu_r = 0.1 \), and \( \mu_r = 0.08 \) for spherical iron ore particles. However, for coal, the 4-sphere clustered particles are close to the experimental data when \( \mu_r = 0.06 \), the pyramid clustered particles when \( \mu_r = 0.08 \) and the spherical particles when \( \mu_r = 0.075 \).

**Figure 4.23** Effect of the loose-poured bulk density and coefficient of rolling friction by the particle shape (a) iron ore and (b) coal.

### 4.3.6.3 Coefficient of Static Friction for Iron Ore and Coal

The three particles shapes for iron ore, as shown in Figure 4.22(2-4) and the three coal particles shape as shown in Figure 4.22(6-8) were simulated on the stainless steel wall surface of the inclination tester. The simulation of each particle shape for iron ore was completed with a constant value of 0.6 for the \( \mu_s(p,w) \), 0.58 for the \( \mu_s(p,p) \), 0.1 for the \( \mu_r(p,p) \) and varying the \( \mu_r(p,w) \) between 0.1 and 0.4, increased in steps of 0.1. This procedure was repeated numerous times to obtain an average of the angle of inclination and the results are shown in Figure 4.24(a). For the coal material as shown the result in Figure 4.24(b) with constant \( \mu_s(p,w) = 0.4 \), 0.6 for the \( \mu_s(p,p) \), 0.1 for the \( \mu_r(p,p) \) and varying the \( \mu_r(p,w) \) between 0.1 and 0.4, increased in steps of 0.1.

**Figure 4.24** The relation between angle of incline and coefficient of static friction (a) iron ore and (b) coal.
Figure 4.24 shows the variation of particle rolling friction ($\mu_{r(pw)}$) to the angle of inclination on the stainless steel wall surface with three particle shapes of iron ore and coal. For iron ore and coal, the spherical particle requires $\mu_{r(pw)} = 0.3$ while for the clustered particles required $\mu_{r(pw)} = 0.1$ to replicate the experimental results. In addition, the $\mu_{r(pw)}$ of the particle shape for the iron ore and coal on the Perspex wall surface is shown in Appendix A.

### 4.3.6.4 Coefficient of Rolling Friction for Iron Ore and Coal

The concept of the swing arm slump test is shown in Figure 4.19 and more detail is described in Section 4.3.5.2 and used the same method described for polyethylene pellets simulations. The coefficient of sliding friction ($\mu_{s(pp)}$) was constant at 0.58 and 0.6 for iron ore and coal particle models while the coefficient of rolling friction was varied. The results are shown in Figure 4.25(a) from the iron ore particles for DEM simulations of the swing-arm slump test where $\mu_{r(pp)}$ was examined between 0.01 and 0.2 against the experimental data using spherical and non-spherical (two spherical cluster and pyramid shape) particles, respectively. It can be seen that in the upper row for the spherical particle model, when $\mu_r = 0.1$ to $\mu_r = 0.15$ the coefficient of rolling friction is very close to matching with experimental data. While the middle and lowest row of Figure 4.25(a) present the spherical clusters and the coefficient of rolling friction is very close to matching with experimental data when $\mu_r = 0.05$ to $\mu_r = 0.1$. Figure 4.25(b) illustrates the results of the three coal shapes (see Figure 4.22). For the spherical and spherical clustered particle, the simulation results match with experimental data at $\mu_r = 0.10$ and $\mu_r = 0.05$, respectively.
Figure 4.25 DEM and experimental comparison of the swing-arm slump tester for the spherical shapes (upper row) and a second shape (middle row) and third shape (lower row) with (a) iron ore (b) coal (see Figure 4.22).

4.4 Conclusion

In this chapter, DEM simulations were used to calibrate the particle shape, particle size and all the parameter inputs required for the EDEM simulations. The parameter obtains from experiments, previous studies and DEM validation all combine to match with the experimental test results. Two groups of parameters are input to DEM software, consisting of material properties and interaction properties. The material properties consist of Poisson’s ratio ($\nu$), shear modulus ($G$) and particle density ($\rho$) of the material samples and geometry of a model in the simulation. Interaction properties include; interaction between each particle and between the particle and geometry, such as; coefficient of restitution occurring between particle and particle ($CoR_{p,p}$), and particle and wall ($CoR_{p,w}$), the coefficient of static friction or sliding friction contained between
Chapter 4: Material Characterisation for DEM Calibration

particle and particle \( (\mu_{s(p,p)}) \), and particle and wall \( (\mu_{s(p,w)}) \), the last interaction is the coefficient of rolling friction during particle and particle \( (\mu_{r(p,p)}) \), and particle and wall \( (\mu_{r(p,w)}) \) interactions. All the interaction properties were tested by inclination tester, the translating tube slump tester and swing arm slump tester.

It was found that the loose-poured bulk density decreases with the increase of coefficient of rolling friction. The coefficient of static friction between the particle and particle and between particle and wall increase the angle of incline with increase the coefficient of static friction \( (\mu_{s}) \). The coefficient of rolling \( (\mu_{r}) \) between particle and particle and between particle and wall used a trial and error method to compare the angle of repose and the height of the heap to match experiments with DEM simulation results. All the three calibrated material models will be used in the DEM and DEM-CFD simulations of the dustiness tester and are summarised in Appendix A.
Chapter 5

Numerical Analysis of Polyethylene Pellets Flow in Dustiness Testers

5.1 Introduction

This chapter will focus on the numerical analysis of DEM modelling and DEM-CFD coupling implementation used to simulate the mechanisms of polyethylene pellets flow in the International Standard (IS) dustiness tester and the Australian Standard (AS) dustiness tester and will be divided into three sections. In the first section, DEM simulation investigation of mono-sized granular material flow mechanisms in the two dustiness testers is compared to those obtained by experimental data shown in Chapter 3. This study proposes the principle of modelling spherical and spherical clustered shapes, which are applied in the 3D dustiness tester models. The results display the volume fraction movement and the velocity of particles in the five sections (bins) along the dustiness testers. The drums are partially filled with material using four different initial positioning of the product sample; at the front, at the back, in the middle and also spread evenly along the bottom of the rotating drums. In the second section, the DEM simulation of binary particle size distributions with different size ratios were applied in both drums, with the particle size ratio varied from 1.17 to 3.5. The segregation in the radial and axial directions, as well as the effect of particle size ratio occurring in both dustiness testers is presented. The last section presents the coupling model combining the discrete element method (DEM) for the solid phase and computational fluid dynamics (CFD) for the air phase. The applicability of the approach regarding typical behaviour of particle flow patterns in the dustiness tester simulations have been investigated, focusing on the behaviour of air and particle flow together in the rotating drums.
5.2 Methodology

Polyethylene pellets were chosen for this investigation to visualise the flow mechanisms of the particles within the rotating drums of the two dustiness testers, but not to measure the degree of dust generated as a result of the testing. This is also vital for the DEM simulations replicating the same experimental tests. The IS and AS testers require differing operating conditions to follow their respective standards. There are two conditions which will be presented in this chapter, the first will simulate the dustiness testers with no air flow and second will be simulating the dustiness testers with air flow to compare the experimental results presented in Chapter 3. The IS and AS tester are shown more detail in Sections 2.2.1 and 2.2.2 and the schematic of both rotating drums for analysis are shown in Appendix B.

5.3 Mathematical DEM Model

The DEM software requires material properties and interaction properties to be input into the DEM simulations. Specifically, EDEM was used exclusively for the simulations mentioned in this thesis. Besides the particle density, the particle shear modulus and the Poisson’s ratio of the material and geometry have to specified as well as interactions such as coefficient of restitution, coefficient of static friction and coefficient of rolling friction between particle and particle, and between particle and wall.

5.3.1 DEM Model Parameters

The simulation configurations are built to match the experiments with equal volume and mass of the material sample. The material properties and interactions parameter are presented in Table 5.1, showing the physical and mechanical properties required for the DEM simulation of the materials, with more detail available in Chapter 4.

The injection plane for generating the particles in the drums were positioned above the bottom wall. The injection plane for the IS tester model for the even spread location was 10×220 mm, in the middle location was 40×40 mm. However, the injection plane for the front and back heap was 40×40 mm with the position of the plane a distance of 40 mm from the front or back wall. In addition, the injection plane of the AS tester model for the
even spread was 40×270 mm, the middle location (80×80 mm), for the front and back
heap was 80×80 mm with the position of the plane a distance of 75 mm from the front or
back wall.

Table 5.1 Particle and bulk properties of polyethylene pellets, stainless steel and perspex.

<table>
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<th>Properties</th>
<th>Polyethylene Pellets</th>
<th>Stainless Steel</th>
<th>Perspex</th>
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<tr>
<td>Particle volume, (m³)</td>
<td>4.91x10⁻⁸</td>
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<td>-</td>
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<tr>
<td>Particle mass, (g)</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution, (mm)</td>
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<td>Particle density (ρ₁p), (kg/m³)</td>
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<td>1200</td>
</tr>
<tr>
<td>Loose-poured bulk density (ρ₁b), (kg/m³)</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Poisson’s ratio (v)</td>
<td>0.45</td>
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<td>Shear modulus (G), (Pa)</td>
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<tr>
<td>Particle coefficient of restitution, (CoR)</td>
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<tr>
<td>Particle coefficient of static friction, (μ₁)</td>
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<td>0.277</td>
<td>0.3</td>
</tr>
<tr>
<td>Particle coefficient of rolling friction, (μ₁)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

5.3.2 Computation Time

The DEM simulation predicts the particle movement and collision in the IS and the AS
tester models with a multiplier of 30% (approximate) being applied to the computed
critical time step for the simulations. The DEM simulations are running on a computer
workstation; DELL Precision T7500, with 24 GB RAM and 4 processor cores. The total
simulation run time for a 60 sec simulation varies from 10 to 50 hours for the mono-size
particle models. Moreover, for the binary mixes of particles under different size ratios in
the range of 1.17 to 3.50, flow in both rotating drums, the simulation time was
approximately 20 to 120 hours, depending on the type of particle model, rotation of the
drum, number of particle and the combination of particle sizes simulated.

For the DEM-CFD coupling software, the DEM simulations were performed using
EDEM version 2.5 and CFD simulations using ANSYS FLUENT 14.5. Both software
employs the DEM in an object oriented user interface, eliminating the need for complex
coding while providing a visual representation of all simulations. The simulations running
in the same machine for both dustiness tester models use a simulation time of
approximately 3 times that of the mono-size particle model DEM simulations.
5.4 Simulation of Particle Flow Mechanisms in Dustiness Testers

This section illustrates a 3D-DEM simulation of particles flowing in both horizontal rotating drums and compares the results with the flow of granular materials in the experimental apparatus, based on the IS and the AS tester. The size and shape of the spherical and non-spherical particle models were varied, which were then applied in the 3D rotating drums. Simulation conditions are similar to those used in both experimental dustiness testers, to validate the simulation method at the particle scale. The drums were partially filled with polyethylene pellets using four different positions for the initial location of the product sample. The DEM simulation models investigate the volume fraction and velocity of particle flow in the drums.

5.4.1 DEM Simulation Condition

The properties of materials were used to construct preliminary DEM models for the polyethylene pellets material, as shown in Table 5.1. The particle shape and particle size of the polyethylene pellets selected in the DEM simulations have been shown in Figure 4.13. There are four particle models discussed in this section, as well as different shapes of particles, with the spherical and spherical clustered particles having the same volume and mass to those measured experimentally. Subsequently, in the DEM simulations, the particles were set with a fixed particle size and shape. The number of particles in the simulations are fixed at 432 and 12330 particles and the fill level for the solid volume fraction is 0.21% and 4.7% for the IS and the AS tester models, respectively. Material flow in the rotating drums was investigated via DEM simulation under different conditions: four loading locations and four particle shapes of the material inside the drum. The simulations began with the particles randomly generated from an injection plane allowing the particles to fall under gravity, with no initial velocity, forming a natural heap at each loading position until all particles reached their most stable positions with zero velocities as a result of the effect of energy dissipation. After a packed bed was formed, then the drum was rotated in a clockwise direction at 4 rpm for the IS tester and 29 rpm for the AS tester for a total of 60 sec.
5.4.2 Validation of the Material Model

The polyethylene pellets flow in the drums has been investigated experimentally for the IS and AS tester and the results compared with four particles shapes and different starting locations with the corresponding DEM simulations. Figure 5.1 and Figure 5.2 demonstrates typical figures of the particles flowing in the IS tester for the experiments and the various particles models in DEM simulation for 1-sphere, 2-sphere, 3-sphere and 4-sphere particle shapes with four different starting locations for the even spread, at the front, at the middle and at the back of the drum. Figure 5.1 shows the experimental as well as DEM results for spherical and spherical clustered particles based on the four initial material locations after 5 sec of rotation in the IS tester. The results in the first column are from the experiments and the other columns for the DEM simulations. Each row is a different starting location. The particles can be seen moving out from the lifting vanes and the spherical cluster results were very similar to the experimental results than the spherical particle shape results. Figure 5.2 shows the same sets of results after 60 sec of rotation in the IS tester (the end of the test). It can be clearly seen that the spherical cluster shape of particles provides very similar results compared to the experiments. Further, there are slight variations visible in the experimental tests based on the initial starting position of the particles in each of the four cases; even spread, front, middle and back, which are also observable in the DEM simulations of the clustered particles. In Figure 5.2, it can be seen that for the DEM simulations using the spherical particles, there is a definite difference to that seen experimentally. As the simulated particles are spherical, all of the particles have already fallen from the upper lifting vane at 112.5 degrees (t = 60 sec) to the far vanes at 22.5 degrees (approximately) from the vertical plane, whereas the clustered particle simulations show particles still falling from the upper lifting vane more closely compared to the spherical model, matching very well with the experimental results. The results show the particles moving along the wall of the drum, colliding with each particle and wall surface of the drum for the different particle shape models and the different starting locations.

The effect of particle shape is shown in Figure 5.1 and Figure 5.2 for the four different starting locations and four different particle shapes. Both starting locations for the front and back heap have similar particle flow and particles begin to spread along the vanes after 1 rev (t = 15 sec). The particles have spread evenly along the full length of the vanes
after 2 revs and all particles move out from the vanes every 2 sec up to 60 sec. Whereas, for the 3-sphere particle model, the particles begin to spread along the vanes for almost 2 revs ($\approx 23$ sec) and the particles spread on the full vanes very close to the end time ($\approx 54$ sec). In contrast, the particles starting at the middle heap on the bottom evenly begin to spread on the full length of the vanes very quickly (at 5 sec), and spread fully on the vanes in 1 rev and then follows the trend of the even spread heap. It is clear that for the even spread heap, during rotation some particles move out from the side of the vanes, but return to the main drum section due to the conical ends.

For the AS tester, the typical figures of the four different loading positions for the experiments and the four particle shapes modelled in the DEM simulations are shown in Figure 5.3 and Figure 5.4 at the simulation times $t = 0.5$ sec and 10 sec. The results in the first column are from experiments and the other columns from DEM simulations. Each row represents a different starting location of the materials. The simulated particles moving to the free space in the axial direction of the drum is very similar to the trends seen in the experimental results.
Chapter 5: Numerical Analysis of Polyethylene Pellets Flow in Dustiness Testers

Figure 5.2 Shows a snapshot of particle flow different initial material locations in the IS tester at times $t = 60$ sec. The colour presents the particle velocity.

Figure 5.3 Shows a snapshot of particle flow different initial material locations in the AS tester at times $t = 0.5$ sec. The colour presents the particle velocity.

It can be seen in Figure 5.3 that there is very little difference between the experimental results and the DEM simulation results for all four initial material locations. Figure 5.4 then shows the same sets of results after 10 sec of rotation in the AS tester. Images were
taken at the 10 sec point of the 600 sec test due to steady-state conditions already being reached at this point of the test. The results after 10 sec of rotation and there are clear differences between the results for the spherical particle simulations compared to the clustered particle simulations. The particles drop on the free surface of the particles in the AS tester, especially the spherical cluster shape follows the experimental results more closely compared to the 1-sphere model, similar to IS tester. The results show the particles moving along the wall of the drum, collision with each particle and wall surface of the drum for the different particle shape models and the different starting locations. It can be clearly seen that the clustered particle simulations better match with the experimental equivalents, with very similar lifting and falling patterns evident in both.

![Image showing particle flow at different initial material locations in the AS tester at times t = 10 sec. The colour presents the particle velocity.](image)

**Figure 5.4** Shows a snapshot of particle flow at different initial material locations in the AS tester at times t = 10 sec. The colour presents the particle velocity.

### 5.4.3 Volume Fraction Movement in the Rotating Drums

The experimental investigation of the particle flow in the IS and the AS testers has been presented in Chapter 3. DEM simulations were also conducted for the corresponding initial material locations for both dustiness testers. For analysis purposes, five cylindrical analysis bins of equal length were created along the drum section of both dustiness testers, as shown in Appendix B. Bin1 is located at the front of each dustiness tester moving to bin5 at the back. The content of each bin was analysed to determine the movement of
particles by measuring the percentage of material in each bin at each simulation time step for the entire duration of each standard dustiness test. Four particle models; one spherical particle model and three non-spherical particle models were investigated in these DEM simulations.

For the IS tester with the results presented in Figure 5.5, sixteen DEM simulations were analysed (4 particle geometries and 4 loading positions) and the particle volume fraction determined for each bin. For the evenly spread loading condition, as shown in the first row of Figure 5.5, even material proportions of approximately 20% exist in each bin and this is maintained for the entirety of the test, with only very minor fluctuations. As expected, for the front loading (second row), middle loading (third row) and back loading (fourth row) in Figure 5.5, the particles undergo an initial period of transient behaviour until the material eventually evenly spreads along the rotating drum. For the front and back loading conditions the results look very similar, with material taking approximately 3.5 revs (50 sec) to evenly spread from the front or back of the main drum section to reach a steady-state condition where all five bins are maintaining even proportions of material (approximately 20% each). For the middle loading condition it takes approximately 1 rev (15 sec) to reach and maintain even proportions of material due to the fact that material can spread towards the front and the back of the drum simultaneously, thus reducing the time required to reach steady-state.

DEM simulations of the AS tester were also completed, investigating the particle behaviour in the drum as a result of the four material loading locations and four particle geometries. Figure 5.6 shows the particle volume fraction versus time, again plotting the results from the five bins used for analysis. Based on the AS tester, the time for one simulation is 60 sec and as such, the simulations have also been set to this time to observe if any transient behaviour of the rotating particles was present. Each graph in Figure 5.6 also contains a plot insert, focusing on the initial 4 revs of the simulation to show more detail of the transient behaviour of the particles as the drum begins to rotate.
In the case of the evenly spread initial loading condition, the even spread of material is maintained for the entirety of the simulation. For the front, middle and back loading positions, the rotation of the drum disperses the material evenly along the length of the drum in approximately 4 sec, after which the even distribution is maintained for the remainder of the test. Due to the quantity of material used per the AS tester standard (1000 grams), the initial heap formed at the front of the drum indicates that there is more material present in bin2 than in bin1, as seen in the second rows of Figure 5.6. A similar result occurs when the initial heap is formed at the back of the drum, with bin4 containing more material than bin5, as seen in the fourth row of Figure 5.6. In the case of the middle loading position, as shown in the third row of Figure 5.6, the majority of the initial material heap is located in bin3 with a smaller quantity of material also in bin2 and bin4, as is to be expected. With respect to the simulations of the four particle geometries, there is very little difference between the results for the 1-sphere particles and the spherical clusters (2-sphere, 3-sphere and 4-sphere).
Further investigation of the motion of the particles in the IS and AS testers looked specifically at the movement of the particles due to the interaction with the internal lifting vanes. The motion of the particles being raised by the lifters and subsequently falling back to the bottom of the drum has been reviewed from the DEM simulations completed for the four particles models (see Figure 4.13).

Cut-away snapshots from the DEM simulations of the IS tester results are presented in Figure 5.7 using the simulated spherical and clustered particles in the four initial material locations. Figure 5.7 shows the particle flow in the IS tester at a time $t = 5$ sec, which corresponds to the initial transient time region, while the time $t = 60$ sec show the results when the particle flow has reached steady-state in all cases. For the time $t = 5$ sec cases, the initial loading positions can be seen quite clearly and in the time $t = 60$ sec cases it is clear that the particles have evenly distributed along the main drum.
Figure 5.7 Particle flow in the IS tester using four different starting locations for the initial transient time region ($t = 5$ sec) and the steady-state time region ($t = 60$ sec)

(a) 1-sphere and 2-sphere (b) 3-sphere and 4-sphere.

The particle flow in the AS tester simulated by DEM for the spherical particle and clustered particles with the four initial material locations is shown in Figure 5.8. Due to the larger volume of material used in the AS tester, as well as the higher rotational speed, the spread of material occurs much quicker than for the IS tester, as can be seen and was...
confirmed in Figure 5.6. There is only minor variation in the way material spreads when comparing the four particle geometries used in the DEM simulations.

Figure 5.8 Particle flow in the AS tester using four different starting locations for the initial transient time region ($t = 0.5$ sec) and the steady-state time region ($t = 60$ sec) (a) 1-sphere and 2-sphere (b) 3-sphere and 4-sphere.
5.4.4 Particle Velocity in the Dustiness Testers

The rotational speed of the drums dictates the way the material is raised by the lifters and subsequently free falls, impacting on either the bottom of the drum or other particles at the free surface of the material rotating in the drum. The particle velocity in the IS and AS tester has been investigated using the same five bins as shown in Appendix B and the same four initial material locations. As the ends of the lifters are not fully enclosed, a small percentage of particles being lifted can escape into the conical sections of the rotating drum of the IS tester and as a result, this can influence the velocity of particles in the adjacent bins. This behaviour was also evident in the experimental tests performed. It has previously been reported that the dynamic angle of repose of particles will increase at the ends of a horizontal rotating drum due to the additional contact with the drum walls (Liu et al., 2008). As a result of this increased dynamic angle of repose, the particles will be subjected to a degree of axial motion. In the case explained by Liu et al. (2008), the drum used had vertical side walls, much the same as the AS tester, however, the IS tester has two inclined end walls due to the conical sections.

Figure 5.9 represents the average velocities of the particle flow in the IS tester for the four different initial material locations and four particle models over the 60 sec test duration. For the even spread condition, there is a very consistent average particle velocity across all bins, however, there are clear variations in velocity across the bins for the front, middle and back loading locations. The lowest velocity for each of these cases falls in the bin in which the material is originally positioned. The most logical explanation for this is the fact that the initial higher density of particles in these respective bins higher the velocity of the particles until they gradually spread throughout the drum as the test progresses. This is also corroborated when referring to the volume fractions shown in Figure 5.5 for each bin.

A similar analysis was performed for the AS tester for the entire 600 sec test and is presented in Figure 5.10. As can be seen from the results, the velocities for each of the bins show very consistent results across all four initial material locations. It has already been highlighted that there is only transient material behaviour for, at maximum, the first three seconds on the test. An additional observation is that the first and last bins (bin1 and bin5 respectively), show the highest material velocities for all four initial material
locations, albeit these velocities are only marginally higher than the three remaining central bins, which in themselves all show very consistent velocities. This slight increase in velocity at either end of the rotating drum has been attributed to the friction of particles in these two bins due to the end wall sections adjacent to each bin. These end wall sections allow additional movement of particles more than the motion itself, is not captured as part of either bin velocity analysis, but the resulting increase in velocity of the particles, which venture into the conical section are included once they return to the adjacent bin. There are different results for the different particle models with the velocity of particle flow in AS tester depending on the number of spheres used to created the particle clusters. The more spheres in a cluster, the lower the average velocity. This trend appears with all four particle starting locations.

![Figure 5.9](image1.png)

**Figure 5.9** Average velocities of the particle flow in the rotating drums with five bins, different initial material locations and four particle shapes in the IS tester.

![Figure 5.10](image2.png)

**Figure 5.10** Average velocities of the particle flow in the rotating drums with five bins different initial material locations and four particle shapes in the AS tester.
5.4.5 Discussion

In this section, DEM models were used to compare the behaviour of particles in the IS and AS testers investigated via experimental tests and DEM simulations and this was validated by experiments using the dustiness testers shown in Appendix B. The particle shapes used in the DEM simulations are shown in Figure 4.13 and the DEM simulations were based on the parameters given in Table 5.1. The four particle shape models were validated by both dustiness testers at two time instances; the first point where particles began to spread and at the end of the simulation for steady-state particle flow in both drums. The model was confirmed by comparing simulation and experimental results regarding the flow patterns observed.

The results show a difference between the experiments and the DEM predictions depending on the coefficient of static friction and coefficient of rolling friction between the particles and between particle and wall and the particle size distribution, especially the model of the particle shape. The starting locations for the particles in the drum is the most important effect determining how particles begin to flow in the drum. For the IS tester, 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 the back 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 (even spread) have some particles moving from the side of the vanes, especially in the first 5 sec. For the AS tester, the particles starting at the front and back show a very similar trend of particle flow, particles starting at the middle evenly spread axially along the drum. After 2 revs of drum rotation, all the particles are evenly spread along the drum from the front to the back.

Four different initial material locations were investigated both experimentally and via DEM simulation. The results presented in this section show a good agreement when the spherical cluster shape simulations compared to the experimental equivalents. Particularly, 2-sphere and 4-sphere particle clusters show better results than other shape and the 2-sphere clusters save computational time. However, as expected, the spherical particle simulations show a variation. This is due to the additional degrees of freedom the
spherical particles have in interacting with other particles and the walls of the rotating drums.

Both the IS and the AS testers require the loaded material to be spread evenly from front to back of the drum before the test commences. Analysis of the DEM simulations for the volume fraction of material in each of the five analysed bins showed the even spread simulations, steady-state conditions occurred from the beginning of the test and remained constant throughout. For the other three loading conditions, there were varying lengths of time to reach steady-state conditions, with the front or back loading conditions taking the longest to stabilise. These observations were also evident in the experimental testing, however, due to the enclosed nature of the rotating drums, the results were qualitative rather than quantitative. The velocities of particles within both dustiness testers were investigated using DEM and it was found that for the AS tester, the magnitude velocity is very similar trend for all particle shapes and four initial loadings, the velocity of spherical shape is higher than the cluster particle of 0.04 to 0.06 m/s for 5 bins. For the IS tester, the average material velocity over the length of the test was consistent for the even spread material loading, however, for the other three loading positions, the average particle velocity for the bin containing the initial heap of material had the highest velocity and gradually increased as the material moved away from the initial bin. In saying this, it must also be recognised that the velocity variations observed in the simulations are in the order of magnitude of only 0.01 to 0.02 m/s, which must be agreed would not be able to be measured accurately in reality.

5.5 Particle Size of Bulk Material Segregation in Dustiness Testers

So far this chapter has investigated DEM simulations using mono-sized particles. This section reports on an investigation into the granular material flow in the IS and the AS tester via DEM simulation using a binary distribution of particles, using the same five bins as before, to analyse the movement of particles in each section of the drum. The same four initial material locations are used and the segregation of particles in both the axial and radial directions are investigated.

On completion of each simulation, the contents of each of the five bins (see Appendix B) were analysed to determine the number of large and small particles in each bin, thus
providing the percentage of each size range. This analysis was performed for the entire simulation to graph how the different sized polyethylene pellets moved throughout the rotating drums. The effect of particle size ratio on the influence of particle segregation within the rotating drums was investigated from the DEM simulation outputs. By using the combination of particle sizes detailed in Table 5.2, DEM simulations were completed for the IS and AS testers and the percentage of each sized particle in each of the five bins were determined via post-processing. Observations have been made focusing on the axial and radial segregation occurring within both rotating drums throughout the simulations and are discussed in the following sections.

5.5.1 DEM Model and Simulation Condition

For accurate DEM simulations to be produced, the particle and bulk properties of the polyethylene pellets needed to be determined as well as the interactions with the stainless steel drums and the acrylic end plate of the AS tester. A summary of the required properties is shown in Table 5.1.

The particle shape used in the DEM simulations is based on the measurement of representative particles, as explained previously in Chapter 4. This investigation attempts to provide insight into the effect of particle size on the motion of particles within the rotating drums and also to observe if any segregation occurs due to variation in particle size. The base particle used in the DEM simulations is shown in Figure 4.13(c) and depicted in Figure 5.11, with key dimensions, \( d_1 = 3.94 \) mm and \( d_2 = 5.25 \) mm, giving an aspect ratio \( d_2/d_1 = 1.33 \).

![Figure 5.11 Representation of the polyethylene particle for the DEM simulations.](image)
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Figure 3.2 showed the measured particle size distribution of the polyethylene pellets. The particle size distribution was determined by mechanical sieving, resulting in 82% of large particles in the 4.0 – 5.6 mm range, 16% medium size in the 3.35 – 4.0 mm range and 2% of small size in the 2.36 – 3.35 mm range. The larger particle size would also allow for DEM simulations to be completed quicker. In this section, the effect of varying size fractions will be investigated. With only 2% of the smallest particles, the decision was made to omit these particles from the simulations and instead adjust the medium size range to 18% rather than 16%. This would have a benefit in reducing simulation time, with little influence on the outcome of the simulations. In light of this, the size distribution of the polyethylene pellets was classed as binary, with 82% classed as large particles and 18% classed as small particles. A series of simulations were devised to investigate the effect of varying particle size, keeping the large particle, P1, the same for all simulations and varying the size of the small particle for each simulation completed. Table 5.2 summarises the \( d_1 \) and \( d_2 \) dimensions for each of the additional six particles used in the simulations. The P2 particle is representative of the smaller sized particle measured experimentally while P3 to P7 are arbitrarily sized particles to generate increasing large to small particle ratios. It should also be noted that for both the large and small particles used in the DEM simulations, a mono-sized particle generation was used, based on the upper size of each size distribution. This was done in the interests of minimising simulation time and should still provide adequate simulation results to show trends based on variation in particle size.

The calculation of the required number of large particles was based on 82%, the number of small particles was based on 18% of the volume of particle sample test of both the IS and AS tester. Table 5.2 also summarises the number of each particle used in the DEM simulations. A simplification was made in the calculation of the number of particles required, that being there was no accounting for the void space that would exist between the particles. Because this simplification was applied to both the large and small particles, the assumption has been made that any error would be spread between the large and small particles, thus negating any over prediction.

Material flow in the IS and AS tester was investigated via DEM simulation using the same four different loading positions as for the experimental tests and also for a range of different particle sizes. The initial homogeneous mixture of the large and small particles
is achieved by the particles being randomly generated via the injection plane. After the formation of the heap was complete, the drum was rotated at 4 rpm for the IS tester and 29 rpm for the AS tester for a total of 60 sec.

Table 5.2 Dimensions of simulated particles and the number of particles required for the DEM simulations.

<table>
<thead>
<tr>
<th>Particle</th>
<th>(d_1) (mm)</th>
<th>(d_2) (mm)</th>
<th>large to small particle ratio</th>
<th>number of particles for the IS tester large / small</th>
<th>number of particles for the AS tester large / small</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>3.94</td>
<td>5.25</td>
<td>-</td>
<td>432 / 0</td>
<td>12330 / 0</td>
</tr>
<tr>
<td>P2</td>
<td>3.35</td>
<td>4.46</td>
<td>P1/P2 = 1.17</td>
<td>345 / 139</td>
<td>9825 / 3928</td>
</tr>
<tr>
<td>P3</td>
<td>2.63</td>
<td>3.50</td>
<td>P1/P3 = 1.5</td>
<td>345 / 295</td>
<td>9825 / 8340</td>
</tr>
<tr>
<td>P4</td>
<td>2.00</td>
<td>2.63</td>
<td>P1/P4 = 2.0</td>
<td>345 / 505</td>
<td>9825 / 19700</td>
</tr>
<tr>
<td>P5</td>
<td>1.57</td>
<td>2.04</td>
<td>P1/P5 = 2.5</td>
<td>345 / 1360</td>
<td>9825 / 38420</td>
</tr>
<tr>
<td>P6</td>
<td>1.30</td>
<td>1.72</td>
<td>P1/P6 = 3.0</td>
<td>345 / 2350</td>
<td>9825 / 66500</td>
</tr>
<tr>
<td>P7</td>
<td>1.13</td>
<td>1.48</td>
<td>P1/P7 = 3.5</td>
<td>345 / 3780</td>
<td>9825 / 106700</td>
</tr>
</tbody>
</table>

5.5.2 Validation of Multi Particle Model

The product flow in both dustiness testers has been investigated experimentally and compared to the results of the corresponding DEM simulations with four different initial heap locations. The results shown in Figure 5.12 and Figure 5.13 will be used to provide comparisons and discussions relating to the DEM simulation results. The experimental results from the IS tester are shown in Figure 5.12(a) for all four initial material locations. Visually, the motion of particle samples after 4 revs of the drum \((t = 60\) sec) show very similar results. Similar experimental results were obtained from the AS tester and are displayed in Figure 5.12(b), showing a snapshot of each test after 10 sec, which equates to 5 revs of the drum. The results for all four starting locations have nearly identical profiles and visual inspection of these tests has shown that for each of these tests, particles have spread the entire length of the cylindrical drum at this time. This implies that steady-state conditions are reached in a very short time.

Both the IS and AS tester simulations were operated at their specified rotational speeds and volume of the test sample, however, the initial positioning of the sample was varied to investigate the influence of the movement of material within the drums while rotating. Four locations were trialled in each tester; an even spread of material from front to back, a heap at the front, a heap in the middle and a heap at the back of the drum. The results from DEM simulations are shown in Figure 5.13. Figure 5.13(a) shows the flow of
particle samples after 4 revs (time = 60 sec) for the IS tester. The results for all four initial loading positions show very similar results to the experimental results. Moreover, similar experimental results were obtained from the AS tester are displayed in Figure 5.13(b). The larger quantity of the test sample is apparent in the images and shows a snapshot of each test after 10 sec rather than at the end of the test due to steady-state conditions already being achieved at this point. The results for all four initial loading positions have similar profiles and visual inspection of these tests showed that for each test, particles had spread the entire length of the cylindrical drum section at this time and again show a good comparison to the experimental results.

**Figure 5.12** The initial material locations of the test samples in the (a) IS tester at time t = 60 sec (b) AS tester at time t = 10 sec.
5.5.3 Effect of Particle Size Ratio

This section investigates the effect of segregation of particles in the axial and radial directions based on the different particle size ratios. For this set of simulations only the even spread loading condition has been investigated as previously it has been shown that steady-state is reached by all four loading conditions at the end of the IS and AS tester simulations. For the IS tester, filling is 0.21% of the drum volume and for the AS tester, filling is 4.7% of the drum volume. The volume fraction of the small particle size vs the five analysis bins along the drum have size ratios of; 1.0, 1.17, 1.5, 2.0, 2.5, 3.0 and 3.5.

Figure 5.14 shows the influence of the size ratio on particle flow in the IS tester. The percentage (volume basis) of the small size fraction at end time \((t = 60 \text{ sec})\) within each bin has been plotted in the range of particle size ratios simulated. Adding together the values present in each bin for a given size ratio will yield 100%, indicating the total volume of small particles present for the simulation, which in turn is 18% by volume of the total material sample added to the drum for simulation. Differing trends are present due to the different size ratios, however, the volume fractions of small particles in each bin fall within a relatively narrow band. This indicates that there is only minimal axial segregation occurring, which is in part due to the small quantity of material used in each test.
Figure 5.14(a) shows the concentration profile of the small particles in the IS tester and as can be seen, is relatively non-uniform for the seven different size ratios. Also, as size ratio increases from 1.0 to 3.5, segregation becomes more prevalent with a higher fines mass fraction close to the end walls. Moreover, for the size ratios lower than 2.0, the small particles migrate to the middle of the drum. Additional analysis was performed for the centre of the rotating drum (bin3), as shown in Figure 5.14(b), where the time history (based on the number of revolutions) of the percentage of small particles for the duration of a 60 sec simulation has been extracted from the simulation data. The observed results show all the particle size ratios are very close to steady-state after 2 revs. Particle segregation in the IS tester is non-uniform and depends on the movement of each particle after dropping and impacting on the drum wall as the particle can rebound in any direction. The plots in Figure 5.14(b) can be linked to the fact that even when a few particles enter or leave bin3, this can have a noticeable impact on the volume fraction due to the small total test sample. An interesting phenomenon was observed when the size ratio of the particles was higher than 3.0. In this case, the small particles move to the end wall of the drum (bin5). The end of the IS tester has a small wall to control the movement of particles and this zone should effect the dust collection while the drum rotates and air flows from the front to the end of the drum. Particularly, the air control and particle moving in the rotating drum are described in the next section.

![Graph](image1.png)

Figure 5.14 The volume fraction of small particle in the IS tester (a) seven different size ratio with even spread loading (b) volume fraction of small particle at the middle of drum (bin3).

The segregation of particles in the IS tester simulations is further evident in the set of images shown in Figure 5.15 showing the various size ratios (large/small) from 1.17 to 3.5 of particles simulated at time $t = 60$ sec. The small particles are shown in red (dark particles) and the large particles are shown in yellow (light particles) and it is apparent that there is a relatively even distribution of both small and large particles along the entire
length of the drum in all cases, which corresponds to the plots previously shown in Figure 5.14. It is very interesting for the size ratios of 3.0 and 3.5 that as there are many more small particles, they have more influence on the segregation occurring because they drop from the vanes at higher angles and rebound from the bottom wall of the drum into the air flow. The effect of this is to effect the separation of small particles in the full drum and may result in some particles moving out from the drum by the air flow from the front to the back of the drum.

For the AS tester simulations, the results are shown in Figure 5.16 and present the segregation of various size ratios, with the average value for each location of the 5 bins at the time $t = 60$ sec. The percentage of small particle segregation varies by size ratio at the middle of the drum over 60 sec.

![Figure 5.15](image_url) Shows binary particle segregation in the IS tester with different size ratio simulated at time $t = 60$ sec.

Figure 5.16(a) shows the influence of the binary mixture of particle flow in the AS tester, different results of the particle volume fraction were observed for the axial segregation. The trend of the axial segregation seen for the range of particle size ratios from 1.0 to 3.5 are shown in the graph, showing the percentage of small particles in each bin. Adding the values present of each bin for a given size ratio will yield 100%, indicating the total volume of small particles present for the simulation, which in turn is 18% by volume of the total sample added to the drum for simulation. When the particle size ratio is low
(lower than 2.5), a larger concentration of small particles is present at both end walls of the rotating drum (bin1 and bin5). However, a higher volume fraction of small particles forms at the middle of the rotating drum (bin3) as the particle size ratio increases (greater than 3.0). The critical point where migration of fine particles moves from the outer walls to the middle of the drum occurs between size ratios of 2.0 and 2.5. It can be seen that the results show a rapid increase in volume fraction of the small particles at the middle of the drum when the size ratio increases from 2.5 to 3.0. Therefore, Figure 5.16(b) focuses on the middle of the AS tester (bin3) and is isolated for further scrutiny. The trend of the concentration of small particles has been followed over the first 60 sec (29 revs) of a simulated test for the range of particle size ratios simulated. It can be seen that for all size ratios, a steady-state concentration of small particles has been reached after approximately 20 revs (40 sec). The results are consistent with those seen in Figure 5.16(a) that the segregation bands can be observed when the size ratio is greater than 3.0 and the coefficient of segregation increases rapidly when the size ratio increases from 2.5 to 3.0. In the first 15 revs, a significant amount of small particles has migrated to the middle of the drum with the larger particles at either end. An interesting phenomenon was observed for the higher size ratio of 3.5. As the particle size ratio increases from 3.0 to 3.5, there exists a small particle size where the dimensionless band width has a minimum value at the middle of the rotating drum.

There is no axial segregation when mono-size particles are mixed, the dimensionless band width is equal to zero when particle size ratio is unity. Figure 5.17 shows the segregation of the small particles of six different size ratio occurring in the AS tester at t = 60 sec. There are substantially more particles present in these simulations compared to those of the IS tester simulation and as a result, there is a clear indication that segregation is
occurring, especially evident for size ratios of 3.0 and 3.5, with a band of small particles forming in the middle of the drum (bin3). Less segregation occurs for size ratios of 2.5 and below. However, the extent of this segregation is obviously increased due to the effect of size ratio in the AS tester. The axial and radial concentration distributions of the small particles after the drum has rotated for 60 sec for the various size ratios. In the axial direction, segregation occurs with the concentration of small particles increasing in the middle of the drum (bin3) as the size ratio increases. This corresponds with the noticeable jump in small particle volume fraction in bin3 seen in Figure 5.17. Even though the volume of material in the drum (4.7%) is substantially lower than for drum mixers (generally >20%), similar axial segregation trends are clearly present.

![Figure 5.17 Shows binary particles segregation in the AS tester with different size ratio simulated at time $t = 60$ sec.](image)

For a binary sized particle system, the higher the particle size ratio, the higher the segregation of small particles after the drum rotates. Whereas, the segregation of the small particles is not as significant when the particle size ratio has a smaller difference. It can be seen that for particle size ratios less than 2.0, large particles move to the middle of the drum, as shown in Figure 5.17. These results demonstrate no apparent influence of the particles size-segregated in the rotating drum, the particle movement has been clipped by a vertical plane passing down through the drum so that the internal distribution of particles can be seen.
5.5.4 Particle Segregation

Segregation is an important phenomenon in the rotating drums. When the drum is filled with two sizes of particles or two different densities, segregation occurs. This process is very fast after the drum starts its rotation. Segregation of small particles depends on the tangential friction at the end wall of the drum. Tangential end-wall friction tends to drag neighbouring particles along and transports them further along the rotation direction of the drum when compared to the particles in the middle of the drum. In addition, the initial location of the material heap inside the rotating drum affects the motion of particles. However, both drums have different quantities of material. For the IS tester, consider all the particles as moving with the drum wall and the large particle size moving out from the vanes and impact with the lower wall surface faster than a small particle. In contrast, for the AS tester, larger particles are surrounded by small particles and move along the inside wall of the drum.

From the analysis of the axial segregation, the volume fraction of small particles present in each bin has already been determined. However, this data does not indicate whether there is any particle segregation present within each bin. It has been well established in research focusing on drum mixers that a central core of small particles forms, surrounded by larger particles. The purpose of analysing the radial segregation is to investigate whether the same trends hold true for dustiness testers, where tests contain much smaller quantities of material. If these ‘pockets’ of smaller particles do exist, especially in physical testing, then there is also a possibility that they inhibit the extraction of a portion of the fine dusty material for which the dustiness testers are designed to capture.

5.5.4.1 Radial Segregation

Figure 5.18 reports the small particle segregation in the radial direction in each section of the IS tester simulations, no bed of material formed at the base of the drum, therefore no radial segregation could be observed. This is evident in Figure 5.18, where a cross-sectional slice in the middle of each bin has been displayed. The quantity of material being elevated by each of the lifters is not large enough to be able to distinguish any discernible segregation pattern. For the IS tester simulations, only the results for the size ratio of 3.5, at time t = 60 sec with four different initial loading locations of material have
been displayed as this ratio had the potential to show the greatest size segregation. The results for the other size ratios displayed very similar results to those in Figure 5.18. The velocity of a large particle falling to the wall was higher than the small particles. After the particles impact on the wall surface, the small particles scattered after the rebound as a result of the movement of the wall and airflow caused by the lifting vanes.

Figure 5.18 Shows the particle flow in the IS tester with size ratio 3.5 simulation with a different location and initial loading at time $t = 60$ sec.

Figure 5.19 shows the binary particle flow in the AS tester simulation with four initial loading positions using the size ratio of 3.5. Slices of the middle of each bin have been produced for each material loading position to visualise any radial segregation that has occurred as a result of drum rotation. As can be seen, after 60 sec of simulation time, there is a clear migration of small particles moving from the front or back of the drum towards the centre (bin3). In all four loading cases, there does not seem to be a substantial difference in the segregation pattern. Another important observation is that there does not seem to be a central core of small particles forming in the large cluster of particles at the bottom of the drum. This goes against the trend seen in regular drum mixing, however, the relatively small volume of particles used in the dustiness tester simulations is the most likely reason for this. It is quite possible that there is a minimum critical volume of
particles required to generate this central core of small particles, although this cannot be confirmed as it was outside the scope of the current investigation.

Figure 5.19 Shows the particle flow in the AS dustiness tester simulation with size ratio 3.5, different location and initial loading at time $t = 60$ sec.

5.5.4.2 Axial Segregation

The axial segregation of the particle flow in a dustiness tester is also affected by flow regimes and drum rotational conditions. For both sets of dustiness tester simulations, five cylindrical analysis bins of equal volume were created along the drum section, bin1 located at the front of each tester simulations and bin5 at the back (see Appendix B). The content of each bin was analysed to determine the movement of particles by measuring the percentage of material in each bin at each simulation time step for the entire duration of each standard test simulation.

Figure 5.20 reports the segregation of the small particles in the middle (bin3) of the IS and AS tester. Figure 5.20(a) focuses on the small particle fraction of the four initial loading positions at the time history up to $t = 60$ sec for the size ratios of 1.17 and 3.5. It
can be seen that for the front and back loading positions, the results are very similar, which should be the case as they are mirrors of each other. The middle loading position shows a rapid decrease in the fraction of small particles present as material spreads in either direction along the drum and the initial even spread loading of material remains constant throughout the test. For the size ratio of 1.17, steady-state conditions are obtained after approximately 1 rev \((t = 15\ \text{sec})\) and 2 revs \((t = 30\ \text{sec})\) for the size ratio of 3.5.

Figure 5.20(b) reports a further investigation of the four material loading positions used in the AS tester simulations showing a variation in results based on particle size ratio for bin3. Again focusing on the small particle fraction within each simulation, the time history up to \(t = 60\) is shown for a size ratio of 1.17 and 3.5. These two size fractions were chosen as they cover the extremes of the size range used in the DEM simulations. As can be seen, when the size ratio is small, steady-state conditions are reached very quickly and the results match with those shown in Figure 5.16(a). For the size ratio 3.5 more time is required (approx. 15 revs) before steady-state is achieved, where the volume fraction of small particles levels out at approximately 50% for all loading positions. This result also matches with the previously displayed data in Figure 5.16(a) and also the graphical representations shown later in Figure 5.17.

**Figure 5.20** Shows the volume fraction in the middle (bin3) of the rotating drum simulation with all loading positions in the (a) IS tester (b) AS tester.
When considering an initial heap of particles at the front, back and middle of the AS tester, the volume fraction of the small particles were rapidly increasing up to 7 revs and remained constant throughout as the drum rotated, but the results of volume fraction at middle heap are slightly higher than both the front and back loading positions. However, for the even spread loading position start from the front to the back of the rotating drum, the small particle volume fraction gradually increased in the first 20 revs approximately and then showed steady-state to the end time.

5.5.5 Discussion

In this study, the behaviour of different binary mixtures of size ranges of polyethylene pellets has been investigated via DEM simulations in the IS and AS tester simulations, based on the parameters given in Table 5.1. Analysis of the DEM simulation data for the four initial material locations also showed that each had different initial transient behaviour for both dustiness testers. Steady-state conditions were reached in a relatively short time, as shown by the plotting of the volume fraction of the small particle component over a 60 sec simulation. Both the IS and AS showed varying levels of segregation in the radial and axial direction for the different binary mixes.

For the IS tester, it was found that regardless of the size ratio of the two polyethylene pellets components, due to the small quantity of product used per simulation, it was not possible to observe or measure any axial or radial segregation occurring within the rotating drum. For the AS tester, the larger quantity of product allowed the formation and observation of axial segregation along the drum length. For low size ratios the small particle fraction migrated towards the end walls of the rotating drum but as the size ratio increased, the small particles migrated towards the centre of the drum. Unlike the trends seen by numerous researchers in drum mixers, only a single banding of small-large-small or large-small-large particles was observed, although this is likely due to the relatively short length of drum used. When considering radial segregation, there was no indication that this was occurring and is likely due to the low percentage fill of the drum (4.7%). This fact is useful to know as the results indicate that there is no central core of small particles, like is generated in drum mixers. If the observations from the DEM simulations were to compare favourably with the experimental equivalents, this would indicate that it is highly unlikely that the extremely fine dust particles being encapsulated within an outer
core of larger particles. This is important to know because the dust particles are critical component of the test product in determining the dustiness of a material.

5.6 Development of a Coupled DEM-CFD with Dustiness Tester Model

This section investigates the two computational techniques available to analyse the air flow patterns with particles moving in two dustiness testers; the IS and the AS tester via DEM and CFD coupled simulations. While DEM focusses on the movement of particles in the rotating drums, CFD focuses on the flow of air in the drums. Therefore, the DEM-CFD coupled method was developed to simulated mechanisms of polyethylene pellets movement and air flow in the rotating drums.

5.6.1 Simulation Condition

The particle shape and size used in the DEM-CFD coupling simulations is the spherical model used to present polyethylene pellets, as explained in Chapter 4 and shown in Figure 4.13, based on the equivalent volume of the product sample. Subsequently, in the DEM simulations the particles were set with a fixed spherical particle size. The geometry of both dustiness testers used in this work are shown in the schematic diagram in Figure 2.1(b), Figure 2.2(b) and type of particles used in these simulations were based on the experimental work. Polyethylene pellets are packed in the bottom of the drum for each test for the simulation the same as in the experiments and the four different loading locations of the product sample have also been used. To produce accurate DEM simulations, the physical properties of the polyethylene pellets and the drums (304 stainless steel) have been used to aid in the determination of the interaction properties, as shown in Table 5.1 and parameter of the air input to CFD as shown in Table 5.3. Air vacuum occurs at the back of both dustiness testers, which is 38 l/min and runs for 60 sec for the IS tester and 175 l/min and runs for 600 sec for the AS tester in the horizontal direction. The AS tester simulations have been stopped when the results are steady-state. The drum rotates at 4 rpm for the IS tester and 29 rpm for the AS tester. The particle flow patterns and velocity fields are recorded during the coupled simulation.

3D models of both dustiness testers, inlet air flow and outlet duct and the rotating drum were created. The computation of the air flow required a CFD mesh applied in the drum
model as an unstructured orthogonal mesh with approximately 12,640 cells for the IS rotating drum and approximately 169,650 cells for the AS rotating drum. The walls of the drum were set as rigid bodies that rotate around the axis along the drum with their respective velocity based on the standards of both dustiness testers. The CFD mesh dynamically adapts to the moving boundary. To account for turbulent flow above the granular assembly as well as in the cavities between the particles, the standard $k-\varepsilon$ model (Lauder et al., 1972) with the standard parameter unchanged were applied. A no-slip shear condition was used as the boundary condition for the fluid flow at each wall. The simulations were set up to match the experimental conditions of the dustiness testers and using the ambient temperature and pressure. The DEM simulation time step is calculated by the Rayleigh time step given by equation 2.40 and setup the volume of time step of $0.3T_R$ for the DEM simulations. The DEM time steps are typically substantially smaller than the CFD time steps, with the ratio of the DEM to CFD time step varying from 10 to 100. This is also vital for the DEM-CFD simulations replicating the same experimental tests.

<table>
<thead>
<tr>
<th>CFD parameters</th>
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</tr>
</thead>
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<tr>
<td>Type of fluid</td>
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</tr>
<tr>
<td>Fluid viscosity (kg.m$^{-1}$.s$^{-1}$)</td>
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</tr>
<tr>
<td>Turbulence model</td>
<td>Realisable $k-\varepsilon$</td>
</tr>
<tr>
<td>Air flow inside the drum (l/min)</td>
<td>38, 175*</td>
</tr>
<tr>
<td>CFD simulation time step, $t_{CFD}$ (s)</td>
<td>1E-03</td>
</tr>
</tbody>
</table>

* 38 l/min for IS tester and 175 l/min for AS tester

5.6.2 Model Validation

The air flow inside the rotating drum is the most important operational parameter for analysis of the particle movement and air flow in the both dustiness tester and this is the major parameter for validation purposes in this section. The velocity of air inside the AS tester, as shown in Figure 5.21, indicates that the simulated air velocity at the inlet of the drum agrees with the experimental data.

For the particles moving in the AS tester with air flow rate at 175 l/min, as shown in Figure 5.22, the particle movement from the DEM simulation are compared with the experimental results. The results show different behaviour on the vanes and the amount
of particles falling on the free surface were affected by the coefficient of static friction and coefficient of rolling friction between particle and particle and between particle and wall and the particle size distribution, especially due to the model of the particle shape.

![Figure 5.21](image1.png) **Figure 5.21** Comparison of simulated and experimentally measured air velocity at different air flow rate.

![Figure 5.22](image2.png) **Figure 5.22** Comparison flow pattern of particle simulation and experiment in the AS tester with air flow rate at 175 l/min.

### 5.6.3 Particle Flow Pattern

Ensight from CEI is a PC based software program that produces high resolution visualisation of data and has been used to post-process the DEM and CFD results together, as shown in Figure 5.23. The frame shape defines the particle flow in the radial direction as the drum rotates and the velocity streamlines of air flow through the particle in a horizontal direction. The swirling flow field is generated from the front as the air is extracted from the back of the drums and are coloured based on air velocity. The effect of the particle velocity and airflow in both drums are shown using the different colours.

It can be seen that the air flow looks like a helically twisted cylinder from the front to the back of the drum. The air flow patterns in the rotating drums are generated by two sources.
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consisting of air generated by the lifting vanes of the drums and air flow generated by the air pump at the back of the drum. The air velocity influences the lift force and drag force in both rotating drums. Figure 5.23(a) shows the particles and airflow in the IS tester. As mentioned previously, there is a small quantity of particle in the IS tester rotated by the lifting vanes. The results showed the influence of air flow generated from the lifting vanes on the lift force acting on each particle falling from the vane is higher than the air generated by the air pump. Figure 5.23(b) shows the particles and airflow in the AS tester, the larger quantity of particles means more particles slide on the free surface of the particles moving in the rotating drum. The particles at the top at the free surface drop from the lifting vanes and affect the drag and lift force in the drum as it rotates.

Figure 5.23 Snapshots showing the particles and air flow in the drum (a) IS tester (b) AS tester.
5.6.3.1 Particle Flow

The flow pattern of the particle movement combined with air flow in the drums shows that most particles congregate at the drum wall for the IS tester or the free surface for the AS tester immediately after the particles falling from the lifting vanes. However, Figure 5.24 to Figure 5.28 shows a particle flow pattern was captured by the current DEM-CFD coupling model. When the particle loading is 35 cm$^3$ and air flow 38 l/min for the IS tester and 1000 cm$^3$ of particle loading with air flow 175 l/min for the AS tester.

![Figure 5.24](image)

*Figure 5.24* The particles movement in the IS tester at various times through the simulation (Particles are coloured by the particle velocity).

Figure 5.24 shows the particle flow in the IS tester as the particles begin to move at $t = 5.0$ sec and all the particles drop from the lifting vanes after a further 0.5 sec. Then another 0.5 sec later all the particles are again on the bottom wall of the drum. It can be seen that at 6.0 sec, the amount of particles on the top vane (location A) is 19.5%, 16% on the bottom of the drum (location C) and most particles are on the middle vane (location B) at 64.35%, approximately. After the drum rotates 1 rev, approximately 50% of the particles move out from the vanes, with approximately 6% falling to the near vane (A), 14% to the bottom of the drum (C) and most particles (approx. 80) fall to the middle vane (B) and this process repeats until the end of the simulation, as shown in Figure 5.25. The different parts of the falling material affects the drag force in the drum in different proportions.
It would also be interesting to know the difference to the particle flow patterns with the four different loading positions of the particles and the air flow in the rotating drums. Figure 5.26 compares the flow patterns between the even spread, front, middle and back heap of particle loading. It clearly is seen that the particle flow patterns have similar results after 1 rev (15 sec) for the IS tester.

Figure 5.27 shows the particle flow pattern captured by the current DEM-CFD model in the AS tester. It can be seen that the particles begin moving out from the lifting vanes at 0.9 sec, falling back to the free surface and repeat the process every 2 sec (approximately) and move down to the bottom of the drum. It is clear that, at $t = 0.6$ sec the particles slide on the top surface of the particle loop in the rotating drum at 0.8 m/s (approximately) towards the bottom of the drum and is higher than the particle velocity at the wall surface (wall velocity is 0.455 m/s). Therefore, most energy occurs on the top surface of the materials and the maximum force appears as the particles drop to the free surface. Moreover, the highest velocity is about 1.9 m/s for the particles dropping to the bottom of the drum. The particle flow in the drum has reached steady state after 10 sec and the process repeats until the end of the simulation.
Figure 5.27 The particles movement in the AS tester at various times through the simulation (Particles are coloured by the particle velocity).

Figure 5.28 compares the flow patterns of particles with different loading positions in the AS tester simulation. The particle flow in the drum has reached steady state after 10 sec. It can be seen that the results for the four initial loading positions are very similarly.

Figure 5.28 The particles movement in the AS tester at t = 10 sec with four loading positions (Particles are coloured by the particle velocity).

5.6.3.2 Air Flow

Figure 5.29 shows the three zones of the rotating drums used for analyse of the air flow in the drum consisting of; the left zone where there is particle flow, right zone (no particles) and the perpendicular plane through the middle of the drum. The left zone and right zone were created at the middle plane of the drum and the perpendicular plane show at the middle length of the drum.
The inner flow structures of the air phase under different simulation times for the flow under different particle loading positions in the two rotating drum are shown in Figure 5.30 to Figure 5.34. They show the air flow in the IS tester simulations and AS tester simulations. Figure 5.30 shows the pressure distributions with the different initial loading position of particles and time steps for the IS and AS tester. It is clear that the pressure is higher on the wall of the drum and can be very close zero along centre of the cylinder drum. The magnitude of the pressure near the wall of the drum region on the left zone with the particles moving is higher than the right zone, where there are no particles. Comparing Figure 5.30(a) and (b) for the IS tester simulation, the pressure in the left zone and back region of the drum disappeared after the particles move out from the vane and drop to the base of the drum. This suggests that the number of particles has a higher impact on the air of the lift zone than on the other zone of the drum. Another obvious trend shown in Figure 5.30(b) is that the particles are falling and the pressure zone decreases as particles segregate in the drum. Figure 5.30(c) and (d) for AS tester simulation show the pressure distributions in the drum as it rotates. This drum has small vanes, most particles slide on the free surface of the material in the lower zone of the drum. There is a small hole for the air inlet to the rotating drum and high-velocity flow in the core of the drum as a result. The pressure distributions are symmetrical and the higher pressure occurs at the middle of the drum at the inlet and outlet zones.

Figure 5.29 Diagram of the analysis zone in the rotating drum.
Figure 5.30 Pressure (Pa) distributions at the centre part of the tester at different simulation times for the IS tester at (a) t = 5 sec (b) t = 60 sec and for the AS tester at (c) t = 0.5 sec, (d) t = 10 sec.

Figure 5.31 shows the tangential velocity distributions with different time steps for the IS and AS testers. The visible trend of the tangential velocity decreases overall with an increase of particles falling, particularly in the back region of the IS tester. It also shows that the particles have a higher impact on the air at the back of the drum than on the other regions of the drum. Another trend shown in Figure 5.31 shows that the distribution of the tangential velocity is very close to symmetrical at time = 5 sec for the IS rotating drum and 0.5 sec for the AS tester. The particles drop down from the vanes as shown at time t = 60 sec and this lift zone show that the tangential velocity is not symmetric with the right zone.
Figure 5.31 Tangential velocity (m/s) distributions at the centre part of the tester at different simulation times for the IS tester at (a) t = 5 sec (b) t = 60 sec and for AS tester at (c) t = 0.5 sec (d) t = 60 sec.

Figure 5.32 shows the axial velocity in the IS and the AS testers. The legend scale displays the velocity of the air flow in the axial and radial directions when particles are moving in a rotating drum. However, the current model can readily produce those velocities. It can be seen that when the particles drop from the vanes to the wall surface at time = 60 sec, as shown in Figure 5.32(b), the velocity moves toward to the centre of the IS tester as the particles drop down. For the IS tester, it is clear that the highest axial velocity zone moved from the front to the back of the drum. This trend is believed to be caused by the vacuum pump at the back of the drum, however, the accumulation of particles in the lift zone in the drum restricts air flowing from the front of the drum to the back of the drum. The reaction force of the particles acting on the air phase is pointed in the axial direction. Figure 5.32(c) and (d) shows the axial velocity for the AS tester simulation, the high velocity is show in the axial direction of the drum from the air inlet (front) to the outlet (back) of the drum, as the left zone of the drum has particles dropping which affects the air flow in the axial direction of the drum.
Figure 5.32 The axial velocity (m/s) distributions at the centre part of the tester at different simulation times for the IS tester at (a) t = 5 sec (b) t = 60 sec and for the AS tester at (c) t = 0.5 sec (d) t = 60 sec.

Figure 5.33 shows the radial velocity in the middle section of the drum at time t = 60 sec for the IS tester and time t = 10 sec for the AS tester. Figure 5.33(a) for the IS tester shows that the two force vortex zone of the drum for pure air flow looks like a helical twisted cylinder. The first zone is the mixture between the air flow and particles falling and is shown as the minus radial velocity, which means the particle velocity is higher than the airflow in the axial direction of the rotating drum. The zone of the air flow without particles shows the axis of the forced vortex in the rotating drum becomes almost straight from the front to the back while near the end wall of the drum the forced vortex is in the same direction as the drum rotates. As particles drop from the vanes, the forced vortex increases in this zone of the drum. Figure 5.33(b) shows the radial velocity for the AS tester at the mid-section of the drum, the air velocity generated from the vanes of the drum rotation has a smaller axial velocity from the vacuum pump.

There is the magnitude velocity of the air flow when particle is moving in the rotating drum. However, the current model can readily produce those velocities. Figure 5.34(a) and (b) for the IS and AS testers show the velocity magnitude in the axial direction of the drum and in the perpendicular plane at the middle of the drum section. The velocity was shown non-symmetric in the rotating drum where the turbulence zone occurs as the particles move down from the lifting vanes to the bottom wall of the drum. In this zone the velocity of airflow is higher than the opposite zone without particles, particularly near the outlet of the drum.
Figure 5.33 Radial velocity (m/s) distributions at the centre part of the tester for (a) the IS tester at time $t = 60$ and (b) the AS tester at time $t = 10$ sec.

Figure 5.34 Magnitude velocity (m/s) distributions at the centre part of the tester for (a) the IS tester and (b) the AS tester.

5.6.4 Effect of Air Flow in the Dustiness Testers

This section investigated the effect of the airflow and compared the dynamics of a particle in the dustiness tester with non-airflow. The particles distribute across the five bins of the rotating drum versus simulation time with mono-particle size flow in both dustiness testers, the initial heap of particle spread evenly along the drum, as shown in Figure 5.35. The volume fraction change was calculated from the different of volume fraction of the
airflow and volume fraction with non-airflow in the IS tester, as shown in Figure 5.35(a) and particle distribution in the AS tester is shown in Figure 5.35(b). The particle distribution is the concentration profile of the particle movement in both dustiness testers and as can be seen, is relatively non-uniform for the five bin positions along the drum. Also, as the particles are a relatively large size and the amount of particles is relatively small, there are not enough to cause the particle segregation with the drum rotating.

Figure 5.35 The mono size of particle distribution change the volume of fraction in the (a) IS tester (b) AS tester.

Figure 5.36 shows the binary particles at the size ratio of 3.5 flowing in the IS and AS tester. It can be seen that the small particle size is important in the first section (bin1). The volume fraction decreased to all the simulation times and increased the large size of the particle in this bin. This drum does not have enough particles to generate a large number of collisions between the particles in the drum as it rotates (for the IS tester). Therefore, all particle distributions in the drum are as a result of the particles falling and rebounding to free space in the drum. For the AS tester, the small particles fall and slide on the free surface to the lower drum. The air flow to the back of the drum is lower than the particle velocity falling from the vanes. Figure 5.36(a) recorded the particle size is 2.0 mm diameter segregation in five locations are flow fluctuate over the simulation time all the each bin of the IS tester. For the AS tester presented in Figure 5.36(b) flow of small particle over the time in the range. It is found that the small particle size decrease in the middle section (bin3), with the air driving the small particle size to the end section (bin5) of the drum.
Figure 5.36 The small particle size of the size ratio 3.5 distribution change the volume of fraction in the (a) IS tester (b) AS tester.

5.6.5 Conclusions

It has been shown that the developed DEM-CFD model is able to study the solids-air flow in a rotating drum and it can satisfactorily capture the flow patterns of solids flow in the radial direction and air flow in the horizontal direction, pressure drop and tangential velocity decrease after the particle falls in the drum as it rotates. The effect of initial particle loading position in both drums has been simulated and analysed. The following findings have been obtained:

1) For the particle flow, for the different particle loading positions in both dustiness testers, there are more particles moving to the back region of both drums due to the air flow. The velocities of particles falling from the vanes to the bottom of the drums are also an important variable affecting the particle and air flow patterns in the drum.

2) For the air flow, the pressure goes up in the zones having particles moving or dropping from the vanes and then decreases for all of the zones without particles. When the air flow in the dustiness tester reaches a dynamically steady-state condition, the tangential velocity and the pressure drop of the air phase decreases steadily when there is an increase of particle flow. The high axial velocity flows on the central axis of the drum, and the radial flow of the air phase is heavily variant, particularly in the particle zone (on the lift zone), where there is an increase of particles dropping in the drum.

Finally, it should be pointed out that this study is conducted for relatively large particles. For smaller particles, the predictions may be different to some extent. However, due to limitations in computing power, it is not yet feasible to simulate the small, ‘dusty’
particles due to time constraints. Therefore, this section is preliminary in nature and mainly aims to expand the understanding of DEM-CFD modelling when applied to the air flow in rotating dustiness testers. More detailed, structured studies are needed to understand the particle characteristics, mechanical and physical properties of material, geometry of the dustiness tester, operational conditions and generate results useful to engineering application, but only once computing power has increased.
Chapter 6

Numerical Analysis of Iron Ore Flow in Dustiness Testers

6.1 Introduction

This chapter presents the DEM simulation investigation effect of particle motion due to various parameters influencing the flow of particles in the IS and AS testers, which is then compared to the particle flow obtained experimentally. This study proposes the principle of modelling spherical shape and spherical clusters which were applied in 3D rotating drums by DEM simulation.

In addition, the simulations have been combined between discrete element method (DEM) and computational fluid dynamics (CFD) to investigate the air flow patterns with particles moving in both dustiness testers. The DEM focusses on the particle movement in the rotating drums and the CFD focusses on the air flow in the rotating drums. Therefore, the DEM-CFD coupled method was developed to simulated flow mechanisms of iron ore and air flow in the rotating drums. The interaction of particle contact effect from the coefficient of static/rolling friction between particle and particle and between particle and wall will be considered. The interaction forces between particle-air, particle-particle and particle-wall on the solid and fluid phase are analysed to understand their influence in terms of typical flow features in rotating drums.

6.2 Methodology Analysis

Iron ore was chosen as the test material for this investigation to visualise the flow mechanisms of the particles within the rotating drums of the two dustiness testers, but not to measure the amount of dust generated during the testing. This is also vital for the DEM simulations replicating the same experimental tests. The IS and AS testers require
differing operating conditions to follow their respective standards, see Section 2.2. There are two conditions which will be presented in this chapter. The first will simulate the dustiness testers with no air flow and second will be simulating the dustiness testers with air flow to compare to the experimental results previously presented in Chapter 3.

6.3 Computer Simulation

This study uses two dustiness testers for simulating the iron ore flow in a system. The DEM simulation predicts the particle movement and collision in the IS and the AS tester models with a multiplier of 30% (approximate) applied to the computed critical time step for the simulations. For the DEM simulation of the IS tester a run time for a 60 sec simulation varied from 10 to 30 hours for all particle models. The AS tester run time for a 600 sec simulation time was approximately 500 – 750 hours, depending on the type of particle model. For the DEM-CFD coupled simulations using the EDEM and ANSYS FLUENT software, the simulation run time was for 60 seconds for the IS tester and 120 sec for the AS tester. The coupled simulations require a simulation time of approximately 3 times more than the DEM simulations for both dustiness tester models.

6.4 Simulation of Particle Flow Mechanisms in Dustiness Testers

This section presents a numerical investigation of the iron ore model flow in the IS and the AS testers using DEM simulation and comparing the results obtained by experimental data. The results focus on the effect of particle contact force under different particle shape and particle size movement in the rotating drums and interaction coefficient between particle-particle and between particle-geometry.

6.4.1 DEM Simulation Conditions

The particle shape and particle size of the iron ore model are equal to the equivalent volume diameter and mass of material, as shown in Figure 4.22. The volume and mass of the particle models matched with the experimental data. Subsequently, particle models in the DEM simulations were set with a fixed particle size and shape, with all the particles generated from the injection plane to the bottom of the drum in 2 sec. The particle size and particle shape of the iron ore model, material properties and interaction between
particle and particle, and between particle and wall selected for simulation by the DEM software for the particle flow in the two dustiness testers are shown in Table 6.1.

**Table 6.1** Particle and bulk properties of iron ore, stainless steel and Perspex.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Iron ore</th>
<th>Stainless Steel</th>
<th>Perspex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size distribution (5.6 - 6.3 mm)</td>
<td>3.38%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (4.0 - 5.6 mm)</td>
<td>15.53%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (2.0 - 4.0 mm)</td>
<td>57.83%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (1.0 - 2.0 mm)</td>
<td>23.03%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle volume, (m³)</td>
<td>0.101</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle mass, (g)</td>
<td>0.276</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle density (ρₚ), (kg/m³)</td>
<td>3867.8</td>
<td>8000</td>
<td>1200</td>
</tr>
<tr>
<td>Poisson’s ratio (ν)</td>
<td>0.4</td>
<td>0.29</td>
<td>0.35</td>
</tr>
<tr>
<td>Shear modulus (G), (Pa)</td>
<td>1.92 x 10⁸</td>
<td>7.75 x 10¹⁰</td>
<td>1 x 10⁹</td>
</tr>
<tr>
<td>Particle coefficient of restitution, (CoR)</td>
<td>0.258</td>
<td>0.269</td>
<td>0.449</td>
</tr>
<tr>
<td>Particle coefficient of static friction, (μₛ)</td>
<td>0.58</td>
<td>0.6</td>
<td>0.348</td>
</tr>
<tr>
<td>Particle coefficient of rolling friction, (μᵣ)</td>
<td>0.1(0.1)</td>
<td>0.3(0.1)</td>
<td>0.3(0.1)</td>
</tr>
</tbody>
</table>

The coefficient of rolling friction are presented as: spherical shape (non-spherical shape).

The simulations of the iron ore particle model (see Figure 4.22) investigate the effect of particle flow in the rotating drums. Table 6.2 summarises the dimensions and number of particles for the four particle sizes used in the rotating drum simulations. The P1 particle is representative of the largest sized particle measured experimentally of 6.3 mm while P2 to P4 are arbitrarily smaller sized particles of 5.6 mm, 4.0 mm and 2.0 mm, respectively.

The calculation of the required number of particles was based on experimental data (Table 6.1) of the particle sample tested in both the IS and the AS testers. A simplification was made in the calculation of the number of particles required, that being there was no accounting for the void space that would exist between the particles. The assumption has been made that because this simplification was used for all particles, any error would be spread between the size of particles, thus negating any over prediction. The simulation configurations are built to match the experiment with equal the volume of material 35 cm³ for the IS tester and 1000 cm³ for the AS tester.
Chapter 6: Numerical Analysis of Iron Ore Flow in Dustiness Testers

Table 6.2 Dimensions of simulated particles and the number of particles required for the DEM simulations.

<table>
<thead>
<tr>
<th>Shape</th>
<th>SP</th>
<th>2-SP</th>
<th>PY</th>
<th>Number of Particles for the IS / AS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d (mm)</td>
<td>w (mm)</td>
<td>l (mm)</td>
<td>w₁ (mm)</td>
</tr>
<tr>
<td>P1</td>
<td>6.3</td>
<td>5.3</td>
<td>7.9</td>
<td>6.8</td>
</tr>
<tr>
<td>P2</td>
<td>5.6</td>
<td>4.7</td>
<td>7.0</td>
<td>6.3</td>
</tr>
<tr>
<td>P3</td>
<td>4.0</td>
<td>3.4</td>
<td>5.1</td>
<td>4.7</td>
</tr>
<tr>
<td>P4</td>
<td>2.0</td>
<td>1.7</td>
<td>2.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>

SP: spherical shape; 2-SP: two sphere cluster; PY: pyramid shape; d: diameter of particle; w₁, w₂: width of particle; h: height of particle

6.4.2 Validated Material Model

Iron ore material flow in the IS and AS testers has been investigated experimentally and the results compared with three particle shapes and four different starting positions in the corresponding DEM simulations. Figure 6.1 and Figure 6.2 show typical figures of the particles flowing in the IS and AS tester for experiments and the various particle models in DEM simulation for 1-sphere shape, 2-sphere cluster shape and pyramid shapes. The figure shows the experimental as well as DEM results for the three particle models based on the four initial material locations at the end time (t = 60 sec) of rotation in the IS tester and 10 sec of rotation in the AS tester. The results shown in the first columns are from the experiments and the other columns for the DEM simulations. Each row presents a different material starting location. Figure 6.1 shows the iron ore model flow for the four different starting locations; the even spread, at the front, at the middle and at the back of the drum and three different simulated particle shapes. The iron ore particles can be seen moving out from the lifting vanes for the experimental and simulated results. For the front, middle and back initial particle locations the particles do not spread long the full drum in the time simulation of 60 sec for the IS tester. In contrast, the particles for the even spread heap, during rotation, move out from the side of the vanes and return to the main drum section due to the conical ends. For the spherical particle DEM simulations, all particles have fallen from the upper lifting vane at 24 degrees from horizontal plane (t = 60 sec) to the vanes below, whereas, the clustered and pyramid particle simulations show particles still on the vanes and matching very well with the experimental results. Therefore, the 2-sphere cluster particles were selected to analyse in this work, as they save simulation time compared to the pyramid shape (4-sphere cluster). Both starting locations for the front and back of the drum show similar particle flows and particles spread along the vanes and move out from the vanes every 2 sec up to 60 sec.
Figure 6.1 shows the experimental and DEM results for the three particle models based on the four initial material locations in the AS tester at $t = 10$ sec. The experimental and DEM results all show the flow of particles moving out from the vanes having similar profiles and visual inspection of these tests and simulations showed that for each, particles had spread the entire length of the cylindrical drum section at this time, indicating a very good comparison between the experimental and DEM results. The non-spherical model particles can be seen moving out from the lifting vanes and moving along the surface of particle heap as the drum rotates colliding with other particles and the wall surface of the drum for the different particle shape models and the different starting locations. Like for the IS tester, the 2-sphere clusters and pyramid shaped particles compared best to the experimental results.
Figure 6.3 compares the results between experimental data and the simulation of the two sphere particle model with five bins and at four time steps with an initial even spread of material. It can be seen that the trend of the particle segregation in the five bins of the AS tester were very similar. The results were different because of two main seasons. Firstly, injection of the particles to the bottom of the rotating drum for the simulation model was based on randomly generating large and small particles from the injection plane in a 2 sec time period, while for the experiments, all particles were mixed in a container and poured into the bottom of the drum evenly from the front to the back of the drum. Secondly, the experimental drum has a slight “wobble” due to the method of manufacture. This causes a slight non-symmetrical movement of particles in the drum towards the back and as a result, the number of small sized particles increase in bin4 of the experimental drum. This is different to in the simulations, with no wobble in the simulated drum tests.
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6.4.3 Effect of Particle Contact Force

The particle flow phenomenon is decided by many parameters, especially the frictional force that could affect the particle movement in a system. It is important to understand the effects of these key parameters on particle flow in the dustiness tester. There are two main types of friction: coefficient of static friction and coefficient of rolling friction which are analysed in this chapter. These two frictions occur between particle and particle and between particle and geometry during the movement of particles in the rotating drums and they affect the particle flow considerably. The effects of four frictional interactions are taken into consideration: 1) particle-wall static friction, 2) particle-particle static friction, 3) particle-wall rolling friction and 4) particle-particle rolling friction. In the DEM simulation model, changes were made to both the coefficient of static and rolling friction for particle-particle interactions and particle-wall interactions. The following sections describe the variation of static and rolling friction for the even spread initial material loading condition only.

6.4.3.1 Effect of Particle and Particle Static Friction

Figure 6.4 shows the velocity of the particle flow patterns in the IS and AS testers with different coefficient of static friction values for the particle-particle ($\mu_s(p,p)$) interactions and leaving all other parameters constant. Figure 6.4(c) represents data in Table 6.1. It is clear that the particle movement is very similar for all $\mu_s(p,p)$ values for both rotating drums. Many particles move out from the vanes at the same angle of drum rotation. The velocity of particle movement in the rotating drum decreases when $\mu_s(p,p)$ reduces from...
0.6 to 0.4 and 0.2. This is because when reducing the $\mu_{s(p,p)}$, particles have less influence on other particles. Particles at the bottom of the drum near the wall, tend to move down to the bottom of the drum because of the voids there and the friction between particles is not enough to resist the movement. As a result, the particles at the bottom become active and could be more easily moved with the drum. The particle flow pattern does not change significantly when increasing the $\mu_{s(p,p)}$ from 0.6 to 0.8. The IS tester simulations show the amount of particles falling reduces when there is an increase in $\mu_{s(p,p)}$. Also, the angle at which particles fall from the vanes increases when $\mu_{s(p,p)}$ increases. The AS tester simulations display a higher angle of the particle heap on the drum with a higher $\mu_{s(p,p)}$. Also, there are many particles close to stationary in the middle of the heap (yellow colour), which are trapped between the moving outer layers.

**Figure 6.4** Particle flow patterns obtained for different coefficient of static friction values of particle and particle (a) 0.2, (b) 0.4, (c) 0.6 and (d) 0.8 in the IS tester at time $t = 5.6$ sec and the AS tester at time $t = 10$ sec.

### 6.4.3.2 Effect of Particle and Particle Rolling Friction

Figure 6.5 shows the velocity of particle flow patterns in the IS and the AS testers for different coefficient of rolling friction values for particle-particle ($\mu_{r(p,p)}$) interactions. The IS tester simulation images are all based on the same time step of 5.6 sec from the start of the simulation and for the AS tester simulation, the images are based on the same time step of 10 sec from the start of the simulation. At both these times, steady-state conditions have been reached. Figure 6.5(b) represents the simulations using the data from Table 6.1 for both the IS and AS tester.
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For the IS testers simulations it is clear that for $\mu_{r(p,p)} = 0.01$, there is very little difference to the results of Figure 6.5(b) but as $\mu_{r(p,p)}$ increases to 0.3 and then further to 0.6, more product remains on the vanes at this time step due to the increased frictional properties, thus fewer particles can be seen falling from the vanes back to the bottom of the drum.

For the AS tester simulations, the flow patterns shown in Figure 6.5(c) and (d) do not change significantly, even though $\mu_{r(p,p)}$ has increased from 0.3 to 0.6. There is a noticeable difference of the flow pattern when the coefficient of rolling friction increased from 0.1 to 0.3 also and decreased from 0.1 to 0.01. The main differences can be seen with respect to the velocity of the particles. For the $\mu_{r(p,p)} = 0.01$ case, it can be seen that due to the very low coefficient of the rolling friction, particles roll or slide from the vanes at the lower angular position. The AS tester display a high angle of the particle heap on the wall of the drum with a higher $\mu_{r(p,p)}$ and the middle of the rising heap (yellow colour) shows more particles when $\mu_{r(p,p)}$ drops to 0.01.

![Figure 6.5](image)

**Figure 6.5** Particle flow patterns obtained for different coefficient of rolling friction values of particle and particle (a) 0.01, (b) 0.10, (c) 0.30 and (d) 0.60 in the IS tester at time $t = 5.6$ sec and the AS tester at time $t = 10$ sec.

### 6.4.3.3 Effect of Particle and Wall Static Friction

Figure 6.6 and Figure 6.7 show the velocity of the particle flow patterns in the IS and AS tester and the effect of particles on the vanes with different coefficient of static friction values for particle-wall $\mu_{s(p,w)}$ interactions.
6.4.3.3.1 Effect of Particle Movement

Figure 6.6 shows the velocity of the particle flow patterns in the IS tester at the time \( t = 5.6 \) sec and the AS tester at time \( t = 10 \) sec with different \( \mu_{s(p,w)} \) values, where all other values are constant. Figure 6.6(c) represents simulations using the data in Table 6.1. It is clear for both the IS and AS tester that the particle flow patterns change significantly when the \( \mu_{s(p,w)} \) decreases from 0.6 to 0.1.

For the particle flow in the IS tester, it can be seen that the particles are moving out from the vanes to the lower part of the drum at a small angle of the vanes rotating from the horizontal, while increasing the \( \mu_{s(p,w)} \) up to a value of 0.9 shows that more particles are remaining on the vanes due to increased friction. The angle of the vane must increase for the same number of particles to fall to the lower part of the drum as \( \mu_{s(p,w)} \), most particles drop to the next vane and display low velocity and forces. In contrast, for the high \( \mu_{s(p,w)} \) values, the particles drop to the lower vanes due to the higher angle of the vanes before the particles fall. As a result, the velocity and force have a greater impact on the bottom wall of the drum and particles rebound to free space.

The particle flow patterns simulated in the AS tester are shown in the second row of Figure 6.6. A large stagnant zone (yellow colour) exists along the drum when \( \mu_{s(p,w)} \) drops to 0.1. In contract, the average velocity of particles increased as \( \mu_{s(p,w)} \) increases. The reason is that the particles near the wall surface suffer from smaller friction from the wall of the drum, so they move downwards more easily. However, the particle flow pattern does change significantly when increasing \( \mu_{s(p,w)} \) from 0.6 to 0.9. The particles falling from the vanes are close to the vertical plane of the drum as it rotates, for the highest value of \( \mu_{s(p,w)} \). However, for the lowest \( \mu_{s(p,w)} \), the images show the particles moving on the free surface as the drum rotates. The particles drop from the vanes at lower angles as the drum rotates and it shows the lowest velocity of particles occurs in this case.
6.4.3.3.2 Effect the Particle on the Vanes

Figure 6.7 shows the effect of particles on the vanes for the IS tester. The time that particles remain on the vanes has been investigated from the time particles start moving out from the vanes until the last particles fall to the bottom wall of the drum, as a result of different $\mu_{s(p,w)}$. The results show that the particles remain on the vanes longer as $\mu_{s(p,w)}$ is increased from 0.1 to 0.9.
Figure 6.8 shows the effect of particles falling from the vanes for the AS tester. The time particles remain on the vanes as the drum is rotating is longer when $\mu_{s(p,w)}$ increases. In this case, particles fall from the vanes at 37 degrees for $\mu_{s(p,w)} = 0.1$ and fall at 45, 57 and 72 degrees when $\mu_{s(p,w)}$ is increased to 0.3, 0.6 and 0.9 respectively.

**Figure 6.8** Particle flow patterns at the end of particles falling from the vanes for different coefficient of static friction values of particle and wall (a) 0.10 (b) 0.30, (c) 0.60 and (d) 0.90 in the AS tester.

### 6.4.3.4 Effect of Particle and Wall Rolling Friction

Figure 6.9 shows the velocity of particle flow patterns in the IS and the AS testers with different coefficient of rolling friction particle-wall $\mu_{r(p,w)}$ interactions. Figure 6.9(b) represents simulations using the data in Table 6.1. The IS tester shows the particles falling from the vanes as shown in the upper row in Figure 6.9, it is clear that the particle flow patterns change significantly when the $\mu_{r(p,w)}$ increased from 0.1 to 0.6 as less particles fall from the vanes at the same position. The AS tester shows very similar trends of particle flow for all the different $\mu_{r(p,w)}$ interactions. Therefore, the results show that the coefficients of static friction plays a more important role than the rolling friction.

The time particles remain on the vanes in the IS tester at the lowest $\mu_{r(p,w)}$ values is 0.7 sec, before the last particle falls from the vanes. When $\mu_{r(p,w)}$ increases from 0.01 to 0.6, the particles remain on the vanes longer, from 0.7 to 0.75, 0.8 and 0.85 sec. The particles drop from the vanes in the range of time = 5.3 – 6.0 sec, 5.4 – 6.15 sec, 5.5 – 6.3 sec and 5.6 – 6.35 sec for the increasing $\mu_{r(p,w)}$ values respectively. The AS tester simulations show the results are very similar for the last particle falling from the vanes at 54 degrees for all the $\mu_{r(p,w)}$ values.
6.4.4 Effect of Particle Size

In this section four distinct particle sizes have been used to observe the effect of size distribution in the AS tester simulations. The IS tester was not simulated due to the small number of particles. The red particles are 2 mm dia., green 4 mm dia., blue 5.6 mm dia. and yellow 6.3 dia.

The size of the particles effects the particle flow patterns significantly when the coefficient of static/rolling friction between particle-particle interaction and between particle-wall interaction vary in the range 0.01 to 0.9. Figure 6.10 shows the results of a sensitivity investigation. For Model A, particle movement changes in the rotating drum when $\mu_{s(p,p)}$ varies in the range 0.2, 0.4, 0.6 and 0.8. The small particles (red colour) are collected and moving to the middle drum faster when $\mu_{s(p,p)}$ drops to 0.2. For Model B, the small particle (red colour) movement changes in the rotating drum when $\mu_{r(p,p)}$ changes in the range 0.01, 0.10, 0.30 and 0.60. The small particles at the lowest values of $\mu_{r(p,p)}$ are collected and move together in the rotating drum. As $\mu_{r(p,p)}$ increases, less small particles are lifted in the moving heap. For Model C, the small particles (red colour) free falling from the vanes show large differences when the $\mu_{s(p,w)}$ changes from 0.1, 0.3, 0.6 and 0.9. The small particles fall from the vanes at higher angles as $\mu_{s(p,w)}$ increases. The small particles very quickly move to the middle of the drum when $\mu_{s(p,w)}$ is increased.
For Model D, the flow patterns of particle flow are very similar with all different sized particles moving in the rotating drum when \( \mu_{r(p,w)} \) changes from 0.01, 0.1, 0.3 and 0.6.

Due to granular particle segregation, the smaller particles move downward through the rotating heap of particles through the voids between particles. As can be seen by the results, when the particles are lifted on the vanes, the large particles fall first and the last particles to fall from the vanes are mostly the smallest particles (red colour). These small particles fall close to the vertical centre line of the drum and would be influenced by the air flow travelling through the drum. This will be looked at further in Section 6.5.

**Figure 6.10** Particle size distribution red particles are 2 mm dia., green 4 mm dia., blue 5.6 mm dia. and yellow 6.3 dia. in the AS tester at time \( t = 10 \) sec with **Model A**: \( \mu_{s(p,p)} \) is (a) 0.2, (b) 0.4, (c) 0.6 and (d) 0.8. **Model B**: \( \mu_{r(p,p)} \) is (a) 0.01, (b) 0.10, (c) 0.30 and (d) 0.60. **Model C**: \( \mu_{s(p,w)} \) is (a) 0.1, (b) 0.3, (c) 0.6 and (d) 0.9. **Model D**: \( \mu_{r(p,w)} \) is (a) 0.01, (b) 0.10, (c) 0.30 and (d) 0.60.

Figure 6.11 shows the particle size distribution of iron ore segregation in the middle section (bin3) in the IS tester at different times and locations in the drum and the number...
of particles, see Table 6.2. Figure 6.11(a) shows the influence of different particle size in the IS tester. It can be seen that for large particle sizes greater than 5.6 mm, there is variance for the entire simulation. The reason the graph of 6.3 mm diameter particles looking different to the others in Figure 6.11(a) is due to the relatively small number of particles in this size range. For particle sizes lower than 4.0 mm, there was very constant moving in the middle section of the rotating drum for the entire simulation. Figure 6.11(b) shows the particle sizes distribution in the five bins of the IS tester at the end time \( t = 60 \) sec. The particles are moving from both end walls towards the centre of the rotating drum.

![Figure 6.11 Particle size distribution in the IS tester at (a) the middle of the drum (bin3) and (b) the axial size distribution of particles in the drum at time \( t = 60 \) sec.](image)

The particle size distribution of the iron ore model in the AS tester is shown in Figure 6.12. Figure 6.12(a) shows the small particle size movement in the middle section (bin3) of the rotating drum. In Figure 6.12(a), it can be seen that there is a very transient behaviour of all particle sizes in the first 20 revs of the simulation. After this time, the different size fractions begin to move axially through the bin. The large particles (5.6 and 6.3 mm diameter) have nearly all left bin3 by the completion of 80 revs. The 4 mm particles have reduced in number by 80 revs and the number of 2 mm particles has increased dramatically by 80 revs. After 80 revs until the end of the simulation the number of each particle size reaches a steady state condition. Figure 6.12(b) shows the large particle size movement to the end walls of the drum (bin1 and bin5) and small size of particle present in the middle (bin3) of the rotating drum. As can be seen, each different particle size has a different trend along the length of the drum. The number of 2 mm particles increases towards the centre of the bin. The number of 4 mm particles initially rises from bin1 to bin2 and bin5 to bin4 the drops again in bin3. The number of 5.6 mm and 6.3 mm particles drops dramatically from the front and back of the drum towards the centre (bin3) of the drum.
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![Figure 6.12](image)

**Figure 6.12** Particle size distribution in the AS tester at (a) the middle of the drum (bin3) and (b) the axial size distribution of the particles in the drum after 80 revs.

### 6.5 DEM-CFD Analysis of Iron Ore Flow in Dustiness Testers

This section investigates three interaction contact forces between particle and air, particle and particle, and particle and wall in the IS and the AS testers. The coupled simulations were completed for different sizes of the iron ore particle model.

The combined DEM-CFD coupled method has been developed and widely used to study interactions between particle phase and fluid phase flows (Tsuji Y. et al., 1992; Xu et al., 1997). The air phase is treated as a continuous phase and solved using computational fluid dynamics (CFD). The air motion in meshed cells of the rotating drum is given by the equation of continuity and calculation of air motion by the locally volume-averaged Navier-Stokes equations. The local void fraction is obtained from the particle locations calculated by DEM.

When a particle moves in a fluid, resistance and shear forces such as lift and drag force act on material. The air-particle drag force $F_D$ is determined by each particle depending on the air void and the relative velocity between particles and air (Ergun, 1952; Wen et al., 1966; Di Felice, 1994). In this study, the Ergun and Win & Yu’s equation was used to calculate the effects of drag of neighbouring particles, as seen in equation 2.29. The lift forces have an important role for the fluid flow around particles, the velocity at the particle are the difference between the top and bottom in a system (Saffman, 1965). In this study the shear lift force is taken to be the sum of the Saffman lift force, as seen in equation 2.34 and the rotational lift force is the Magnus lift force, as seen in equation 2.36 acting on a particle due to the rotation of the particle.
6.5.1 Simulation Condition

The geometry of the testers and type of particles used in these simulations were based on the experimental work. To produce accurate DEM simulations, the physical properties of the iron ore and the drums (304 stainless steel) have been used to aid in the determination of the interaction properties for the DEM (see Section 2.5) and DEM-CFD coupling (see Section 2.7). The processes used for many of these tests has been reported in Chapter 4, including the particle shape and particle size of the particle model used in the DEM simulations and the particles were set with a fixed particle size are summarised here in Table 6.2 and air parameter as shown in Table 5.3, and more detail setup for the coupling method (DEM-CFD) of iron material model is same as for the polyethylene pellets (see Section 5.6.1).

6.5.2 Particle Motion and Air Flow in the IS Rotating Drum

According to the numerical model of this work, the three interaction forces are investigated to better understand the nature of the flow in the IS tester such as interaction force between particle-particle, between particle-wall and between particle-air occurring in the dustiness tester with air flow from the front to the back of the drum is 38 l/min and fill the particle of 0.21% level for the solid fraction.

6.5.2.1 Particle and Air Interaction Force

The DEM-CFD coupled method is achieved mainly through the particle–fluid interaction force, which is at the computational cell for the air phase and at the individual particle for the particle phase. This calculates the particle–fluid interaction forces, particularly the drag force which can be based on the equation of the Di Felice model. The lift force based on the Saffman Lift force develops due to the non-uniform pressure distribution on the surface of a particle and Magnus Lift force due to particle rotation model. It is very difficult to use the algorithm for solving flow on a small scale for the instantaneous flow of particle movement in a fluid flow, so large scale particle movement in the fluid is investigated. The particle diameter should be smaller than the cell of fluid. However, it should be small compared to the total fluid domain field. Figure 6.13(a) shows an example of the air flow and particle movement in the IS tester. It can be seen that the air flow is
generated from two sources; the air inlet from the front in the centre axial of the rotating drum and air generated from the vanes as the drum rotates, as shown in Figure 6.13(b) and (c). Both modes of air generation interact with the particles falling from the vanes to the base of the drum. The colour shows air stream and particle flow are present and represent the magnitude of air and particle velocity. The velocity of a particle falling from the vanes is higher than the velocity of air flow in the drum. The air enters, from the inlet at the front of the drum, in a circular motion in the direction of rotation of the rotating drum, then the air stream flows to the middle of the drum in the axial direction and expands to the full cross section of the drum. This is because the outlet is small so the velocity and pressure are higher than the other zones. The air generated from the vanes flows in the same direction as the drum rotation and converges to the core and mixes with other air flowing from the front of the drum. The air flow at the back section of the drum is variant due to the effect of the small sized particles moving to the back and the dust (fine particle) flows out of the drum at the outlet of the dustiness tester.

![Image of particle and air interaction in the IS tester](a)

![Image of particle and air interaction in the IS tester](b)

![Image of particle and air interaction in the IS tester](c)

**Figure 6.13** Particle and air interaction in the IS tester (a) ISO view, (b) front view and (c) top view.

The particle distributions, as a result of drag force acting on individual particles when particles pass the air flow in the IS rotating drum are shown in Figure 6.14. Thus, it can
be expected that the drag force from the velocity of the airflow effects the particle movement in the drum including different sized particles and locations of particle dynamics in the drum, as it rotates. Figure 5.31 to Figure 5.33 show that the air velocity in the axial direction of the airflow is higher than the tangential and radial velocities of the air flow in the IS tester.

Figure 6.14(a) shows the average magnitude velocity of the different sized particles after falling from the vanes. The drag force was calculated due to the influence of the air around the individual particles of different size, as shown in Figure 6.14(b). The values are averaged from the number of particles and air flow in the drum and is higher with the larger sized particles and decreases as the simulation time increases. The small sized particles have a low effect on the air drag force in the air flow in the rotating drum, it is steady-state for the whole simulation. Figure 6.14(c) shows the drag force at the time $t = 60$ sec and as can be seen, there are very similar results for the five different locations and four particle sizes. This is because the number of particles and particle size is not sufficient to effect the air stream. When the velocity of the air and particle velocity are compared, the air velocity is less than the particle velocity flow in the IS rotating drum. Figure 6.14(d) also shows the drag force acting in the axial direction, pointing from the front at the centre of the drum and is the focus from the four different size of particles and five locations. The distribution of radial pressure decreases gradually from the wall surface to the centre of the drum, similar to the results for polyethylene pellets (see Figure 5.30). The magnitude of the pressure is higher in the lift zone (see Figure 5.29) and the region near the drum wall has lower drag force but the region a little away from the drum wall has higher drag force towards to the centre of the drum. The drag force on particles near the drum wall is low due to the no-slip condition between the drum wall surface and the air phase. The air velocity is lower close to the wall and thus, the drag force is lower since the magnitude of the drag force is strongly related to air velocity.
Chapter 6: Numerical Analysis of Iron Ore Flow in Dustiness Testers

Figure 6.14 Particle distribution in the air flow (a) particle velocity (b) different size of drag force (c) drag force at different locations and (d) drag force and air flow in the IS tester at time t = 60 sec.

6.5.2.2 Particle and Particle Interaction Force

The interaction of particles is associated with the attrition or impact of each particle, which is important in separating the particles from the air stream. Information about the compatibility of the particle-particle interaction with different particle sizes is shown in Figure 6.15(a) and (b). These two figures clearly indicate that the total and averaged interaction forces between particle-particle are lower than the interaction forces between particle-wall as a result of particles dropping from the vanes in the air flow through the rotating drum. Moreover, Figure 6.15 shows that the magnitude of the normal force and tangential force of particle-particle interaction forces increases when the particles drop from the vanes. The particle concentration increases as more particles fall from the vanes, thus increasing the chance for particle-particle interaction to occur.

6.5.2.3 Particle and Wall Interaction Force

The particle-wall interaction forces occurring in the rotating drum relate to the particles impacting with the wall of the drum and can cause wear damage or particle breakage,
which could be a problem for the drum operating under normal operating conditions. The information of the normal force between particle-particle interaction and particle-wall interaction, different particle size impact on the drum wall and the number of particle contacts in the rotating drum are shown in Figure 6.15. This presents the magnitude of the normal force occurring for particle-particle interactions and is just lower than the particle-wall interactions, therefore suggesting that the particle-wall interaction is a more significant factor in the modelling of particle flow in the rotating drums. Moreover, Figure 6.15(a) shows that the total normal force for particle-wall interaction force increases when the particle is falling from the vanes and impacts on the wall of the drum. Figure 6.15(b) shows that the averaged normal force for particle-particle interaction, particle-wall interaction force decreases, which is an effect of the size of the particles. The particle-wall interaction force increases as the size of particles increases, as shown in Figure 6.15(c). The increase in force is due to the increased mass of each larger particle and small particles will be protected from large particles before those particles impact on the drum wall. All particles cannot collide with the drum wall; only a few particles collide with other particles and some particles return (via bouncing) from a collision with the drum wall. The distribution of the normal force is different when the particles of different size are falling, particularly particle contact on the bottom wall surface of the drum. As the particle size increases, the area of the bottom wall to accommodate a particle-wall interaction increases. Figure 6.15(d) shows the maximum normal force is higher than the tangential force of the particle movement in the rotating drum to the end simulation time. The number of particle contacts in the drum is a peak when the particles drop and impact on the drum wall and rebound, impacting with other particles within the rotating drum. Generally, particles falling from the vanes at the high angle as the vanes rotate, record higher normal forces on the bottom wall of the drum. The contact point of the particles dropping and colliding with the surface of the drum will change their flow directions significantly. The total and average particle-wall interaction force acting on the drum are higher than the particle-particle interaction force. The relatively small number of particle contacts in the flow in the IS tester were not enough for analysis. For the drum rotation, the tangential force is generally lower than the normal force occurring from the particles dropping.
The aerodynamic force influence to the size of particle movement in the IS rotating drum is shown in Figure 6.16. Each particle size moves in the axial direction with the airflow. The aerodynamic force is influenced by the particles moving in the rotating drum to the end simulation time $t = 60$ sec. Figure 6.16(a) shows the volume fraction of particles in the middle drum (bin3) and is compared to the back of the drum (bin5), as shown in Figure 6.16(b). The air flow does not affect the large sized particles as the particles fall from the vanes and after they impact on the drum wall, the particles rebound to the free space in the axial direction of the drum. However, the small sized particles (lower than 4.0 mm) move to the back of the drum (bin5) as a result of the air flow when the drum is running for a long period of time.
Figure 6.16 Shows the segregation of particles under different size ratios in the axial direction of the drum (a) middle of the drum (bin3) and (b) back of the drum (bin5).

6.5.3 Particle Motion and Air Flow in the AS Rotating Drum

There are three interaction forces acting on the particle flow in the AS tester, particle-air interaction, particle-particle interaction and particle-wall interaction occurring in the drum with air flow. The air flow enters the drum centrally at the front on the vertical plate due to the vacuum pump positioned beyond the back of the rotating drum. The airflow passes the particles falling from the vanes and particles sliding on the top free surface of the rotating drum heap at the bottom wall to the back of the drum, at a flow rate of 175 l/min. In this section, the three forces are investigated to better understand the nature of the particle flow and air flow in the rotating drum.

6.5.3.1 Particle and Air Interaction Force

The fluid flow around the particles generates particle-fluid interaction forces due to the shear stress of the fluid on the particle surface. This interaction force is the driving force for the motion of the particles. Therefore, particle-fluid interaction forces in a computational cell must be properly considered, particularly the total drag force over the small and large sized particles, which can be based on the equation of the Di Felice model. The lift force, based on the Saffman lift force, develops due to the non-uniform pressure distribution on the surface of a particle and the Magnus lift force is due to the particle rotation model. It is difficult to use the algorithm for solving flow of fluid on a fine sized particle, so particles of the size range 2.0 mm – 6.3 mm moving in the fluid are considered. Fluid cells are set to be larger than the particle diameter. However, each cell should be smaller than the total fluid domain. Figure 6.17(a) shows the air flow and particle movement in the AS rotating drum. It can been seen that the air flow is generated from
two sources, the air inlet hole from the middle front along the central axis of the drum and air flow is also generated from movement of the vanes, creating flow around the internal wall as the drum rotates. The velocity of a particle falling from the vanes is higher than the velocity of air flow in the drum for all particle sizes (2.0 – 6.3 mm). The air flows from the inlet hole at the centre of the front plate of the drum to the back section of the drum, the air stream moving with the rotating drum is the full cross sectional area at bin5 before the air flows through at the outlet hole. The air stream flow is not symmetrical in the drum, there is a higher air velocity in the particle zone, see Figure 6.17(c). Bin5 is a very important zone of the drum, where the wall of the drum is in the vertical plane with a reducing exit cone. Therefore, the air flow has a varied effect on the small sized particles and the dust (fine particles), with the flow out through the outlet hole of the dustiness tester. For the air flow in the radial direction of the drum, as shown in Figure 6.17(b), the air velocity effect on the free surface of the particle sliding to the bottom of the drum as it rotates. The air flow is in the same direction as the drum rotation; which is opposite to the particle flow direction on the free surface. The air flow velocity has no effect on the velocity of particle flow on the free surface.

In this section, the air drag force is related to the air velocity. It is expected that the distribution of the air drag force will follow the trend of the velocity of the air flow. This is confirmed by Figure 6.18 which shows that the particle velocity under the four different particle sizes and five bins in the rotating drum. As already shown in Figure 5.31 to Figure 5.33, air velocity is mainly in the axial direction and the velocity of the air flow is much bigger than the tangential and radial velocities. Figure 6.18(a) shows the magnitude velocity of particles in the rotating drum for the full 60 sec simulation. It can be seen that after 30 sec steady-state conditions exists to the end time. The small particle size has higher magnitude velocity at the start of the test before the particles begin to concentrate at the middle of the drum, and then the velocity of the smaller particles drops below the larger particle velocities to the end simulation time. The drag force on particles decreases as the simulation time increases, due to the particle size segregation occurring in each section of the bin, as shown in Figure 6.18(b). The large particles show the high drag force and decreases as the size of particles reduces. The axial velocity is greater at the front of the drum (bin1), as previously shown in Figure 5.32. Thus, the drag force is highest in bin1 since the magnitude of the drag force is strongly related to air velocity and decreases towards the back of the drum (bin5), as shown in Figure 6.18(c). The particles
and air flow inside the AS tester are shown in Figure 6.18(d). The maximum velocity of the air flow is generated at the front and moving to the back of the drum, as shown on the horizontal and vertical middle analysis planes. Meanwhile, the particles fall from the vanes to the lower part of the drum through the zone of the air stream. Generally, the small particle sizes move to the outside of the drum with the high velocity of the air stream. But, for these models the air velocity do not directly affect the particles in the size ranges of 2.0 mm to 6.3 mm.

Figure 6.17 Particle and air interaction in the AS tester (a) ISO view, (b) front view and (c) top view.
Figure 6.18 Particle distribution in the air flow (a) particle velocity (b) different size of drag force (c) drag force at different locations (d) particle and air flow in the AS tester at time $t = 60$ sec.

6.5.3.2 Particle and Particle Interaction Force

There are many particles moving in the rotating drum and particle-particle interaction forces are necessary to separate the particles from the air stream. Figure 6.19 shows the information of the particle-particle interactions under different particle size flows in the AS tester. It clearly indicates that the total particle-particle interaction forces are lower than the total particle-wall interaction forces. On the other hand, the averaged particle interaction shows that the particle-particle interaction is higher than the particle-wall interaction force. A lot of small particles are able to fill the voids between the larger particles and block the larger particles before impact on the wall of the drum, suggesting that the modelling of particle-particle interaction forces are quite significant in the modelling of the particles and air flow in the rotating drum. Moreover, Figure 6.19 indicates that the magnitude of the total particle force and averaged particle force and particle interaction forces increases with particle dropping and impact to other particles and slide on the free surface to the bottom of the drum. When the particle concentration is high, the chance for particle-particle interaction is great. It clearly is seen that there are strong particle-particle interactions on the particle heap and moving with the rotating drum, the particles fall and impact on the top free surface in the same direction as the
particle velocity. Outside the particle heap, there are very few particle-particle interactions so the interaction force is quite small.

6.5.3.3 Particle and Wall Interaction Force

The particles in the rotating drum undergo dynamic motion in the rolling region and some particles fall from the vanes to the free surface and slide to the bottom of the drum. Moreover, particles move up the drum wall as the drum rotates and they fall and slide to the lower part of the drum around the stationary zone. The small sized particles move to the bottom of the drum passing the voids between the large particles and it blocks the large particles before moving to the drum wall by the small sized particles. The small sized particles flow in the drum after the large particles have dropped from the vanes and have impacted on other particles or the wall of the drum. This is very important for the particles breaking to a smaller size, which could be a serious problem for the particle flow in the rotating drum because with enough breakage dust will form. The information of particle-wall interactions is shown in Figure 6.19(a). It is demonstrated that the magnitude of total particle-wall interaction force is higher than the particle-particle interaction force when the particles fall from the vanes and particles impacting on the free surface are in the same direction as the interaction force and passes to the wall of the drum, changing the particle flow directions significantly. Moreover, the average particle-particle interaction force is just higher than the particle-wall interaction force, suggesting that the particle-particle interaction force is a significant factor in the modelling of air flow in the rotating drum, as shown in Figure 6.19(b). Due to the different particle sizes, with an increase of the size ratio, there is an increase in the interaction force as the drum rotates. The averaged particle-particle interaction force decreases with an increase in the collection of small sized particles at the middle of the drum and the large sized particles move out to both end walls of the drum. The averaged interaction force between particle and wall could be due to protection by the other particles. Therefore, not all of the particles can collide with the drum wall; most particles collide with the other particles after the particles drop from the vanes and a few particles just returned from a collision with another particle on the free surface or the wall of the rotating drum. The interaction force increases when the size of particles increase and the normal force on the drum wall is higher because the high density of particles moving out from the vanes and dropping to the free surface and then colliding with the surface of the drum wall heavily, where they
change their flow directions significantly. Figure 6.19(c) shows the maximum force is higher than the tangential force of the particles moving in the AS rotating drum over the range of simulation time. The number of particle contacts is at a peak when the particles are falling on the top free surface and rebounding and impacting with other particles.

![Figure 6.19](image)

**Figure 6.19** Show the normal force interaction of the particle flow in the AS rotating drum (a) total normal force (b) average normal force and (c) maximum force and number of contact.

The aerodynamic force influence with respect to the particle size and number of particles moving in the AS tester is shown in Figure 6.20. Each particle size is moving in the axial direction of the air flow. The particle movement is shown in the rotating drum over the simulation time. Figure 6.20 shows the volume fraction of the particles at the front of the drum (bin1), in the middle of the drum (bin3) and the back of the drum (bin5) and will be compared. The large particle sizes affect the air flow in the axial direction of the drum after they impact and slide on the free surface. The high velocity of the air flow in the rotating drum occurs at the free surface of the particles and it is driving the particles to the end section of the drum (bin5). While the small particle size (lower 4.0 mm) after impact on the free surface try to move to the voids between the large particles to the bottom drum and move toward the middle of the drum (bin3).
The increase of friction due to the particle movement between themselves and the drum wall is caused by the decrease of tangential velocity. A number of particles flowing in the AS rotating drum is about 4.7% by volume fraction. Therefore, most particles are moving with the drum as it rotates and a small amount of particles (2% by volume of all particles) are lifted by the vanes and drop to other particles and slide on the top free surface. The top layer of the free surface is rough and the tangential velocity under the rough condition of the free surface is lower than that under the air particle flow condition.

6.6 Conclusions

A DEM study has been conducted on the effect of interaction between particle-particle and particle-wall contact in the drum under the particle movement in the drum for a rotation of 4 rpm and 29 rpm for the IS tester and AS tester, respectively. These results show the relationship of the particles when the coefficient of static friction and rolling friction in the drums are varied. The results show:

1) The coefficient of particle and particle static friction ($\mu_{s(p,p)}$) for the particle flow in the IS tester shows the amount of particles heaped on the vanes longer before falling and increased the angle of the vanes for the particle falling when increasing $\mu_{s(p,p)}$. The AS tester showed a higher angle of repose for the particle heap on the bottom of the drum when increasing $\mu_{s(p,p)}$. The particle flow pattern does not change significantly for the higher $\mu_{s(p,p)}$ from 0.6 to 0.8. The particles move with the drum rotation and the particles slide on the top free surface to the bottom wall of the drum.
2) The coefficient of particle-particle rolling friction ($\mu_{r(p,p)}$) for the particle flow in the IS tester simulations shows that more particles remain on the vanes when the $\mu_{r(p,p)}$ value increases. For the AS tester simulations, the lowest $\mu_{r(p,p)}$ resulted in the particles falling to the lower part of the drum faster than for the highest $\mu_{r(p,p)}$. This is because when increasing the $\mu_{r(p,p)}$, there is more resistance to particle rolling as the drum rotates. The angle of repose also increases with increasing $\mu_{r(p,p)}$.

3) The coefficient of particle-wall static friction ($\mu_{s(p,w)}$) for the particle flow in the IS tester has shown the particles fall from the vanes at a lower angle of the vanes while rotating from the horizontal. The particles remain on the vanes longer as $\mu_{s(p,w)}$ is increased from 0.1 to 0.9. The particles fall from the small angle of the vanes as they rotate to the next vane and display low velocity and forces. In contrast, for the high $\mu_{s(p,w)}$, the particles drop to the bottom of the drum at a higher angle of the vanes before the particles fall and the velocity and the forces have a greater impact on the drum wall and then the particles rebound to free space. The particle flow pattern in the AS tester shows the average velocity of particles increases when $\mu_{s(p,w)}$ increases. This is because the particles falling from the vanes are close to the central vertical plane of the drum. On the other hand, the lowest $\mu_{s(p,w)}$ shows the particles moving on the free surface as the drum rotates and the particles drop from the vane at a lower angle and it shows the lowest velocity of particles occurs in this case. The time particles remain on the vanes as the drum is rotating is longer when $\mu_{s(p,w)}$ increases.

4) The coefficient of particle-wall rolling friction ($\mu_{r(p,w)}$) for the particle flow in the IS and AS testers shows the particle flow patterns have very similar trends of particle flow for all the different $\mu_{r(p,w)}$ interactions. Therefore, the results show that the coefficients of static friction plays a more important role than the rolling friction.

5) The effect of particle size distribution in the AS tester effected the particle flow patterns significantly when the coefficient of static/rolling friction between particle-particle and particle-wall interaction changes. The particle movement changes in the rotating drum, where the small particles are collected and move to the middle of the drum faster when $\mu_{s(p,p)}$ drops to the lowest values. The small particles at the lowest values of $\mu_{r(p,p)}$ are
collected and move together in the rotating drum. As $\mu_{r(p,p)}$ increases, less small particles are lifted in the moving heap. The small particles fall from the vanes at higher angles as $\mu_{s(p,w)}$ increases and very quickly move to the middle of the drum when $\mu_{s(p,w)}$ is increased. The flow patterns of particle flow are very similarly with all different sized particles moving in the rotating drums when $\mu_{r(p,w)}$ changes.

6) The particle size distribution in the IS tester shows that for the large particle sizes greater than 5.6 mm, there is a variance for the entire simulation. For particle sizes lower than 4.0 mm, there was very constant particle movement in the middle section of the rotating drum for the entire simulation. The particle size distribution in the AS tester has very transient behaviour for all particle sizes in the first 20 revs. In the range of 20 to 80 revs, the large particle sizes (higher than 4.0 mm dia.) have reduced and moved away from bin3 and the number of the smallest particle size of 2 mm has increased dramatically in bin3. After 80 revs until the end of the simulation, the number of each particle size reaches a steady-state condition. It shows the large particle sizes move to the end walls of the drum (bin1 and bin5) and the small sized particles present in the middle (bin3) of the rotating drum.

The DEM-CFD coupled method was able to study the particle movement and airflow in both dustiness tester models. Thus, this study has been conducted on the flow features in a rotating drum such as particle-air interaction force, particle-particle interaction force and particle-wall interaction force of the particle movement with air flow in the rotating drum. The drag force of different particle sizes has been analysed for the particle flow in the rotating drum. The following findings have been obtained:

1) For the particle-air interaction force, which shows the particle movement and airflow, the particle velocities are higher than the air flow in both the IS and AS rotating drums. The air flow is generated from the inlet hole at the front of the drums and is also generated from the vanes of the drums as they rotate. From the two sources of air flow, the air streamlines are mixed at the back section of the drums. The drag force of the air flow is the force related to the air velocity. The lowest drag force exists at the zones close to the drum wall and increases toward the centre of the drum. The drag force influences the particles when there is an increase in the size of particles, with increasing force effect on
the particles and has most effect to the particles at the front of the drum (bin1) and is reduced toward the back section of the drum (bin5). For the AS tester, there is more effect from the air velocity on the top free surface of the particles sliding to the lower part of the drum.

2) The particle flow in the IS tester shows the total force and average force from the interaction between particle-wall is higher than the interaction between particle-particle. The force of particle-wall interaction increases as the size of particles increases. For the AS dustiness tester, it is a contrast between particle and particle and particle-wall interaction. This is a significant factor in the particle-particle interaction modelling of air flow in the rotating drum. The tangential force occurring in the rotating drum is lower than the normal force over the simulation time.

3) The air flow in the IS and AS testers shows turbulence of the airflow occurs towards the back of the drum (bin5) and there is an increase in the velocity of air and pressure in this zone over the simulation time. There is a high axial velocity at the centre of the drum moving from the front to the back of the drum and the air velocity in the radial direction increases with the particles falling from the vanes.
Chapter 7

Numerical Analysis of Coal Flow in Dustiness Testers

7.1 Introduction

This chapter presents the DEM simulation investigation effect of particle motion, velocity, force and energy dissipation when coal particles flow in the IS and AS testers. The particle models used are spherical and spherical clusters flowing in the 3D rotating drums, which are then compared to the trend of particle flow obtained from experimental data. In addition, the simulations have been combined between the discrete element method (DEM) and computational fluid dynamics (CFD) to investigate the airflow patterns and particle velocity, particle collision and energy dissipation occurring in the both dustiness testers. The DEM focusses on the particle movement and the CFD focusses on the airflow in both dustiness testers. Therefore, the DEM-CFD coupling method was developed to simulated flow mechanism of coal movement and the air flow.

Individual particle movement in the IS and AS testers is investigated, including particle velocity, particle flow patterns and force structure in the DEM simulation. Moreover, the particle-particle, particle-wall and particle-air interaction, effect of drag force, particle collision frequency and collision energy under different particle size are considered in the axial and radial directions. The interaction of particles has then been analysed to understand their role in governing the complicated flow.

Coal was chosen as the test material for investigation of the flow mechanisms of the particles within both dustiness testers, but not to measure the degree of dust generated as a result of the testing. This is also vital for the DEM simulations, in replicating the same experimental tests. The IS and AS testers require differing operating conditions to follow their respective standards, see Section 2.2. Two conditions will be presented in this
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Chapter 7, the first will simulate the dustiness testers with no airflow and the second will be simulating the dustiness testers with airflow to compare the experimental results previously presented in Chapter 3.

7.2 Mathematical Model

This study uses two standard dustiness testers to predict the coal flow in the IS and the AS testers. There are two sections considered, including the DEM simulation for the particles moving without airflow and coupling DEM-CFD simulation for the particles moving with airflow. The DEM model adopted used the 3D model simulation of the particle movement in both dustiness testers as the particles translated and rotated in the EDEM software, as can be described by Newton’s laws of motion, given by equations 2.11 and 2.12. For the modelling of the particle-particle contact and particle-geometry contacts, a non-linear Hertz-Mindlin contact model is applied. The simulation programs can separate the normal components of the contact force (equation 2.13) and tangential force (equation 2.14). For the DEM-CFD coupling model, the Navier-Stokes equation connected with the $k - \varepsilon$ turbulence model are solved using the airflow of the mass and momentum conversation equations given by equations 2.21 and 2.22. The interaction forces, including drag and lift were considered; the drag force is based on the Ergun model (Ergun, 1952) and the Wen & Yu model (Wen et al., 1966) and the lift force is a combination between the Saffman lift force model and the Magnus lift force model. The equations for the drag and lift force are described in Section 2.7.5. The DEM simulation predicts the particle movement and collision in both dustiness tester models, with a multiplier of 30% (approximately) applied to the computed critical time step for the simulations. The time-step for the DEM simulation is calculated by the Rayleigh time step, $T_R$, given by equation 2.40. Time step values of $0.3T_R$ are generally suitable for most simulations. For the DEM simulation, the IS tester run-time for a 60 sec simulation time varies from 10 to 25 hours for all particle models. Moreover, for the AS tester run time for a 600 sec simulation time was approximately 700 – 800 hours, depending on the type of particle model, while the AS tester run-time was for 180 sec (after this time the result shows steady-state). All the simulations were run on a computer workstation: DELL Precision T7500, with 24 GB RAM and 4 processor cores.
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7.3 Simulation of Coal Flow Mechanisms in Dustiness Testers

The IS and the AS testers use DEM simulation and compare the results for the trend of particle movement obtained by experimental data. In the simulation model, the focus is on the flow patterns under different particle shape models and the effect of individual particle motion, particle velocity, force structure and collision energy under different particle sizes moving in both dustiness testers. The initial loading of particles is spread from the front to the back of the drum.

7.3.1 Simulation Condition

The particle shape and particle size of the coal particles were more irregular and dimensions hard to determine by measurement of the materials. Particle models were based on equivalent volume diameter and mass of the particle, as shown in Figure 4.22. The simulated volume and mass of the particle model was matched with the experimental data. Subsequently, particle models in the DEM simulations were set with a fixed size and shape. All particles were generated from an injection plane and allowed to fall due to gravity alone to the bottom of the drum in 2 sec. The particle size and particle shape of the coal model, material properties and interaction between particle and particle and between particle and wall selected for simulation by DEM software for the two dustiness testers are shown in Table 7.1

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</tr>
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<td>Particle coefficient of static friction, (μₛ)</td>
<td>0.6</td>
<td>0.4</td>
<td>0.43</td>
</tr>
<tr>
<td>Particle coefficient of rolling friction, (μᵣ)</td>
<td>0.1(0.05)</td>
<td>0.3(0.1)</td>
<td>0.3(0.1)</td>
</tr>
</tbody>
</table>

The coefficient of rolling friction is presented as spherical shape (non-spherical shape)
Table 7.2 summarises the dimensions and number of particles required for the four particle sizes used in the rotating drum simulations. The P1 particle is representative of the larger sized particle measured experimentally at an equivalent volume diameter of 6.3 mm while P2 to P4 are arbitrarily smaller sized particles of equivalent volume diameters of 5.6 mm, 4.0 mm and 2.0 mm, respectively.

The calculation of the required number of particles was based on experimental data (Table 7.1) of the particle samples tested in both dustiness testers. A simplification was made in the calculation of the number of particles required, that being there was no accounting for the void space that would exist between the particles. The simulation configurations are built to match the experiment with equal the mass and volume of material 35 cm$^3$ for the IS tester and 1000 cm$^3$ for the AS tester.

### Table 7.2 Dimensions of simulated particles and the number of particles required for the DEM simulations.

<table>
<thead>
<tr>
<th>shape</th>
<th>SP</th>
<th>4-SP</th>
<th>PY</th>
<th>number of particles for the IS / AS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d (mm)</td>
<td>w(mm)</td>
<td>l(mm)</td>
<td>t(mm)</td>
</tr>
<tr>
<td>P1</td>
<td>6.3</td>
<td>5.70</td>
<td>7.97</td>
<td>4.44</td>
</tr>
<tr>
<td>P2</td>
<td>5.6</td>
<td>5.64</td>
<td>7.65</td>
<td>3.87</td>
</tr>
<tr>
<td>P3</td>
<td>4.0</td>
<td>4.17</td>
<td>5.31</td>
<td>2.80</td>
</tr>
<tr>
<td>P4</td>
<td>2.0</td>
<td>2.17</td>
<td>2.55</td>
<td>1.40</td>
</tr>
</tbody>
</table>

SP: spherical shape; 4-SP: four sphere cluster; PY: pyramid shape; d: diameter of particle; w, w1, w2: width of particle; l: length of particle, t: thickness of particle, h: height of particle

### 7.3.2 Validation of Material Model

Figure 7.1 and Figure 7.2 show the particle flow in the IS and AS testers comparing DEM simulation and experimental results for the particle loading spread from the front to the back of the drum with three different particle shapes (see Figure 4.22). Figure 7.1 shows the particle flow in the IS tester at two different times and compares the data of three particle models with the experimental results. It clearly is seen that the overall flow patterns obtained from experiments and simulations are comparable. The volume of particles is 35 cm$^3$ loading from the front to the back of the IS tester and the rotational speed is 4 rpm. All of the particles remain on the vane to an angle of 14.7 degree above the horizontal centre line of the rotating drum. Subsequently, the particles continue to move from the vanes from time $t = 5.3$ sec to the end time of the test ($t = 60$ sec). The non-spherical particle models showed very close comparisons to the experiments.
whereas the spherical particle model did not. The pyramid shape gives the better result the particle models.

Figure 7.1 Particle flow in the IS tester, upper row is the time $t = 5.3$ sec and lower row is the time $t = 60$ sec.

Figure 7.2 displays the experimental results and compares these results with the three particles shapes flow in the simulation of AS tester. The particle flow in the radial direction is shown at time $t = 10$ sec (upper row) and the particle segregation in the axial direction is captured at time $t = 60$ sec (lower row). It can be seen that the particles dropping from the vanes have similar profiles and particles have spread the entire length of the cylindrical drum section and again show a very good comparison to the experimental results. The volume of particles is 1000 cm$^3$ loading in the even spread position in the AS tester and the rotation speed is 29 rpm. The particles move more vigorously due to a higher chance of collisions between each particle and the wall of the drum. It is clearly seen that the large sized particles move to both end walls (front and back) and the smaller sized particles move to the centre of the rotating drum. In all cases, as the drum rotates particles near the drum wall move up the drum surface, due to friction as well as interaction with the lifters, and then fall back down to the free surface of material at the bottom of the drum. The non-spherical models can be seen moving out from the lifting vanes and moving along the axial direction of the drum as it rotates, which matches with the experimental results when compared with the spherical model. Therefore, as a result of this study, all the simulations used the pyramid shape model, due to its saving simulation time and memory of the computer, better in preference to the four-sphere model with more than four times the simulation time.
In the experimental investigation, the particles were mixed in a container before the particles were spread from the front to the back of both rotating drums during operation. For the DEM simulations, the particles were randomly generated across an injection plane along the length of the drum for both dustiness testers. The particle segregation is shown by the use of four different colours for the different sizes in the IS and the AS rotating drums (see in the colour Figure 7.2). The yellow colour shows particle diameter 6.3 mm, the blue colour is diameter 5.6 mm, the green colour is diameter 4.0 mm and the red colour is diameter 2.0 mm. For the axial segregation, particles separate in the axial direction along the drum, caused by the collision of particles after particle movement. The axial segregation is much slower than radial segregation, with the small particle sizes moving towards the middle of the drum and the larger particle sizes moving to both end walls as the drum rotates. It should be noted that the volume of particles in the IS tester is not enough to influence the particle movement in the drum.

7.3.3 Particle Motion Analysis in the Dustiness Testers

Particle movement analysis can be presented based on information such as the trajectories of particles and the transient forces on individual particles flowing in the dustiness testers, which can be readily generated from DEM simulation outputs. This information can be used to establish a general understanding of the particle flow in the dustiness testers. This
section will focus on the particle trajectory related to the flow, velocity and force of particles at the steady-state condition under different loading positions and different particle sizes moving in the IS and AS testers.

### 7.3.3.1 Individual Particle Motion

One particle was made the focus for detailed tracking by recording the coordinates of a particle collision in the system. The particle starts moving from the middle of the rotating drum. The particle trajectories are shown in Figure 7.3, with the red colour indicating a fast particle velocity and the yellow colour indicating a slow particle velocity. The trajectories of four typical particles of different dimensions were chosen to track in the front and side planes of the IS and AS testers (\(P_{6.3, 5.6, 4.0}\) and \(P_{2.0}\)). The particle motion information consisted of the radial and axial direction of the particle trajectory in the rotating drum. All particles are moving in the drum with a velocity field having a cyclic flow pattern. In this section, the radial and axial velocities of the particle have a relatively strong interaction with other particles showing a large fluctuation in forces. Therefore, a particle’s trajectory is largely governed by the contact force between particles. The first trajectory shows a particle moving on the wall via the lifting vanes and then falling from the vanes very close to the same section and then rebounding to the free space after impact on the lower drum wall. Depending on the angle of the drum wall surface for the particle impact, each particle is immediately re-trapped by the wall and it bounces around a few times off neighbouring particles and repeats this process to the simulation end time. The particle bounces around shearing against the upward moving layer of particles, impacting on the wall of the drum and experiences many higher energy collisions.

For the IS tester, as shown in Figure 7.3, one particle from the entire simulation is shown moving in the dustiness tester with four different particle sizes starting at the middle of the drum (bin3). It can be seen that the particle movement is in the radial direction has a very similar trajectory for all four particle sizes and shows the lifting by the vanes and subsequent falling to the bottom of the drum and repeating the process. In the axial direction, the large particle size moves from the initial position to the front or the back of the drum. For the small particle size, it moves in the same section from the initial position in the rotating drum. It is clear that the particles moving in the IS tester are affected by
the size of the vanes and by the amount of particles moving after impact on the wall and rebounding as the drum rotates.

For the AS tester, as shown Figure 7.4, one particle starting at the middle of the drum (bin3) is shown moving in the dustiness tester with four different particle sizes. It is clear that for the larger particle sizes (5.6 mm and 6.3 mm diameter) there is sliding from the top of the free surface to the lower part of the drum. For the small particle sizes (2 mm and 4 mm diameter), we see the particle moving to the drum wall and then moving up with the lifting vanes and then dropping to the free surface, as shown in the radial direction (see Figure 7.4(a)). For the axial direction (see Figure 7.4(b)), the large particles are observed moving to the end wall of the drum and the small particles moving in the middle section (bin3) of the drum.

7.3.3.2 Particle Velocity Field in Dustiness Testers

The average particle velocities in the radial and axial directions with different particle size for the IS tester are shown in Figure 7.5. Figure 7.5(a) shows the regions where the average particle velocity was recorded with four different sizes. In the radial direction, it shows the velocity of the particles when falling from the vanes and the velocity after rebounding from impact on the drum wall, shown in Figure 7.5(b). The velocity of a particle falling from the vanes is higher than the particle rebound velocity. At the start of
the simulation, the large particles dropping have the highest velocity and then once steady-state is reached, the small sized particles have the highest velocity. The small particle size moving via vanes to the high angular angle shows the highest velocity. The velocity profile in the radial direction indicates that the particles move upward as the drum rotates, from the bottom of the drum by the lifting vanes to an angle of approximately 120 degrees from the vertical line. The particles dropping from the high angle of the lifting vanes obtain high velocities and then accelerate towards the drum bottom wall where they collide with the drum wall and other particles. This study indicates that the flow of particles is driven by the vanes of the rotating drum. Then, the particles drop from the vanes and are influenced by the drum wall. The velocity of particle flow in the axial direction component is lower than the angular velocity component.

Figure 7.5(c) shows the average velocities over simulation time (60 sec) with four particle sizes and different five bins positions for the IS tester. The highest velocity occurs in the centre of the drum for all sizes of particles, while the lowest velocity of the particle flows in bin1 as the end wall of the drum is the cone. A small percentage of particles also move out from the side of the vanes and slide on the cone wall to the bottom of the drum. Each particle size in each of the bins shows very close velocities.

Figure 7.6 shows the average particle velocities with different particle size distributions in the radial and axial direction from simulations in the IS tester. The highest velocity of each particle size was generated after approximately 0.5 revs, which is the first time all
particles remain on the vanes and move out together to the lower part of the drum wall. The particle motion information of the two portions consists of their radial positions (average from the x and z-directions, perpendicular along the drum) and axial positions (y-direction along the drum), and the velocity of particle flow in the radial \( V_{\text{radial}} \) and axial \( V_{\text{axial}} \) direction were considered. Figure 7.6(a) shows the average radial velocity of all particles flowing in the perpendicular direction of the drum axis over the full simulation time. The positive velocity indicates the particle velocity movement with the rotating drum and the negative velocity shows the particle drop to the lower part of the drum wall. Figure 7.6(b) shows the velocity of a particle movement in the axial direction of the drum with four particles size over the full simulation time. The positive velocity refers to the particles moving to the back while the negative velocity refers to the particles moving to the front of the drum. Generally, the particle movement in the axial direction occurs after impact on the drum wall and rebounding to free space.

The average particle velocities falling from the vanes to the lower part of the rotating drum in the AS tester are shown in Figure 7.7. The distribution is obtained by calculating average velocity for particles after the particle drop from the vanes or the four different particle sizes. Figure 7.7(a) shows the small sized particles are moving with a steady-state velocity over the simulation time; this is for the small sized particles moving near the
drum wall as the drum rotates. The small sized particles on the vanes move to a high angle on the vanes, therefore, obtain the highest velocities, whereas the large sized particles in the drum show fluctuation and most particles slide on the free surface and have lower velocities (see Figure 7.7). Figure 7.7(b) shows the average velocities for different particle sizes flowing in the five bins in the axial direction, indicating particles are drawn falling from the vanes to the free surface and impact on the wall of the drum. Since the axial flow is restricted, the order of the magnitude of the axial velocity component is very low as compared to the radial velocity component. It can be seen that the velocity of particles increases when the particle size decreases in all the bins of the drum.

![Figure 7.6 Particle distribution in the IS tester under different size (a) radial velocity (b) axial velocity.](image)

![Figure 7.7 Particle distribution of velocities in the AS tester (a) in the radial direction (b) in the axial direction.](image)

The particle velocity distributions in the AS tester, as shown in Figure 7.8 presents the velocity in the radial and axial directions over the full simulation time. It is clear that Figure 7.8(a) shows that the radial velocity ($V_{radial}$) is steady-state for the entire simulation time except for the short initial transient time, where the highest particle velocity results from dropping particles from the vanes to the free surface. The positive velocity represents the particles moving in the direction of drum rotation and the negative velocity represents the particles moving down on to the free surface. The velocity profile
in the radial section indicates that the small particle sizes rotate from the bottom of the drum with the vanes to a high angular position before falling to the free surface. The high angle from which the particles fall from the vanes results in high particle velocities as they fall to the bottom wall of the drum, where they collide with the wall and other particles. Figure 7.8(b) shows the axial velocity ($V_{axial}$) under different time steps with four different particle sizes. The velocities of the large particle size moving along the axial direction have the peak values near the free surface and are faster than the other particle sizes to both end walls of the drum. The small sized particles gradually migrate into the centre of the rotating drum. The positive velocity is the particle movement to the back of the drum and the particles moving to the front are displayed as negative velocity.

**Figure 7.8** Particle distribution in the AS tester (a) radial velocity (b) axial velocity.

### 7.3.3 Particle Flow in the IS Dustiness Tester

The pattern of particle flow in the IS and AS testers at the simulation end time with different locations (5 bins) and different particle sizes (4 sizes) is presented. Figure 7.9 shows the distribution of particle flow behaviour in the axial direction in the IS tester. It can be seen that particles are carried on the vanes rotating to 30 degrees above horizontal and then they drop to the bottom wall of the drum. The four sizes of particles spread along the drum, with the small particle movement to bin1 higher than to bin5. All the particles easily move in bin1, slide on the cone wall and do not affect the segregation of particles moving in the rotating drum. Due to the end wall of bin5 having a small vertical wall, this wall blocks the movement of the particles. In the radial direction, many particles remain on the first vane to lift the particles and they begin to move to the middle of the drum more than the other sections as they fall to the lower part of the drum, as shown in Figure 7.9(a) for time $t = 5.6$ sec. For the end time (time $t = 60$ sec), as shown in Figure 7.9(b), the particles are now being consistently lifted by two vanes due to steady-state flow being
reached. Figure 7.9(c) shows the small particle size (2.0 mm diameter) in all five bins of the IS tester, with most particles remaining close to the end wall. Four sizes of particles move in the middle section (bin3), as shown in Figure 7.9(d). For bin3 the small sized particles (4 mm diameter and 2 mm diameter) are moving in a very similar way; the large sized particles (5.6 mm diameter and 6.3 mm diameter) fluctuate for the particle movement over the simulation time.

![Figure 7.9 Particle distribution in the IS tester](image)

The particle distribution in the AS tester is shown in Figure 7.10(a), presenting the particle flow behaviour in the axial direction at time t = 600 sec (simulation end time). The large sized particles move to both end walls and the small sized particles move towards the centre of the drum. The yellow colour shows particle diameter 6.3 mm, the blue colour is 5.6 mm diameter, the green colour is 4.0 mm diameter and the red colour is 2.0 mm diameter. When looking at the falling particles (simulation end time), this shows the small particle size (red colour) moving near the drum wall and remaining on the vanes to the high angle before falling to the free surface. The percentage of the smallest sized particles is not enough (10% by volume) for segregation moving to the centre of the drum. Therefore, the green colour (4.0 mm diameter) moved to the middle zone and as can be seen in Figure 7.10(b), the steady-state condition has been reached after 90 revs. Figure
7.10(b) demonstrates the smallest particle size is moving in bin3. The small sized particles (2.0 mm diameter) are very similar in all five bins (20% of the particle volume fraction). This is not enough for the solid volume fraction of the particle segregation. Whereas the 4.0 mm diameter particles have a higher volume fraction in the simulation, resulting in the most effective segregation as the drum rotates. For both end walls (bin1 and bin5) the number of particles decreased to 90 revs and the steady-state condition to the simulation end time is 15% of the volume fraction. On the other hand, the particle increase to the highest value fraction in the middle drum is 22 – 25%. For the large particle size (not shown in the Figure), the particle moving to both end walls, especially the particle of 6.3 mm diameter, is the highest particle volume fraction in both end walls higher than 5.6 mm diameter, approximately 30%. The particle volume fraction of the 6.3 mm diameter is seen to be approximately 30% at both end walls and 12 – 15% of the particle volume fraction for bin2 – bin4.

Figure 7.10 Particle distribution in the AS rotating drum (a) particle flow at time \( t = 600 \) sec (b) particle flow in the bin3.

7.3.3.4 Force Structure in the Dustiness Testers

Particle flow mechanisms which have been identified in the dustiness tester are directly related to the contact forces on other particles and walls of the drum, as related to (Yang et al., 2003). It is important to quantify the forces between particle and particle and between particle and wall interactions. In this section, the magnitude of three forces was analysed: the average normal contact force \( F_{n(avg)} \) and average tangential contact forces \( F_{t(avg)} \), the maximum normal and tangential contact forces \( F_{n(max)} \) and \( F_{t(max)} \) and the total normal and tangential contact forces \( F_{n(tot)} \) and \( F_{t(tot)} \) of all particles per time step over the simulation time in the dustiness testers. The average particle force at a contact with another particle or the drum wall is calculated by the contact particle force
at a given time step according to equations 2.13 and 2.14. The maximum force in a contact of a particle in the dustiness tester can be determined according to the value of the maximum particle force in the drum for each time step. The total particle forces in the dustiness tester are the sum of all contact forces between particles and between particles and drum wall per time-step. Figure 7.11 shows the particle distribution in the IS tester of the contact force with different particle sizes. In Figure 7.11(a) it is evident that large normal contact forces are occurring on the particles falling from the vanes and impacting on the drum wall or other particles. The high peak of the force took place when the particles of higher density fall and impact on the drum wall. Relatively large forces can also be found on the bottom wall of the drum positions, where particles with high velocities impact on the drum wall and move with different velocities. The tangential force occurring in the IS tester is shown in Figure 7.11(b). When the particles contact other particles or the wall of the drum, the tangential force is the force from the particle displacement of the contact point to the point at the contact end or the point at which the particles begin to roll or slip. Particularly, the highest velocity in the drum has been shown to be the highest force as compared with a different particle size, as shown in Figure 7.11(c). It can be seen that increasing the size of the particle increases the contact force when the particle falls and impacts on the drum wall. However, the contact force occurring between particle and particle depends on their relative velocity. That means the particles at high velocities may not create the highest contact force if their relative velocity is small. Therefore, the contact force is not necessarily correlated with the velocity of the particles; it should be based on the systems and operating. However, the size of particle and percentage of particle volume fraction or mass of particle fraction were an influence on the contact force during the drum rotation.

Figure 7.12 shows the particle force distribution in the axial direction of the contact force with four different sizes under five locations (bins) in the AS tester. Figure 7.12(a) gives the average contact normal force occurring on the particles which are in direct contact with one another or with the drum wall. It can be seen that most of the forces generated in the dustiness tester are in very steady-state for the entire simulation time. However, the particle displacement of the contact from the first point to the end of the contact point before that particle begins rolling or slipping is called the tangential contact force, as shown in Figure 7.12(b). Figure 7.12(c) shows the average total contact force of particle
acting in the dustiness tester as compared with different size of particles moving within the rotating drum over the entire simulation time.

Figure 7.11 The distributions of the particle contact in the IS tester (a) normal contact force (b) tangential contact force (c) total normal contact force.

Figure 7.12 The distributions of the particle contact in the AS tester (a) normal contact force (b) tangential contact force (c) total normal contact force.
7.3.4 Collision Energy

The energy loss in the dustiness tester depends on the particle and particle and particle and wall interactions. The normal energy loss is defined as the energy loss during a particle collision with another due to normal direction overlap. The tangential energy loss is defined as the energy lost during a particle collision with another particle or the drum wall due to the tangential overlap. Total energy loss is the sum of the normal and tangential energy loss due to the particle collision. These factors are impossible to quantify in a physical experiment. In this section, a numerical method by DEM simulation was used. By this method, the motion of particles and their interactions with others, and the energy dissipation when the particle collision can be determined. The energy losses in the normal and tangential directions, collision energy and collision frequency were determined from all particle collisions in the drum. Figure 7.13 shows the number of particle collisions and average energy loss in the IS tester. Figure 7.13(a) shows the number of particle-particle and particle-wall collisions in the drum. The initial transient behaviour of the particles shows peak values as all particles fall together to the bottom of the drum before steady-state conditions establish after 1 rev of the drum. It is clearly seen that the particle-particle collisions have a higher value than the particle-wall collisions due to the formation of the bed of material involving many particle interactions. Figure 7.13(b) shows the average energy loss per time-step of all particles moving in the IS tester. The particles falling from the vanes and impacting on the lower surface of the drum is higher than the particle movement on the wall surface of the drum as it rotates.

![Image](7.13.png)

Figure 7.13 The distributions of particle collision in the IS tester (a) number of collision (b) energy loss of particle.

In regards to the behaviour of particle flow in the AS drum, most particles slide on the wall of the drum as it rotates in the clockwise direction (see Figure 7.2). Figure 7.14(a)
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displays the number of particle-particle collisions and particle-wall collisions and it clearly is seen that there are many more particle-particle collisions. For the average energy loss per time step, as shown in Figure 7.14(b), it can be seen that the energy loss is steady-state over the simulation time (after the initial transient period) and the normal and tangential energy loss are very similar as to the energy loss as the drum rotates.

Figure 7.14 The distributions of particle collision in the AS tester (a) number of collision and (b) energy loss of particle.

Additionally, the particle flow in the IS and AS testers will be analysed in terms of collision energy \( (C_E) \) and collision frequency \( (C_F) \). The collision energy is defined as the collision energy per collision of a particle within a second. Both particle and particle and particle and wall collision energy in terms of kinetic energy are calculated by

\[
C_E = \frac{1}{2} m_i v_{ij}^2
\]

where \( m_i \) is the mass of particle and \( v_{ij} \) is the relative velocity of two particles \( (v_{ij} = |v_i - v_j|) \) when the particle comes into collision with another particle or between particle and wall of the drum; it is the relative collision velocity between the two objects. Collision frequency in the dustiness tester is defined as the number of collisions per particle as recorded per second. Figure 7.15(a) shows the average of the collision energy and collision frequency of the particle flow in the IS tester. The peak location of the particles distributing the collision energy corresponds to the location of the high density of particle collisions. At the bottom wall of the drum, particles moving with the drum rotation have the same velocity as that of the drum. Particles on the vanes, before falling to the bottom drum, are relatively densely-packed and there are a rapid series of collisions with their neighbours, leading to high collision frequency. On the other hand, after particles move
out from the vanes to the bottom drum wall, there is a relatively long distance before they collide with other particles or the wall of the drum, leading to a low collision frequency. Figure 7.15(b) shows the collision energy and Figure 7.15(c) shows the collision frequency occurring in the different particle sizes over the simulation times. The large particle size movement in the rotating drum produces the highest energy loss compared to the other particle sizes.

Figure 7.16(a) shows the average collision energy and collision frequency of all particle sizes flowing in the AS tester. The distribution of all particles is steady-state after the drum rotates 2 revs. Figure 7.16(b) and Figure 7.16(c) show the collision energy and collision frequency for the four particles of different sizes in the range of the simulation time into the steady-state condition. It can be clearly seen that the collision energy and collision frequency increases as the particle size increases, based on the number of particles moving in the system.

Figure 7.17 shows the average collision energy and collision frequency with different particle sizes moving in the drum with five locations (bins) in the IS tester. It can be seen that high collision frequency does not necessarily always correspond to high collision energy. The average collision energy and collision frequency were calculated for each particle size and five location bins. This calculation is carried out for the simulation time $t = 60$ sec. The results are, finally, average values of the collision energy and collision frequency over simulation time. Figure 7.17(a) shows that the particle distributions in the IS tester combining high collision energy with low collision frequency (Figure 7.17(b)) corresponds to each section of five bins and peak of collision energy at the middle drum (bin3) where particles obtain high velocities due to falling from the lifting vanes. The low collision energy corresponds to both sections close to the end wall (bin1 and bin5) and highest collision frequency at the bin1. This is the particle collision all the time before particles begin sliding on the cone wall of the drum. Both collisions of energy and frequency are related to many factors, including the static and rolling friction of the particles, movement of the particles and operating conditions of the dustiness tester.
Figure 7.15 Energy of particle distribution in the IS tester (a) collision energy and collision frequency for the all particle size (b) collision energy and (c) collision frequency for the different particle size.

Figure 7.16 Energy of particle distribution in the AS tester (a) collision energy and collision frequency for all particle size (b) collision energy and (c) collision frequency for the different particle size.
Figure 7.17 The particle distributions in the IS tester with different particle sizes and 5 bin positions (a) average collision energy (b) average collision frequency.

Figure 7.18 shows the average collision energy and collision frequency with four particle sizes and 5 bin positions in the AS tester. The results are, finally, an average record when the particle flow is steady-state at the simulation time $t = 60$ sec, the average collision energy and collision frequency. Figure 7.18(a) displays the highest collision energy occurring on the large particle size at both end walls of the rotating drum. The collision energy and collision frequency are both affected by the vertical end wall blocking the other particles moving in the axial direction of the rotating drum. The highest collision frequency occurs on the small particle size at both end walls of the drum. Like for the IS tester, the collision energy and collision frequency are related to many factors, including static friction and rolling friction of the particles, movement of the particles and operating conditions of the dustiness tester. Figure 7.18(b) suggests the high collision frequency does not necessarily always correspond to high collision energy.

Figure 7.18 The particle distributions in the AS tester with different particle and 5 positions (a) average collision energy (b) average collision frequency.
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7.4 Mathematical CFD-DEM Coupling Model

This section investigates the dynamics of the particle flow and airflow, particle and particle and wall collision and the effect of drag force in the dustiness testers. The DEM-CFD coupled simulations were completed with different sizes of the coal particle model.

7.4.1 Simulation Condition

The geometry of the dustiness testers and the type of coal particles used in these simulations were based on the experimental work. The physical properties of the material, the dustiness tester and the interaction properties are as shown in Table 7.1. The boundary conditions for the CFD and DEM-CFD coupling are the same as for the polyethylene pellets (see Section 5.6.1).

7.4.2 Particle and Fluid Dynamics

One of the most interesting aspects of the DEM-CFD coupling simulations is the analysis of the particle collision dynamics and airflow continuous in the system. In both dustiness testers, particle movement is strongly dependent on the particle collision velocity and the collision frequency. Colliding particles will rebound after a collision with another particle or with the drum wall. According to the numerical model of this section, there are three interactions; particle and air, particle and particle and particle and wall collisions; all the interactions effect the drag force in the dustiness testers.

Figure 7.19(a) shows the particles moving in the clockwise direction and airflow 38 l/min from the front to the back of the IS rotating drum. It can be seen that there is a high velocity of airflow and airflow fluctuations occurring close to the drum wall and back of the drum. At the back of the drum, the airflow remixed from two sources; air generated from the inlet at the front of the drum along the central axial direction of the dustiness tester and air generated as a result of the vane rotation. Air generated from the vanes has the largest effective on the particles falling. The velocity of airflow and particle flow are in opposite directions. In this section, the air velocity increases from the front to the back (bin5) in the axial direction and decreases from the drum wall to the centre in the radial
direction. From both sources, the fluctuating airflow occurs in the back section of the drum. Therefore, this zone is the most important for the smallest sized particles. If fine dusty particles were to be present in the DEM-CFD simulations, they should be extracted from the drum as they are caught in the airflow. Figure 7.19(b) shows the air generated from the front in the axial direction of the drum, the streamlines of the airflow pass by the particles falling from the vanes moving to the back section of the drum and flows out of the drum. The airflow and particles moving in the radial direction, as shown in Figure 7.19(c), show that the direction of the airflow is the opposite to the particles falling. The air is generated from the vanes flowing in the same direction of the drum rotating and converges to the core and mixes with other airflow from the front of the drum. It is very important for the velocity of the particles falling that the fine or lightweight materials must move with the airflow in the axial direction towards the back of the drum for extraction. Figure 7.19 shows that the velocity of a particle falling is higher than the velocity of airflow in the middle of the drum. The air generates from the inlet at the front of the drum flow a circular motion in the same direction of the drum rotation, the air stream flow in the middle of the drum in the axial direction expands to the full cross-section at the back of the drum. This is because the outlet is smaller; therefore, the velocity and pressure are higher than other zones. The airflow at the back section of the drum rotating has a fluctuating effect to the small sized particles moving to the back of the drum and the dust (fine particle) flow out at the outlet of the dustiness tester.
Figure 7.19 Snapshots showing the particles and air flow in the IS tester at time $t = 60$ sec
(a) mixing air flow (b) air flow in axial direction  and (c) air flow in radial direction.

Figure 7.20(a) displays the air flow of 175 l/min and 4.7% volume fraction of particles moving in the AS tester. It shows that the high velocity of air generated from the inlet at the front in the central axial of the dustiness tester is higher than air generated from the vanes and flowing around the axial direction as the drum rotates. The velocity of a particle in the range $2.0 \, \text{mm} - 6.3 \, \text{mm}$ falling from the vanes to the lower surface of the drum is higher than the velocity of airflow occurring as a result of the drum rotation. Figure 7.20(b) shows the air generated from the inlet moving in the axial direction to the outlet of the dustiness tester. The dimension of the air streamline is the same of the inlet diameter; the streamline expands to the large size and moves in the angular direction with the drum rotation before flowing out at the outlet hole. The particle and airflow in the radial direction, as shown in Figure 7.20(c), shows air generated from the vanes when the drum rotates in the clockwise direction around the axial direction of the drum. The highest air velocity occurs on the drum wall and reduces to the centre at the axis of the drum. Both airflows generated from the front and vanes moved past the free surface on the particle heap. The particles sliding on the top free surface and falling from the vanes are an influence on the airflow in the drum. Generally, the small particles and light weight of
the particles result in their moving from the front to the back of the drum by airflow and moving out at the outlet hold for the fine particles (dust).

**Figure 7.20** Snapshots showing the particles and air flow in the AS tester at time $t = 60$ sec (a) mixing air flow (b) air flow in axial direction and (c) air flow in radial direction.

### 7.4.3 Particle Interaction in the IS Tester

This section investigates the interaction between particle dynamics and air flow in the IS tester, focusing on the particle and particle and particle and wall collision, particle and air interaction velocity and effect of drag force.

#### 7.4.3.1 Particle and Particle and Particle and Wall Collisions

Figure 7.21(a) shows the average particle-particle collision velocity and average particle-wall collisions velocity as a function of the simulation time (in revs). The data of the collision velocity has been averaged at every one second of simulation time and is displayed for the full simulation time of 60 secs. It clearly is seen that the collision
velocity between particle-particle and between particle-wall were very similar in their trends after the drum has rotated for 1.5 revs. The peak of collision velocity is recorded in the particle falling and impact on the bottom wall of the drum. The low collision velocity of the particles corresponds to the particles moving up via the vanes from the bottom to the top angle of the drum rotation before the particles again fall to the bottom of the drum. This process of the particles falling occurs every 2 sec to the simulation end-time. In the IS tester, the peak average particle–particle collision velocity is 0.102 m/s, which is 14% higher than in the average relative velocity of particle and wall collisions (Figure 7.21(a)). The average particle and particle and wall collision velocities are 0.02 and 0.09 m/s respectively. Figure 7.21(b) presents the collision frequency (collisions per particle per second) of the particle and particle and particle and wall collisions, which were recorded over the simulation time, \( t = 60 \) sec. The magnitude of collision frequently shows a very similar trend after simulation times of 2 revs. Mainly, the particles moving via the vanes regions of the investigated particles accounts for the high collision frequency for the particle-particle and particle-wall interaction, whereas, for the particles falling from the vanes, the collisions between particles and particle-wall are shown to be higher than the particle-particle collisions. On average, the particle-wall collision frequencies peak at the 1st revolution of the drum rotation (15 sec) for all particles falling and impacting on the drum wall (11,793s\(^{-1}\)). The average of the particle-wall collision frequency in the 1st revolution is twice as high as the frequency observed from the other revolutions (2nd and 3rd) to the simulation end-time. In the IS tester, the average particle collision frequency on the wall is 3.15x10\(^3\)s\(^{-1}\), which is 11% higher than its overall average particle-particle collision frequency and 26% lower than the average total particle collision frequency in the rotating drum.
Figure 7.21 Particle collision distribution in the IS tester (a) average particle and particle, and particle and wall collision velocity (b) average particle and particle, and particle and wall collision frequency.

Figure 7.22 presents the particles moving on the drum wall and falling from the vanes to the bottom wall of the drum, and repeating this operation in the rotating drum to the end simulation time. Figure 7.22(a) shows that the average collision velocity in the five bins of the drum increased 9% from the 1st to 2nd revolutions and constantly increased 2% every 1 rev to the simulation end-time. At the middle of the drum, the particle collision velocity and particle kinetic energy are recorded at the maximum value in bin3 and reduces towards both end walls of the drum. The average particle kinetic energy of the colliding between particle and particle and particle and wall constantly increased from the 1st revolution to the simulation end-time, as shown in Figure 7.22(b). Therefore, it was found that the kinetic energy increased with the particle velocity. Figure 7.22(c) shows the average particle-wall collision frequency is highest at both end walls of the drum (bin1 and bin5). There are more particles moving at both end walls (see Figure 7.9(c)), the particles collide in bin1 and bin5 more than in the other bins. Therefore, the particle-wall collision is higher than the particle-particle collision in the other bins. There are more particles moving on the drum wall via the vanes at the beginning of the simulation before the particles begin to fall from the vanes. Figure 7.22(d) shows the largest particle and particle collision frequency is the highest in the 1st revolution (high collision frequency) and then is relatively consistent for the remainder of the simulation.
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7.4.3.2 Particle Velocity and Air Flow in the Testers

The drag force on the particles is the most important in the air-particle interaction in the dustiness tester. The air velocity increases from the front to the back section (0.046 m/s to 0.212 m/s) of the drum and decreases from the wall surface to the axial location of the rotating drum, at a degree of 0.1 m/s to 0.04 m/s. The average particle velocity in the radial and axial direction is shown in Figure 7.5. The drag exerted on the particle model is calculated according to equation 2.29. This individual drag force in the drum must also be modified due to the flow and pressure effect from surrounding particles. Figure 7.23 shows a calculation the particle and air velocity distribution in the IS dustiness tester at the steady-state time $t = 60$ sec. Figure 7.23(a) shows the behaviour of the particle motion in the IS tester. Particles were continuously moving out from the vanes and dropping to the lower drum wall. The number of particles and particle size of this simulation is shown in Table 7.2. From the results, the particles were initially transported from the bottom wall of the drum via vanes to the top angle and fall to the bottom of the drum and this process is repeated until the end simulation time. Particles are coloured by the particle
velocity with the red colour indicating a fast particle velocity, green colour indicating a medium particle velocity and the yellow colour indicating a slow particle velocity. Figure 7.23(b) upper shows the air velocity in the radial direction was higher than in the axial direction with the air stream input from the front of the drum, and that the air velocity at the back of the drum was 60% higher than the front. The air velocity and flow pattern vary due to the airflow generated from the front of the drum and as a result of the rotating vanes. In the centre of the rotating drum, the air velocity was much lower than the drum wall speed. The velocity at the vanes generated the swirling flows inside the dustiness tester over the simulation time, as shown in the lower images of Figure 7.23(b).

Figure 7.23 Distribution of velocity flow in the IS tester (a) particle velocity and (b) air velocity (Legend scales are in m/s).

7.4.3.3 Effect of Drag Force in the IS Testers

The IS tester has a small particle size (fine particle) falling from the vanes which are affected by the air dynamics from the front at the inlet position to the back at the outlet position of the rotating drum. In the simulation model, analysis of the effect of air flow on the particles was conducted via the computational fluid dynamics (CFD) and an Application Programming Interface (API), which is a module available in the EDEM software, which analysed the effect of drag forces on the particles. The equation for drag force is a function of the particle coefficient of friction ($C_D$), a particle’s cross-sectional area ($A$), air density ($\rho$), and velocity of the airflow passed the particle ($v$), as shown in
equation 2.25. The streamline of the high air velocity in both rotating drums occurs in the middle of the cross section from the front to the back of the drum, as shown in Figure 5.32. The diameter of the inlet hole for the IS tester is 150 mm and for the AS tester is 40 mm. Therefore, the particles are falling from the vanes or rebounding on the wall and are diffusing throughout the rotating drum. Some particles move into the streamline of the air flow from the front to the back and the particles change to a new position in the axial direction of the drums, as they rotate.

This section investigated the effect of the drag force on the particles flowing in the drum. The drag force is in the opposite direction to the air stream flow from the inlet. The drag forces in the drums were classified as the airflow, due to the air being vacuum pumped at the outlet of the rotating drum and an opposite drag flow, which was due to the possible reverse air dynamics at the inlet hole at the front of the rotating drum. The airflow from the inlet (front) to the outlet (back) direction of the drum was called “air flow” which was assigned an air flow value of 0.212 m/s at the outlet hole, which is equivalent to the experimental flow rate 38 l/min. The opposite air flow from the outlet to the inlet direction (from the back to the front) in the horizontal direction was called “drag flow”. The effect of the drag flow on the particle distribution was tested at different particle sizes. Airflow created forces that prevented the particles from flowing freely around the drum. An example of this behaviour of particle flow in the IS tester, as show the velocity in Figure 7.24(a) recorded the particle movement in the drum with non-air flow. The left image of Figure 7.24(a) shows a snapshot of the particles moving at the time $t = 60$ sec and the colour represents the velocity (m/s) of particles flow is faster “red colour” and slower “yellow colour”. The right image of Figure 7.24(a) plots the particle volume fraction in the five bins. As can be seen, the highest number of particles are moving in bin1 when the drum rotates without airflow. The particles behave in a similar manner for all the drag flow modelled. Figure 7.24(b) presents the particle movement in the drum with airflow. It can be seen that there is an air effect on the particles falling from the vanes and particles are moving to the back of the drum. The number of particles in bin1 has decreased and are moving to the next bin, with the highest number of particles shown in bin3 at the end time of the simulation. The particle movement is much more steady than was seen for the no airflow case of Figure 7.24(a). It can clearly be seen that the particles in bin1 and bin5, show the most difference of particle volume fraction when the drum rotation with non-air and with air are compared. The particle movement in each bin has a very steady-state.
condition, where bin1 maximum reduction is 38% and the back of the rotating drum (bin5) showed a particle increase up to 12%.

![Particle drag distribution in the IS tester](image)

**Figure 7.24** The particle drag distribution in the IS tester (a) non-air flow (b) with air flow.

### 7.4.4 Particle Interaction in the AS Tester

This section investigates the interaction between particle dynamics and airflow in the AS tester, focusing on the particle and particle and particle and wall collisions, particle and air interaction velocity and effect of drag force.

#### 7.4.4.1 Particle and Particle and Particle and Wall Collisions

Figure 7.25 shows the average particle collision velocity and average collision frequency over the simulation time. The particle collision velocity in the AS tester is shown in Figure 7.25(a). It clearly is seen that the particle and particle collision velocity has a cyclic trend over the whole simulation time in the investigated range for 20 revs and is 0.114 – 0.132 m/s. For the average particle and wall collision, velocity also varies with a cyclic trend in the range 0.103 – 0.18 m/s, which is 46% higher than in the average velocity of particle-particle collisions. The average particle–wall collision velocity in the AS rotating drum
is 0.123 m/s. For the particle collision frequency, Figure 7.25(b) presents the collisions per particle per second. Both of the particle collision frequencies for particle-particle, and particle-wall interactions are very similar trends and constant over the simulation times in the range for 20 revs. The magnitude of the particle and particle collisions is higher than the particle and wall collisions by a factor of 344%. Mainly due to the particles moving up via the vanes regions and sliding down to the lower part of the drum on the free surface of the particle heap, these investigated particles have a high collision frequency. The average particle and particle collision frequencies in the rotating drum (38.35 s\(^{-1}\)) are 4.4 times higher than the particle and wall collision frequency (8.63 s\(^{-1}\)), showing there is more interaction between particles than the walls.

The air velocity in the axial direction at the inlet is 2.32 m/s and the highest velocity of air at the outlet is 25.8 m/s. The high velocity in the radial direction of the drum is 0.6 m/s at the 10 mm far from the drum wall decreases to the 0.25 m/s (at bin1) and 0.03 m/s (at bin5) at the 25 mm far from the axis of the drum (see Figure 5.32). Therefore, the airflow effect on the particles falling from the vanes or rebounding on the wall of the drum were diffusing throughout and the particles moved to a new position in the rotating drum.

The particles moving in the middle drum (bin3) have the lowest collision velocity and particle kinetic energy, as shown in Figure 7.26(a) and (b). Both end walls of the drum (bin1 and bin5) have the highest collision velocity, collision frequency of the particle and wall interaction and particle kinetic energy, but have the lowest particle-particle collision frequencies. The average velocity of the particle collisions increases with the increase in simulation time, but the kinetic energy is much more stable over increasing simulation
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time. The collision frequency for the five bin locations is shown in Figure 7.26(c) and Figure 7.26(d). It shows the particle and wall collision frequency at both end walls is higher than the other zones by around 10 - 20%. It clearly is seen that the particle-particle collision frequencies in Figure 7.26(d) have a much more scattered result.

![Figure 7.26 Particle distribution under different simulation times and locations in AS tester](image)

(a) average particle velocity magnitude  
(b) particle kinetic energy  
(c) particle and wall collision frequency  
(d) particle and particle collision frequency  
(case1: 15s, case2: 30s, case3: 45s and case4: 60s).

7.4.4.2 Particle Velocity with Air Flow in the AS Tester

The drag force occurs on the particles falling from the vanes and on the top free surface of the particles moving when the drum rotates. The drag force is the most important for the air-particle interactions in the rotating drum. The drag force on the particle model is calculated according to equations 2.28 and 2.29 relative to the air velocity. The Ergun and Wen & Yu drag model proposed for the individual drag force in the drum must also be modified due to the flow and pressure effect from surrounding particles. Figure 7.27(a) shows the result of the particle motion of the front view (upper row) and the top view (lower row) in the AS tester. The colour of the particles and air flow in the diagram are represented according to their velocity. The number of particles and the particle size used in the simulations are shown in Table 7.2. From the results, the particles initially
transported from the bottom wall move up via the vanes and fall back to the bottom of the drum, then repeat this process until the simulation end time. The large variation of particle velocity is recorded when the particles are falling from the vanes to the free surface below. Approximately 5% of the particles are falling from the highest angle of the vanes as they rotate and the particles are falling very close to the vertical plane at the centre of the drum. These falling particles have an effect on the air flow and velocity in the drum over the simulation time in this range, 60 sec.

Figure 7.27(b) shows the streamlines of air velocity distribution in the AS tester under steady-state conditions. The streamline flow in the rotating drum mainly swirled around the rotational axis of the drum. The airflow is generated from two sources; from the front of the drum at the inlet, flowing to the back at the outlet of the drum and from the rotation of the vanes, causing a swirling effect. The dimension of the streamlines moving from the inlet to the outlet of the drum stay relatively uniform in diameter but there is some expansion in the back half of the drum. The air generated from the vanes shows the streamline flow around the central axis of the drum as it rotates. In the radial direction, the highest air velocity occurs at the drum wall and reduces to the lowest velocity at a radius of \( r = 75 \) mm and increases again at the central axis of the drum. Considering both airflows in the drum, it was found that the air velocity in the radial direction was higher than in the axial direction at the back position of the drum. Especially, the air velocity at the front section (bin1) was higher than the back section (bin5) of the drum by approximately 3%. The lower image of Figure 7.27(b) shows the air velocity at the middle of the drum from the front view. The transition of the air velocity is shown, with air generated from the front mixed with the air generated from the vanes. The airflow rotates around the drum due to the motion of the vanes, however, when the particles fall from the vanes, the particle stream interferes with this airflow rotation. This traps the air until all particles have fallen from the vane, when there is a short period of time before the next group of particles falls. The small-sized particles distribute to the free space before collecting with other particles on the bottom drum. The velocity of the airflow on the free surface had the effect that for the small particles, the air must be driving the fine particles (dust) to the back section and diffusing again by airflow in the drum. The airflow in the voids between the large particles has the effect that for the small sized particles, it is easy to move from the front to the back of the drum. The small sized particles take time to move through the voids to the bottom of the drum.
7.4.4.3 Effect of Drag Force in the AS Tester

The actual dustiness tester has an airflow effect on the particles, since the particles are moving in the radial and axial directions as the drum rotates and airflow is from the front of the drum at the inlet position to the back at the outlet position. In this section, analysis of the effect of airflow on the particles was conducted using computational fluid dynamics (CFD) and an Application Programming Interface (API), a module available in the EDEM software, which would analyse the effect of drag forces on the particles. It was considered that the particles dropping through the centre zone of the air stream from the front to the back of the drum, the particle falling on the free surface of the particles, sliding from the top to the lower part of the drum as it rotates. The equation for drag force is a function of the drag coefficient ($C_D$), a particle’s cross-section area ($A$), air density ($\rho$), and velocity of the airflow past the particle ($v$), as shown in equation 2.25. Given the fact that the particles are falling from the vanes and spread over the rotating drum, as described earlier, this section investigates the effect of drag force at the back of particles in the opposite direction to the inlet stream flow. The drag forces in the drum were classified as the airflow, due to the airflow being created by a vacuum pump at the outlet of the rotating drum, and an opposite drag flow, which was due to the possible reverse direction air dynamics at the outlet in to the drum. Based on the AS standard, the airflow rate in the drum is 175 l/min, which equates to an airflow velocity at the outlet of 25.8 m/s. The opposite air dynamics from the outlet to the inlet direction, from the back section to the
The front section of the drum in the horizontal direction was called “drag flow.” The air dynamics from the bottom to the top direction of the particles was designated “lift flow”. The effect of the drag flow and lift flow on the particles distribution was tested at different particle sizes. The airflow created forces that prevented the particles from flowing freely as the drum rotated. Figure 7.28 represents the velocity of faster particles as “red colour”, medium particles as “green colour” and lower particles as “yellow colour” moving in the rotating drum at the simulation time $t = 60$ sec. An example of this behaviour of particle flow in the AS tester is shown as the velocity of the particle flow with the non-air flow case in Figure 7.28(a). It can be seen that Figure 7.28(a) also displays the graph of the particle volume fraction with non-air flow for the five bins in the range simulation time and that the particle movement in each bin is very similar, at approximately 20% each. The same simulation was then repeated with the coupled CFD software and the results are shown in Figure 7.28(b). The particle distribution across the drum for the drag and lift flow versus simulation time is also plotted in Figure 7.28(b). The result for the coupled DEM-CFD model is clearly seen, since the number of particles decreases in bin1 and increases at the middle section (bin3) over the simulation time. The highest velocity of airflow in the axial direction occurred at bin1 and drove the particles to move from this bin towards the next bin of the drum (bin2, bin3 and bin4).

![Figure 7.28](image)

**Figure 7.28** The particle distribution in the AS tester (a) non-air flow and (b) with air flow.
7.5 Conclusions

A DEM model was developed to simulate and monitor particle flow in rotating drums. The experimental and numerical results are compared in terms of flow pattern and segregation of particles. Particle distributions related to flow structure and force structure with different particle size and location of the particle movement in the dustiness testers has been analysed. The key findings are summarised below.

The geometry of the drum, the number of particles and the particle size show a critical role in segregation of particles in the dustiness testers. Particle sizes do not distribute to the segregation uniformly in the rotating drums. Flow patterns and particle distribution have shown that the large sized particles are more densely packed near both end walls and the smaller sized particles move to the middle of the drum. The radial direction shows the high velocity of air flow near the drum wall, as shown in Figure 7.23(b) and Figure 7.27(b) with the tangential velocity being the most prominent component (see Figure 5.31). In the axial direction in each section (bin) along the drum, the particles falling from the vanes are affected by the velocity of the air flow moving from the front to the back of the drum. Force variation in the radial direction gives the peak values near the wall when the particles drop and impact on the drum wall and the tangential force has a linear relation with the normal force.

Collision energy and frequency are two important parameters for characterising dustiness tester performance. The distributions of collision energy and collision frequency indicate that high collision frequency does not necessarily correspond to high collision energy. For the dustiness testers considered, high collision frequency occurs in the region of the particles moving via the vanes on the drum wall, and high collision energy occurs when the particles are falling from the vanes. The collision energy of particles is closely related to the particle velocity of the contact forces of the particles. The relationship between the maximum force and collision energy can also be derived from the contact force equations.

For the DEM-CFD simulations of the air flow with particle movement in the dustiness tester, the drag force has an effect on the particles falling from the vanes and the particles sliding on the free surface. It was seen that the small particles on the top of the vanes fall to the bottom of the drum from a higher angular position of the vanes as the drum rotates.
The particles lifted by the vanes fall very close to the vertical plane, which interact directly with airflow from the front of the drum to the back of the drum in the axial direction for both dustiness testers. This indicates that any dusty material present in the sample being tested has a high chance of being extracted successfully. The collision velocity and collision frequency in the IS and AS dustiness testers have been shown to be very stable over the full simulation time. The collision energy and collision frequency are related to the coefficient of static friction and rolling friction of the particle movement and operating conditions of the dustiness testers. The high collision frequency does not necessarily always correspond to high collision energy. In the IS tester, particles at the drum bottom wall show low collision frequency but show high collision frequency on the vanes as the drum rotates. In the AS tester, the average particle velocity in the bottom of the drum is only 0.29 m/s, which is 40% lower than its overall average particle velocity. The average collision frequency between particle and particle is higher than the particle and wall collision. The small sized particles have a higher effect on the airflow in the drum as it rotates.
Chapter 8
Dust Generation in Dustiness Testers Using DEM-CFD

8.1 Introduction

This chapter presents a procedure for dust emissions during the vertical falling of particles and during the particle sliding on the heap on the bottom of the rotating drums. Three particle models, for polyethylene pellets, iron ore and coal, have been used to investigate the particle movement in the IS and AS dustiness testers using the DEM-CFD coupling method to analyse the mechanisms of material flow. For these particle models, the following characteristics have been investigated: impact force for particle breakage, energy dissipations during particle collisions, particle and air velocity, size distribution and behaviour of dust emissions in the rotating drums.

8.2 Material Properties

Three materials have previously been investigated in the dustiness testers; polyethylene pellets, iron ore and coal. As polyethylene pellets do not degrade during testing, breakage characteristics cannot be determined but results are still presented in this chapter in relevant sections to compare to iron ore and coal. The iron ore and coal are both granular materials and can readily be broken down into smaller multiple particle sizes and generate dust because of impacts and rotation in the dustiness tester.

The iron ore and coal models have very similar particle shape and size, but different particle density, the iron ore having a density approximately two times higher than the coal. For the iron ore model, the particle and bulk properties are described in Table 6.1 and the particle model is presented in Figure 4.24(a) and the size and shape of the particle model and number of particles use in the IS and AS tester simulation shown in Table 6.2.
Moreover, the coal model is described in Table 7.2 for the particle and bulk properties and the particle model is presented in Figure 4.24(b), with the size and shape of the particle model and number of particles used in the IS and AS testers shown in Table 7.2.

8.3 Particle Dynamics

8.3.1 Mechanism of Particle Breakage

The main breakage mechanism of the particles is due to particle impacts on other particles or the wall of the rotating drum. The particles will break into smaller particles if the particle impact stress is larger than the internal particle strength, calculated based on Griffith’s theory and Hertz’s theory. The mechanics of size reduction processes present in a typical dustiness tester are body breakage and surface breakage. Body breakage is as a result of high-energy impact events, the impacting particle moves perpendicular to the plane of contact and produces a normal particle size distribution. Surface breakages are low energy impact events, resulting in the production of large amounts of fines, although taking place at low energies there is a high frequency of occurrence. The importance of surface breakage has been confirmed in previous numerical modelling (Morrison et al., 2004; Powell et al., 2008). The particle movement in the rotating drum is predominantly sliding and rolling, which provides an ideal breakage environment (Gao et al., 1995).

8.3.2 Particle Breakage Model

There are two components to describe the procedure of particle breakage; the particle impact stress acting on the drum wall or other particles and the particle strength. Figure 8.1 demonstrates the two main methods of how a particle can be broken. When a particle falls and impacts on the drum wall or other particles at an impact velocity \( v_p \), that particle has an impact stress \( \sigma_1 \). If the impact stress \( \sigma_1 \) is larger than the particle strength \( \sigma_s \), the result is particle breakage. The particle then separates into multiple smaller sized particles.
Particle Strength ($\sigma_3$) is determined by Griffith’s theory (Smagorinsky, 1963). In that preliminary investigation, it was found that the particle strengths could be predicted experimentally based on the distribution of crack length. The experimental result was not measured and therefore no comparison could be made for particle breakage.

Particle contact Stress ($\sigma_1$) for the spherical particle impacts on the drum wall or on other particles is determined by taking the maximum load impact in the drum and dividing by the projected area of a particle. This results in the average contact stress of the particle impact in the rotating drum per second. For the IS tester, the results are shown in Figure 8.2(a). It can be seen that the particles with higher particle density produce the higher contact stress. The particle movement in the drum is as a result of two different motions, particles moving on the drum wall and falling from the vanes to the bottom of the drum. The particles start moving up on the drum wall via the vanes in the drum, but in this section, forces are not generated on each particle and the velocity of the particles is the same as the drum as it rotates. The particles falling from the vanes display the highest force acting on the bottom wall and create the high contact stress on each particle. The particle movement in the AS tester is shown in Figure 8.2(b). It can be seen that the contact stress of the iron ore and coal have very similar trends over the simulation time. Both materials vary in particle size in the range 2.0 mm to 6.3 mm and the particle shape is very similar, but the density of the iron ore higher than coal so the iron ore shown higher contact stress. Additionally, the polyethylene pellets show the lowest contact stress. The particle size of materials is mono-sized and the shape is close to cylindrical and density of the particle is lowest so the contact stress is lower than iron ore and coal.
8.3.3 Energy Dissipation

The impact energy referred to as the kinetic energy, is calculated by

$$E_{imp} = \sum_{i=1}^{n} \frac{1}{2} m |V_r|^2$$  \hspace{1cm} 8.1

where \( m \) is the particle mass, \( V_r \) is the relative velocity for a particle and particle or a particle and wall collision and \( n \) is the total number of collisions. The impact energy generated within the exact time has a distribution, depending on the particle size and operating conditions of the drum as it rotates. This impact energy is calculated by the kinetic energy of particles contacting (\( \delta = 0 \)), as shown in Figure 2.6(b) is summed up for all the contact points within 1 sec but the kinetic energy during contacting is not calculated. Accordingly, the impact energy thus obtained corresponds to the maximum kinetic energy of particles at the collision per unit time.

The impact energies dissipated during collisions between particles, and between particles and vanes/wall can be measured and recorded at any angular position as a function of time during a drum revolution. The normal component of the relative velocity represents a particle falling from the vanes to the lower drum. Apart from that, the tangential force is related to normal force through the friction coefficient. Therefore, impact energy in the shear direction has already been included in the calculations. Figure 8.3 shows the distribution of particle impact energies in the IS tester on other particles or the drum wall for the three material models. Moreover, the particle distribution in the AS tester, are shown later in Figure 8.5. It can be seen that the DEM simulations can predict impact energy occurring on the individual particle movement in the rotating drums.
Impact energy is defined as collision energy per collision of a particle on other particles or the drum wall within 1 second. Figure 8.4 presents the average impact energy per unit time for the IS tester. After the drum has undergone 0.5 rotations, there is a noticeable energy increase with more density packing and particles falling from the vanes to the lower part of the drum. The impact energy of three materials all show similar trends of energy increase when the particles drop to the drum wall and do not generate energy as the particles are lifted by the vanes. This process is repeated until the simulation end time. The energy dissipation of each particle model increases with the increase of particle velocity. The range of energy dissipation depends on the range of particle size flow in the drum. The polyethylene pellets are mono-size and show a small range of energy dissipation, while iron ore and coal have a wider range of particle sizes, as the particle velocity increased with the 4 different particle sizes moving in the rotating drum. For the IS tester, there is a small amount of particle flow in the drum (small test sample size), so approximately 50% of the particles are falling from the vanes to the drum wall every 2 sec. The highest of the impact energy occurs with the particle impact on the drum wall. The experimental impact energy was unable to be measured and hence no comparison can be made for the simulated energy dissipation.
Figure 8.4 Shows the impact energy in the IS tester (a) over the simulation time and (b) per impact velocity.

The particle impact energy in the AS tester is shown in Figure 8.5. There are three material models shown in the AS tester at steady-state conditions (at t = 10 sec). It can be seen that as the solid density increases, the energy and more amount of particles are greater than 0.1mJ of the energy dissipation in the drum. There is more energy generated on the particle impact on the free surface of the particles moving in the drum as it rotates. The polyethylene pellets are mono-sized and most particles are falling and sliding on the free surface of the material. The iron ore and coal show very similar trends of particle flow in the rotating drum. The small sized particles move up to high angular positions before dropping to the free surface. The iron ore has the higher density and results in the falling particles having a higher impact force on the particles in the moving bed, as can be seen in Figure 8.5.

Figure 8.5 The distribution of particle impact energies in the AS tester at 10 sec for (a) polyethylene pellets, (b) iron ore and (c) coal.
Figure 8.6 shows the average impact energy per second for the particle impacts and rebounds and the velocity of the particles with respect to their energy during the contacts of each particle. Figure 8.6(a) displays the distribution of the impact energy for the three material models and can be seen to be very steady-state over the simulation time. The mono-sized polyethylene pellets show the lowest impact energy dissipation and is a constant value of 1.6 mJ when compared other materials. The iron ore and coal have the same particle size range (2.0 – 6.3 mm), but different solid densities and different amounts of particles for each size range of material. The iron ore has the higher particle density and also recorded the higher impact energy when compared to coal. In addition, Figure 8.6(b) shows the particle velocity increases the effect of the impact energy in the rotating drum. The polyethylene pellets falling and sliding on the free surface shows the velocity of particles in the range of 0.303 - 0.324 m/s and records impact energy in the range of 1.54 – 1.82 mJ. For the iron ore (having the highest particle density), the recorded the impact energy (2.82 - 3.47 mJ) is greater than for coal at the lower velocity range of 0.294 – 0.355 m/s. For the coal, the impact energy increases from 1.93 to 2.85 mJ as the velocity increases from 0.355 to 0.429 m/s.

![Figure 8.6](image)

Figure 8.6 Shows the impact energy in the IS tester (a) over the simulation time and (b) per impact velocity.

8.4 Particle Flow Mechanisms in the IS Tester

8.4.1 Air Velocity in the Rotating Drum

In the IS tester, the air streamlines are generated from the inlet at the front of the drum as a result of the vacuum pump at the outlet of the drum operating at an airflow rate of 38 l/min and also as a result of the rotation of the vanes of the drum. Figure 8.7 shows the air velocity contours in the radial and axial directions. Figure 8.7(a) is a top view of the
IS tester showing the horizontal mid-plane and the dashed line represents the location where the air velocity data was measured. Figure 8.7(b) is a front view of the IS tester showing a vertical plane cutting through the middle of bin1 and the dashed line represents the location where the air velocity was measured. Each of the five bins had one of these vertical mid-planes and was analysed the same as bin1. The results from the five bins can be seen in the graph of Figure 8.7(b). Also refer to Appendix B for further details of the measurements.

Figure 8.7(a) shows that the velocity slowly increased from the inlet to the end of bin5 of 81% and then rising rapidly to the outlet hole of 168%. The maximum speed (0.212 m/s) at the outlet is higher than the inlet hole by a factor of 388%. Figure 8.7(b) shows the air velocity in the radial direction, at the position of \( r = 125 \) mm from the axis of the drum recording a peak velocity of 0.09 m/s and lowest velocity of 0.04 m/s at a radius of \( r = 50 \) mm. The air velocity at the middle plane of bin1 to bin4 displays an air velocity of 0.05 m/s and increases 25% in the middle section of bin5. It can clearly be seen that the small vertical wall at the end of bin5 has an effect on the air velocity, which has increased 20% from the middle of the bin.

Figure 8.7
(a) Shows the air velocity in the IS tester (a) central plane on the top view and (b) central plane on the front view.
8.4.2 Particle Velocity in the Dustiness Testers

The particle movement in the dustiness testers is caused by two components; particles falling from the vanes to the lower section of the drums and particles moving up the drum by the vanes of the drum as they rotate. The velocity of the polyethylene pellets models in the drum is shown in more details in Section 5.4 (Chapter 5). The iron ore and coal particles were generated using 4 particle sizes in the range 2.0 to 6.3 mm, as described in more detail in Chapter 6 and 7, respectively. These two materials showed similar trends of particle velocity in the rotating drum; even though they have different particle density, particle size and amounts of particles for each size range in the drum.

In this section, Figure 8.8 shows the results for three material samples which were compared at five different positions in the IS tester. It can be seen that the highest average velocity over the full simulation time is at the middle of the drum when the particles are falling from the highest angle of the vanes and at high-density of particle packing. This means that particles having a higher coefficient of friction remain on the vanes for a longer time. The smaller particle sizes can pack to a higher density and keep on the vanes longer as the drum rotates. Figure 8.8(a) represents the average velocities in the IS tester over the 60 sec of the simulation time. The velocity of particles for each material model falls in the bin in which the material is originally positioned. The lowest velocity for the mono-particle size of the polyethylene pellets at both ends of the rotating drum and the highest velocity at the middle drum. Iron ore and coal models have a different particle size but particle movement is very similar, as well as the velocity in all five bins in the drum. The most logical explanation for this is that the initial higher density of packed particles in these respective bins has a higher velocity until they gradually spread throughout the drum as the test progresses. The average velocity of each material recorded over the simulation time is shown in Figure 8.8(b), where the particle velocity is at a peak every 1 revs of the drum as it rotates.

8.4.3 Particle Movement in Air Flow

The trajectory of particles falling from the vanes to the lower section of the drum occurs at the radial distance $r_1 = 85$ mm to $r_2 = 100$ mm from the central axis of the drum on the horizontal, as shown in Figure 8.9. The particle velocity at this point is presented in Figure
8.8. The magnitude of the air velocity at this stage is 0.05 m/s to 0.06 m/s from bin1 to the bin5 (see Figure 8.7(a)). Therefore, the air flow has little effect on the particle movement in the IS tester of the particle size range of this study.

![Figure 8.8](image)

**Figure 8.8** The average velocities of the particle flow in the IS tester (a) five positions (b) over simulation times.

![Figure 8.9](image)

**Figure 8.9** Diagram of radial distance of particle falling.

The mechanism of particle distribution in the IS tester is as a result of two components. Particle movement on the drum wall is in the same direction as the drum rotates, the lifter drives all particles to move up to the high angular angle with a velocity of 0.062 m/s. The speed of air (generated by the vanes) is in the same direction of the particle movement. This air velocity does not affect the particles on the vanes as the maximum amount of particles present on each vane is 0.1% by volume of the drum, as can be seen in Section 5.6.5.1. Particles fall from the vanes to the lower part of the drum at the high angle and it is mainly the small particle size that keeps on the vanes for a longer time than the large particles. As the particles fall, the voids between particles increases and the air velocity entrains the smaller particles, moving them towards the back of the drum. Moreover, after the particle impact and rebound, the smallest particles are the most effected by the air flow and also move to the back part of the drum. In addition, the fine particles (dust)
move to the back section (bin5) and fall from the vanes or rebound after impact on the drum wall; moving out from the drum at the outlet hole by the vacuum pump.

Figure 6.13 and Figure 7.19 show air velocity distribution in the IS tester for the iron ore and coal particle models, respectively. The streamline of air flow in the rotating drum mainly swirled around the rotational axis of the drum. The air velocity at the circumference of the rotating drum was higher than those in other areas. Especially, the air velocity at the front (inlet) of the drum was lower than the main drum. The air velocity continues to decrease until the minimum velocity of airflow occurs over the transition zone of the air generated from the front and air generated from the vanes. The streamline of airflow swirling inside the drum from the front to the back and flow pattern are different when the particles drop from the vanes through the air streamline in the central core of the drum, which affect the particle movement. The airflow in the dustiness tester affects the circulation of the particles, moving them to a new position in the drum as it rotates. Figure 8.9 presented the effect of the airflow with particulate matter and compared the dynamics of a particle with non-airflow in the dustiness tester. The particle distribution across the five bins of the rotating drum versus simulation time of the initial heap of particle spread evenly along the drum is shown. The particle volume fraction change was calculated from the difference between volume fraction of the particles with airflow and volume fraction of the particles without airflow, for the iron ore particle model, as shown in Figure 8.9(a) and coal particle model, as shown in Figure 8.9(b). The particle distribution is the concentration profile of particle movement in the dustiness tester and as can be seen, is relatively non-uniform for the five bins along the drum.

**Figure 8.10** Particle volume fraction change (a) iron ore and (b) coal.
8.4.4 Size Distribution

DEM-CFD coupling represented the simulation investigation of particle and air flow in the IS tester. The four different particle size distributions across the five bins over the simulation time are shown in Figure 8.11. The particle segregation is demonstrated by the use of four different colours for the different sizes in the dustiness tester, shown in Figure 8.11(a) and Figure 8.11(c). The yellow colour shows particle diameter 6.3 mm, the blue colour is 5.6 mm dia., the green colour is 4.0 mm dia., the red colour is the 2.0 mm dia.

The smallest particle size is important for the segregation and movement in the dustiness tester. Figure 8.11(a) shows a snapshot of the iron ore model segregation in the drum at the end time \( t = 60 \) sec. The small particle size of 20\% (by volume) moves in the drum over the simulation time as shown in Figure 8.11(b). It can be seen that the particle volume fraction increases at both end bins of the drum (bin1 and bin5) and decreases for bin2 and bin4 and is steady-state constant for bin3. Figure 8.11(c) shows the coal model segregation in the drum at the simulation end time of \( t = 60 \) sec. The small particle size of 10\% (by volume) moves through the drum the most. It clearly is seen that the particle flow fluctuates over the simulation time. Particle size in the range 4.00 – 6.3 mm are shown in Appendix D. The number of particles (see Table 6.2 and Table 7.2) do not affect the particle segregation in the drum after particle collisions with other particles or the drum wall. For the particle sizes of 4.0 mm and 5.6 mm diameter, the flow is stable after 2 revs of the drum rotation, as the particle volume fraction of 20\%. Whereas for the large particle size (6.3 mm dia.), the flow fluctuates over the whole simulation. It is found that the percentage of small particle size increase, the small particle movement to the back section of the rotating drum.

8.5 Particle Flow Mechanisms in the AS Tester

8.5.1 Air Velocity in the Rotating Drum

Figure 8.12 presented the magnitude of air velocity contours in the axial and radial directions of the drum. The velocity of air in the AS tester showing the horizontal mid-plane and the dashed line represents the location where the air velocity data was measured, as shown in Figure 8.12(a), and showing a vertical plane cutting through the
middle of bin1 and the dashed line represents the location where the air velocity was measured. Each of the five bins had one of these vertical mid-planes and was analysed the same as bin1. The results from the five bins, as can be seen in the Figure 8.12(b). Also refer to Appendix B for further details of the measurements. The vacuum pump at the back of the drum controls the airflow rate in the AS tester at a rate of 175 l/min. The air velocity was captured at the middle plane along the drum at t = 60 sec, as shown in Figure 8.12 (left) and the air velocity recorded at the axis of the drum (dot line) then shows the air velocity at different positions (see Figure 8.12 right). It is clearly seen that the velocity in the axial direction decreases from the inlet to bin5 as the lowest position in the drum, with the velocity dropping from 1.82 m/s down to 0.31 m/s and then rapidly increases again to the outlet hole, at a maximum velocity of 8.2 m/s. In the radial direction, the air velocity shows the peak velocity in the middle of the drum for bin1 to bin2 and air flow velocity in bin3 is the same velocity as that occurring on the rim of the vanes, at the radial distance $r = 14.3$ cm from the central axis of the drum. The air velocity along the central axis of the drum for bin4 and bin5 is lower than at the drum wall; with a 14% drop for bin4 and a 68% drop for bin5.

Figure 8.11 Particle distribution in the IS tester (a) snapshot of iron ore at 60 sec, (b) 2mm diameter of iron ore segregation, (c) snapshot of coal at 60 sec and (d) 2mm diameter of coal segregation.
8.5.2 Particle Velocity in the Dustiness Tester

The particle velocity in the AS tester has four positions to be taken into consideration; particles falling from the vanes, particles sliding on the top free surface, particles move up by the lifting of the drum as it rotates and the stationary zone. The highest velocity of the particle movement in the drum occurs when the particles fall from the vanes. The particles sliding on the top free surface are moving in the opposite direction of the drum rotation. The particles are lifted by the vanes at the same velocity as the drum rotation. Also, there is a stationary zone occurring within the middle of the heap of particles moving in the rotating drum.

A similar analysis was performed for the AS tester for the entire 600 sec test of the three materials, as shown in Figure 8.13. As can be seen from the results, the velocities in each of the bins show very consistent results across all three materials, see Figure 8.13(a). It has already been highlighted that there is only transient material behaviour for, at
maximum, the first three seconds of the simulated tests. An additional observation is that the first and last bins (bin1 and bin5 respectively), show the highest material velocities for three material models, albeit these velocities are only marginally greater than the three remaining central bins, which in themselves all show very consistent velocities. This slight increase in velocity at either end of the rotating drum has been attributed to the friction of particles in these two bins due to the end wall sections adjacent to each bin. These end wall sections allow additional movement of particles, which is not captured as part of any bin velocity analysis, but the resulting increase in velocity of the particles, which venture into the conical section are included once they return to the adjacent bin. There are different results for the different material models, with the velocity of particle flow in the AS tester depending on the density of materials, material properties, size and shape of materials models and percentage of materials in each particle size. The magnitude of particle velocity in the rotating drum is steady-state over the simulation time. The mono-size of the particles for the polyethylene pellets had a slight range of particle velocity from 0.364 – 0.408 m/s. Four particle sizes of the iron ore model are moving in the rotating drum. The volume of the smallest particle size (2.0 mm) of 20% volume move to the middle of the drum, the particle velocity slowly decreased from 3.4 m/s to 3.15 m/s (with a 0.03m/s fluctuation) after the drum had rotated 80 revs (approximately) and was then steady-state to the simulation end time. On the other hand, the coal model has a low volume of the smallest particle size of 10% volume, with a large range of particle velocity fluctuation over the simulation being 0.36 – 0.42 m/s and an average particle velocity of 0.39 m/s for the steady-state condition over the simulation time.

**Figure 8.13** The average velocities of the particle flow in the AS tester (a) five locations and (b) over the simulation times.
8.5.3 Particle Movement in Air Flow

The trajectory of a particle falling from the vanes to the lower section of the drum occurs at the radial distance of $r_1 = 63$ to $r_2 = 95$ mm from the axis of the drum, as shown previously in Figure 8.9. The particle velocity at this point is presented in Figure 8.13. The magnitude of air velocity in the axial direction at this state slowly drops from 1.8 m/s (bin1) to 0.33 m/s (bin5), as shown in Figure 8.12(a). Therefore, the air flow in the front section of the drum has a significant effect on the particles falling through this zone and does not affect the particle movement at the back of the drum in the AS tester for the particle size range used in this study.

The behaviour of particle distributions in the AS tester are broken into three groups. The first group is many small particles falling from the vanes after the large sized particles have already fallen to the lower section of the drum, where the particles fall from the vanes and spreading out and impact onto other particles on the free surface. Like for the IS tester, as the particles fall, the gaps between particles increases and the air velocity drives the smaller particles to a new position, towards the back section of the rotating drum. After the smallest particles impact and rebound, they too move to the back section of the drum due to the air flow. In addition, it is critical for the fine (dust) particles falling from the vanes or rebounding after impact to be captured by the streamline of the air flow from the inlet to the outlet of the drum, where the fine particles are collected by the vacuum pump at the outlet hole. The mass of particles that move out of the dustiness tester is the dust for that material. In the second group, the particles are moved by the vanes to an oblique angle of 10 degrees to the horizontal plane, where more particles fall and slide on the free surface. The air flow around the axis is in the opposite direction to the particles sliding on the free surface and the movement of air through the voids between each particle results in some particles moving to the back section of the drum by airflow. The last group is mainly small sized particles moving on the drum wall in the same direction of the drum rotation. The particle velocity in this section is the same velocity as the drum rotation, 0.455 m/s.

Previously, Figure 6.17 and Figure 7.27 showed the streamline air flow and particles moving in the dustiness tester of the iron ore and coal model distribution, respectively. The streamline of air generated from the front directly flows to the outlet of the drum and
air is generated from the vanes as it rotates, mainly due to swirling around the rotational axis of the drum. The air velocity at the axis of the rotating drum was higher than in other areas. Especially, the air velocity at the front (inlet) of the drum was greater than in the main cylindrical drum section. This is because of the cross-section area of the air inlet being lower than for the main drum section. The profiles of air velocity are different and lowest in the transition zone where the air flow is generated from the inlet and from the vanes. The particles drop from the vanes through the higher air velocity zone, the particles are effected by the air flow and are transport to the new position at the back section of the drum.

Figure 8.14 shows the effect of the airflow and compares the dynamics of a particle in the dustiness tester with non-airflow. The smallest particles distribute across the five bins of the rotating drum over the simulation time in the range 60 sec, the initial heap of particle spreads from the front to the back of the drum. The particle volume fraction change was calculated from the different volume fraction of the airflow and volume fraction without airflow in the AS tester, for the iron ore particle model and is shown in Figure 8.14(a) and the results for the coal particle model are presented in Figure 8.14(b). The smallest particles distribution is the concentration profile of the particles movement in the dustiness testers and as can be seen, is relatively non-uniform for the five bin positions along the drum.

![Figure 8.14](image)

Figure 8.14 Particle volume fraction change (a) iron ore (b) coal.

### 8.5.4 Size Distribution

The simulation investigates the particle and air flow in the AS tester using the DEM-CFD coupling method. Four particles sizes are distributed across the five bins of the rotating
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drum versus simulation time, as shown in Figure 8.15. The particle segregation is shown by the use of four different colours for the different sizes in the dustiness tester (see in the colour Figure). The yellow colour shows particle diameter 6.3 mm, the blue colour is 5.6 mm dia., the green colour is 4.0 mm dia., the red colour is the 2.0 mm dia.

The smallest particle size is important for the segregation and movement in the dustiness tester. Figure 8.15(a) shows a snapshot of the iron ore model segregation in the drum at the simulation time $t = 60$ sec. The small particle size of 20% by particle volume moves to the middle of the drum over the simulation time, as shown in Figure 8.15(b). It can be seen that the particle volume fraction decreases at both end bins of the drum (bin1 and bin5), increasing from the start of the drum rotation to 7 revs and slowly decreases to 20 revs and then steady-state condition for the bin2 and bin4, the particles move from the both end wall to the middle drum part the both bins (bin2 and bin4) of the drum rotation. The small particle steady-state condition up to 7 revs and slowly increase to 25 revs and stable particle flow over the simulation time. Apart from that, Figure 8.15(c) shows the coal model segregation in the drum at the simulation time of $t=60$ sec. The small particle size of 10% by particle volume flows in the drum. It clearly is seen that the particle flow fluctuates over the full simulation time. Particle size in the range 4.00 – 6.3 mm are shown in Appendix D. The number of particles (see Table 6.2 and Table 7.2) do not affect the particle segregation in the drum after the particle collision with other particles or the drum wall. For the particle size 4.0 mm, this produces the most particle volume fraction flow in the drum, they move from both end walls (bin1 and bin5) to the middle section (bin2 to bin4) and the particle 5.6 mm and 6.3 mm move to bin1 and bin5. Moreover, the particle volume fractions are not symmetrical between bin1 and bin5 or between bin2 and bin4, this is the effect on the air flow in the rotating drum, also the volume fraction in the back section of the drum is higher than the front section (bin5 > bin1 and bin4 > bin2). The particle segregation in the drum after 60 sec are stable along the rotating drum to the end time of the test.

The large particle size has a higher effect on the drag force than the small particle size. However, the velocity of the large particle size occurs greater than the speed of air in the drum, therefore it does not affect the movement of a particle on the air flow from the front to the back of the rotating drum. When compared with the smallest particle size (0.1 mm dia.), the speed of air in the axial direction of the drum is higher than the velocity of the
particles falling from the lifting vanes. If the speed of air in the axial direction of the drum is greater than the velocity of particles drop from the lifting vanes, the velocity of air drives the particles to change to a new position, moving from the front section to the back of the drum.

![Image](image1.png)

![Image](image2.png)

**Figure 8.15** Particle distribution in the AS tester (a) snapshot of iron ore at 60 sec, (b) 2mm diameter of iron ore segregation, (c) snapshot of coal at 60 sec and (d) 2mm diameter of coal segregation.

### 8.6 Mechanism of Dust Generation

Dust production occurs when air flows past the fine particles falling from the vanes or after particles impact on the drum wall and rebound to other positions, moving into the air streamline in the axial direction. The particle motion in the air flow depends on the size of particles carried by air into new positions, shown schematically in Figure 8.16. There are three particle models; suspended particles, saltating particles and creeping particles. Suspended particles occur to the smallest particles entrained by the air flow and are suspended as “dust” and are carried away once liberated from the larger particles falling from the vanes. Saltating particles belong to the next category. These particles are small enough to be picked up by turbulent airflow at the surface of the particle heap but larger than suspended particles. The motion of these particles is lifted by the air flow across the surface of the particle heap and then the particles fall to the lower part of the
dust generation in dustiness testers using DEM-CFD

...
rotating drum. This is shown schematically in Figure 8.17. No-slip boundary conditions were defined on the boundary of the rotating drum for the airflow. Particles spread after impact on the drum wall or the other particulate matter and no longer collided with their neighbours. The particles were removed when they reached the outer boundary, as they did not contribute any further dust to the system. The DEM simulation for the particle impacts on the wall and for rebounding after impact was long for all particles to contact on the drum wall and spread, after which the particles were no longer in contact. Therefore, the simulation was sufficiently long to generate the maximum amount of dust from the dustiness tester.

The amount of dust produced from each material fall depends on the total mass of the particles and is independent of particle diameter. The particle model was based on the experimental results. Each simulation used the same Hertz-Mindlin contact model and the same simulation conditions as used in the previous chapters for the polyethylene pellets (Chapter 5), iron ore (Chapter 6) and coal (Chapter 7). When considering dust production in the simulations, the small particles fall in the zone of the air flow in the axial direction of the drum and the particles rebound after impact on the wall. Even though the iron ore and coal particles fall from different heights (due to different angular positions of the lifting vanes) the rebounding particles showed very similar results.

The smallest particles are shown in Figure 8.17, for the IS and AS tester. The majority of the small particle size occurred upon impact with the drum wall. The dust was entrained in an air flow from the front of the drum through the particle falling, forming on the bottom wall of the drum after impact and spreading outwards from the impact point and upwards along the bottom drum. The particle velocity stream is shown in Figure 8.17, with the formation of particle impact on the drum wall. The formation and subsequent dispersal of this dust cloud was independent of the particle size and simulation resolution. The dust formation occurs mainly from the right side of the falling trajectory stream and the upper surface of the particle bed. The air flow from the inlet drives the dust liberation to the outlet hole. Particles on the left side of the trajectory stream interact with the airflow, which is at a lower velocity, and therefore their movement is less influenced by the air, but instead by the rotating drum.
8.7.2 Dust Generation from the Particle Heap

The ability of the model to predict dust pick-up from the free surface of the particle heap on the bottom wall of the drum as it rotates by modelling air flow over a particle heap is shown in Figure 8.17. Figure 8.3 and Figure 8.7 showed the particle movement and air velocity in the IS rotating drum, Figure 8.17(a) demonstrates the streamline of air flow with the particle transported. It can be seen that the air streamline from the inlet to the outlet does not affect the particle heap on the wall as the drum rotates. Figure 8.17(b) shows the particles on the bottom wall of the AS tester as it rotates. Particles rotating in the AS tester from a moving heap with dynamic angle of repose of 40 degrees and the particles fall from the vanes and slide on the free surface of the particle heap. The top surface of the particle heap forms a near flat but inclined surface. The air pressure gradient and boundary conditions around the axis of the drum allow air recirculation. The air velocity and dust mass flow are measured at the end of the domain. It can be seen that the air flow from the inlet to the outlet does not affect the free surface of the particles in the drum as it rotates, as shown in Figure 8.17(c).
Figure 8.18 The air flow over a particle heap on the (a) IS tester and (b) AS tester.

8.8 Conclusion

Dust emissions typically cohere to the fine particles falling from the vanes in the air stream. The contact stress is the force of particle impact on the drum wall or other particles and the particle breaks when that particle contact stress is higher than the internal particle strength and then the particle is broken to smaller multi-particle sizes. The mechanisms of the particle breakage are; the body breakage for the high-energy impact and the surface breakage for the low-energy impact. The high contact stress increases with higher density of materials and is increased for the particles falling from the vanes and impacting on the drum wall or impacting on other particles in the drum as it rotates. For the particles moving in the AS tester, the particles move up the drum wall by the vanes of the drum and slide on the top free surface after they fall. The energy dissipation increases when the impact velocity increases.

The DEM-CFD method investigates dust production and distribution of small particle size in the dustiness tester. The model of particle dynamics using DEM simulation and the CFD method was used to model the air flow. The methods were coupled through particle drag relations. Dust production was determined from the impact energy for each particle in DEM. This energy was split into particle collisional energies, resolved by the DEM simulations.
Dust production measurements from simulations were measured using a particle falling from the lifting vanes in the drum, the particle falling under gravity and impacting the free surface. During the small particle falling through the air flow from the front, that air drives the small particles to the back of the drum and towards the outlet hole by a vacuum pump. The air flows over the particle heap on the drum bottom wall, small particles are then picked up from the free surface of the particle heap by the air flow. In a dynamic particle, the energies dissipate when the particle impacts on the drum wall, the higher density particles recorded the higher impact energy.
Chapter 9

Conclusions and Further Works

The research in this thesis was conducted to study the mechanisms of dust generation in two dustiness testers using experimental and numerical methods. The experimental methods investigated the material flow mechanisms and segregation in both dustiness testers. The numerical method investigated the particle flow mechanisms in both dustiness testers and compared the results with the experimental data and observations. The DEM simulations predicted the particle behaviour of material movement in the dustiness testers. Additionally, the DEM-CFD coupling investigated the particle flow mechanisms and the interaction of air flow in the dustiness testers. This chapter summarises the conclusions of the thesis and provides recommendations for relevant topics for further research.

9.1 General Conclusions

The conclusions presented in this section can be divided into two main areas: experimental studies and numerical studies.

9.1.1 Experimental Work

A detailed understanding of a granular system is required for the micro (particle) or macro (bulk) scale movement of particles in the dustiness testers. One aspect that is particularly important is correctly identifying the granular material properties (physical and mechanical properties). The optimisation procedure developed to calibrate the DEM models described in this thesis were developed to apply to a range of materials and therefore a contrasting set of granular materials were chosen. The three granular materials tested in this study were:

1. Polyethylene pellets: having the lowest particle density, they are non-dusty and are mono-sized particles. The equivalent volume diameter of the particles is 4.56 mm.
2. Iron Ore: having the highest particle density, irregular particle shape and a size range of 2.00 – 6.3 mm.

3. Coal: having a medium particle density, irregular particle shape and a size range of 2.00 – 6.3 mm.

9.1.1.1 Experimental Particle Flow Mechanisms in the Dustiness Testers

Two laboratory devices were chosen for this thesis, as described in Chapter 3: the dustiness testers based on the International Standard (IS) and Australian Standard (AS). These devices were chosen as they can produce particle responses that are repeatable and relatively easy to qualify, as well as generate distinguishing results and behaviours of particle movement.

The particle responses determined from these dustiness testers were the particle flow mechanisms and segregation of particles in both dustiness testers. The particle volume fraction was determined to be 0.21% and 4.7% for the IS and AS testers respectively and the rotational speed being 4 rpm and 29 rpm for the IS and the AS tester models respectively. Additionally, four different initial loading positions for each material were used in this research.

The key results of the physical particle experiments can be summarised as follows:

1. The general trend for all of the granular materials is an increasing angle of the lifting vanes before the particles fall, as the coefficient of static and coefficient of rolling friction increase.

2. Three different granular materials showed contrasting bulk responses influenced by two main parameters: the particle aspect ratio (defined as the major to the intermediate dimension ratio) and the particle sliding friction.

3. For the same filling method with four initial locations and three different materials, a range of time simulations were produced. For the IS tester, all the particles spread evenly along the full drum after the drum had rotated 4 revs for the particle fill starting at the front and back heap and after 1 revs for the particle starting at the middle heap of the drum as it rotates. For the AS tester, all the particles spread evenly along the full drum after 2 revs (front and back of particle heap) and 0.5 revs (middle heap).
4. For the binary particle segregation, bands can be observed when the size ratio is greater than 3.0, a significant amount of small particles migrate to the middle of the drum with the larger particles at either end. The small particle size where the dimensionless band width has a minimum value at the middle of the rotating drum and lower angle of repose when compare with the larger particle at the both end wall of the drum.

**9.1.1.2 Measuring Experiment Particle Characteristics for DEM Simulation**

Test materials have been selected by their relatively spherical nature and uniform size ease of modelling. Polyethylene pellets were tested and validated with the analytical models and discrete element modelling via experimental testing, so the results were conclusive. Iron ore and coal materials were considered to have the same particle characteristics as the first material, however, were more irregular in shape.

The mechanical and physical properties are important. It has been demonstrated in Chapter 4 that measuring individual particle properties is different from measuring bulk properties. Four experimental test rigs were used to determine the particle and bulk parameters of the three products. Poisson’s ratio and shear modulus are based on data obtained from the literature as these are difficult to measure for bulk materials. The inclination tester is used to find the coefficient of static friction for particle-particle and particle-wall interactions. Particle drop tests were completed to validate the coefficient of restitution for particle-particle and particle-wall. The results calculated from the square root of the height of the particle after impact and the initial high before particle impact. The slump testing and swing arm testing machines were used to predict the angle of repose of the particles to validate the coefficient of rolling friction between particles. All the results are summarised in Appendix C.

**9.1.2 Numerical Simulations**

In this study, the flow mechanisms of the three materials in the IS and AS rotating drums under different operations and conditions was used to focus on the particle movement and air flow in the rotating drums. The discrete element modelling (DEM) simulations have presented the velocity of the particles, volume fraction in each position of the drum,
contact forces, collision energy and the degree of particle segregation in the rotating drums. The contact model has been carefully verified mathematically to ensure that the contact model has been correctly implemented in the DEM simulations. A parametric study of the DEM contact model parameters was conducted to understand the effects of input parameter on the simulated bulk behaviours.

1. The coefficient of friction of the contact is an important parameter influence the particle flow in the system. Also, the interaction between particles is affected by the movement of the particles.

2. The inter-particle friction and the shape were found to have a strong influence on the particle movement. Typically, the higher the coefficient of inter-particle friction is, the higher the particles are lifted on the vanes before dropping to the lower part of the drum.

3. Static friction and rolling friction were found to have a significant effect on the particle flow, with a significant decrease in material movement for increasing static and rolling friction, which added extra frictional and shearing resistance to the assembly.

4. Particle shapes and sizes were also found to be important factors that can affect the particle flow and the segregation in the radial and axial directions as the drum rotations.

5. Particle interlocking for non-spherical particles allowed larger tangential forces to be transmitted through the contacts, thus increasing the strength of the assembly. Greater interlocking in non-spherical particles also has the effect of larger dilation of the sample in the shear bands, due to the additional resistance to rolling.

9.1.2.1 DEM Input Parameters

The DEM simulations required numerous particle and bulk parameter inputs, including: particle density, Poisson’s ratio, shear modulus, particle shape and particle size. Additionally, there are three kinds of interaction input to DEM simulation, the coefficient of restitution, the coefficient of static friction, and the coefficient of rolling friction.

Calibration and verification methods for granular material with DEM are vital to ensuring accurate simulations can be achieved, which reflect the experimental results. It was found that varying the inter-particle friction coefficient was crucial for a good resemblance of
the real bulk material. From a parameter sensitivity analysis, it became clear that both inter-particle friction coefficients $\mu_s$ and $\mu_r$ are sensitive parameters. Although the inter-particle static friction coefficient ($\mu_{s(p,p)}$ and $\mu_{s(p,w)}$) are considered sensitive, the time particles remain on the vanes as the drum is rotating is longer when $\mu_s$ increases. The particles falling at the high angle of the vanes effect the particle velocity and force on the particle. For the inter particle rolling coefficient ($\mu_{r(p,p)}$ and $\mu_{r(p,w)}$), there is more resistance to particle rolling when $\mu_r$ increases. The results of the coefficients of static friction play a more important role than the rolling friction.

Results obtained from the coefficient of friction for the particle-particle flow test indicated that the values were lower than the particle-wall interactions. This result indicates low coefficient of friction between particle-wall as the particles move faster than the high coefficient of friction. The difference in the particle-particle friction causes a change in the speed of the particle flow.

9.1.2.2 Coupled DEM-CFD Input Parameter

The DEM-CFD approach originally applied to study the particle and air flow was extended to study the particle movement in air flow at a particle scale. The proposed model was validated by comparing with the experimental results. It demonstrated it has the ability to investigate the particle flow mechanisms in the dustiness tester. Three interaction models (particle-air, particle-particle and particle-wall) were considered in the proposed model, and their contribution to the contact force and collision energy was quantified and analysed.

Generally, with superficial air velocity increasing, the contribution of particle-air interaction increases gradually, more significantly after the particles fall from the vanes as the drum rotates. The air flow is an influence to the small particle sizes as they fall in the air stream. However, the significance of the contribution of particle and airflow depends on the local particle structure and air flow structure.

The discrete-based approach of DEM-CFD was employed to investigate the particle flow in models of the dustiness tests and validated by comparing the particle flow pattern from
the experiments conducted under comparable conditions. Its use can overcome the
difficulty in the determination of the constitutive relations for continuum modelling. The
result confirms that under the non-particle zone, the air flow is steady-state, with
increasing particle flow rate in the particle zone due to the enhanced interactions among
particles. Particle-wall sliding friction is an important factor affecting the size and shape
of the stagnant zone through the resistance force from the particle-particle and the
particle-wall impacts. However, rolling friction also plays a minor role in the formation
of the stagnant zone, which differs from the mechanical and physical properties of the
materials flow in dustiness tester. The relationship between local air velocity and local
porosity was obtained, showing porosity increasing with air velocity instead of the
spacing of particles. The effect of the air phase on particle movement was confirmed and
identified at a microscopic level. The simulation results confirm that increasing the air
flow rate increases the size of the stagnant zone. Small particle analysis of the flow and
force structure indicates that increasing air velocity decreases particle contacts. More
importantly, the information obtained from the DEM-CFD simulation about the small
particles helps to develop a more comprehensive understanding of air particle flow in the
rotating drums, such as the mechanism formation of the stagnant zone.

9.1.2.3 Parametric Optimisation Methodology

The thesis proposed a DEM model parameter optimisation procedure which consisted of
three steps:

Step 1. The measurement of the physical experimental data consists of size and shape of
the particles, static friction and angle of repose. The bulk response parameter used
to calibrate the angle of repose by slump test using DEM simulation.

Step 2. The creation of numerical datasets was used to describe how the DEM parameters
influence the bulk behaviour. The numerical bulk response was created by
simulating the bulk physical tests, varying the DEM parameters and monitoring
the effects of the input parameters on the numerical dynamic of particle
movement.

Step 3. The optimisation of the DEM parameters used the results from Step 1 and 2. The
technique used in the optimisation procedure (Step 3) was a simple method based
on Microsoft Excel’s Solver algorithm coupled with a weighted inverse distance
method. It was shown that the Excel solver algorithm required less time to
determine the optimised parameters, but was limited by the design of the experimental dataset resolution and could perform an optimisation based on two bulk responses. Finally, verification and validation of the methodology were presented using the optimised parameters of particle flow in the dustiness testers.

### 9.1.3 Segregation During Drum Rotation

It has been explained that granular materials consisting of particles of different physical properties, such as particle size and shape, can cause segregation. Segregation due to the size difference is observed to occur during drum rotation. At the early stage of the drum rotation, the small sized particles moved down into the lowest section of the particle heap and filled the void space near the wall of the drum.

Based on the segregation behaviour, the large particle size distribution shows the most serious segregation at both ends of the drum wall. There are two factors to consider for the rotating drums. Firstly, the bigger particles create more space during the particle movement, resulting in more space available for the smaller particles to move through the voids to the lower section of the drums. Secondly, the large particle size distribution provides bigger gaps between the large particles, allowing smaller particles to percolate much more easily, thereby encouraging segregation to happen more readily.

Radial and axial segregation of particles in the rotating drums has been studied of the particle dynamics to conduct both axial and radial experiments. In this study, two methods of measuring particle segregation in a dustiness tester were used. The first method employed the use of a video camera to measure segregation of particles in the radial direction. To capture the segregation of particles at the front of the drum an 8 mm thick transparent Perspex acrylic plate was used as the front of the drum for the AS tester. This method enabled the formation of segregation to be captured continuously with the video camera without stopping the drum. The second method was only employed for the measurement of axial segregation and distribution of particles. The drum was divided into five equal sections and the samples from each of these sections was analysed. This method enabled the analysis of axial distribution and segregation of particles along the drum axis, although sampling could only be done when the drum was stopped.
9.1.3.1 Radial Segregation of Particles

Radial experiments were carried out of the rotating drum so that the axial segregation could be neglected. The radial segregation of particles in the drum is a faster process. The small particle size is movement to the drum wall past the void between large particle sizes, move up by the lifting vanes, and remain on the vanes longer as the drum rotates.

9.1.3.2 Axial Distribution of Particles

Segregation of particles due to size difference was observed during the study of the axial distribution of particles. Fine particles were observed to form a band at the centre of the drum while the large sized particles were pushed to the end walls of the drums. This leads to the conclusion that breakage rates in a rotating drum are as a result of the variation in particle movement. A lower breakage rate is expected in a region near the end walls of the drums. A high breakage rate is expected at the drum centre because of the increased encounter frequency between each particle and the drum walls. On the other hand, the particles moving in the rotating drums may be inhibited by the cushioning of large particles by the smaller particles.

9.2 Recommendations

This research has presented mechanisms of the particle flow and particle contact in the IS and AS testers. The numerical results are compared with experimental data. The model has been calibrated from bulk experiments to replicate the flow function of the polyethylene pellets, iron ore and coal. An exploratory study on the effects of cohesion on dustiness testers has been performed as well. The following section elaborates on several areas where further investigation would be beneficial.

9.2.1 Experimental Work

The effect of moisture content on the development of cohesion in the iron ore and coal fines has been evaluated. The observation made during the characterisation of the materials shows that wet samples of the fines left to dry after testing display slightly different behaviours.
Iron ore and coal fines were found to dry to agglomerates that were quite strong and required significantly more pressure to break than smaller particles. It is likely that due to the addition of moisture and the slightly different chemical makeup for the two types of fines, a different long-term caking behaviour exists between each material. Further testing is required to investigate this phenomenon and to determine the factor that leads to the different behaviours. All experimental studies presenting on the material in the range of 2.0 – 6.3mm were carried out at a room temperature. During transport, fine material was subjected to an elevated temperature between 30-70°C. The elevated temperature may affect the chemical makeup of the iron ore and coal fines in the presence of moisture differently. Observation made during drying of samples suggests that material fines are more susceptible to cracking at a high temperature.

9.2.2 Numerical Simulations

There is one major mismatch between the numerical and experimental results, caused by the lack of plasticity in the contact model used (Hertz-Mindlin no-slip). This means that no plastic deformation occurred in the numerical simulation, resulting in an excessive elastic rebound during impacting. In the experiments, further permanent deformation occurred during further sample movement cycles, which was absent from the current viscous-elastic DEM contact model. An elastoplastic contact model needs to be implemented in the EDEM code to address this anomaly. A bonding contact model needs to be investigated to simulate particle breakage.

9.3 Future Works

The work particularly focuses on the DEM-CFD aspect. The size of particles that were used had a relatively large particle size due to limitations in computing power. Particles of a micro size should be used when computer capability increases in the future. This section provides some recommendations for further research relevant to the work performed in this thesis.

1) Particle breakage
A bonding model should be used to analyse the mechanisms of the particle impact on the wall or other particles and flow in the rotating drums, combined with air flow. It should
be investigated whether fracture breakage plays a more important role than attrition breakage in a dustiness tester because it was found that the normal force magnitude was greater than the tangential force. The change in breakage mechanism will cause a difference in the percentage of coarse and fine particles in the system. The breakage of the particles will have a combined effect on the kinetic energy and number of collisions happening in a given time. Both kinetic energy and collision frequency are influenced by dustiness tester operating parameters. Shear volume can be used as a criterion to assess the effect on a dustiness tester. A higher shear volume number can provide higher normal and tangential force magnitude, but the ratio of normal force to tangential force increases with shear volume. The dustiness tester with higher shear volume will lead to more fracture breakage than attrition.

2) Discrete Element Modelling (Need for smaller sized particles)
Current computing limitations restrict the creation of micro sized particles. Future simulation research should include the micro sized particle scale to directly investigate the particle mechanisms in the dustiness tester with air flow. The micro sized particles represent the dust and will be the most affected by air in the systems.

3) Investigation of the simulated drag of flow around particles
The simulation of the air flow around spherical/non-spherical particles in this thesis covered only the profiles of the particle and air flow in the rotating drums. As a turbulent model at the transition point of the flow coincide causing the flow separation. The small particles flow through the narrower wake region and there is a significant reduction in drag coefficient. More cases of simulation at this level are needed for further understanding of the flow characteristics around the particles during the running of a dustiness tester.

4) Effect of Moisture
In this work, the study was based on a dry material. There may be a different interaction between variables for different moisture contents in the dustiness tester. The interaction of some key variables should be included in future work. As moisture level increases, it is likely that the fine particles will collect and pack on the wall of the drums, especially, on the vanes or stick to larger particles. This will affect the flow of particles as the drums rotate. Different amounts of particles will stick to the drum wall and vanes depending on
the level of moisture in the product. Also, the DEM-CFD coupling method should be used to analyse the effect of air when particles stick on the drum wall. Fine particles will increase their weight due to the added moisture and as a result, to set particles will drop faster to the lower section of the drum. These particles will be less affected by the air flow, so the dust emission should be reduced when compared with a dry material.

5) Comparing the particle distribution between experimental and DEM Simulation
In this work, the study used mono-sized particles and the particles different size ratio to investigate particle movement in the International Standard dustiness tester and Australian Standard dustiness tester. Section 5.4.3 investigated the particle size distributions in the 5 bins of the DEM simulations. It would be worthwhile attempting to replicate these results in the experimental test rigs of the IS and AS testers to allow a direct comparison to be made. This could be completed at various time steps to allow for comparative graphs to be produced.
References


References


References


focus on passive dust control in transfer chutes", in Dust: Sources, Environmental Concerns and Control, pp. 99-142.


References


References


References


References


References


## Appendix A

### Summary of Parameters Used in the DEM Simulations

<table>
<thead>
<tr>
<th>Property</th>
<th>PP</th>
<th>IO</th>
<th>Co</th>
<th>PA</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Solid density (kg/m³), ( \rho_s )</td>
<td>907.6</td>
<td>3867.8</td>
<td>1442.24</td>
<td>1200</td>
<td>38000</td>
</tr>
<tr>
<td>Particle Loose-poured bulk density (kg/m³), ( \rho_b )</td>
<td>532</td>
<td>1475</td>
<td>695</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Equivalent volume diameter (mm), ( d_e )</td>
<td>4.56</td>
<td>6.02</td>
<td>5.90</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (5.60-6.30mm)</td>
<td>-</td>
<td>3.38%</td>
<td>13.15%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (4.00-5.60mm)</td>
<td>-</td>
<td>15.53%</td>
<td>26.42%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (4.00-4.75mm)</td>
<td>81.83%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (3.35-4.00mm)</td>
<td>15.81%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (2.36-3.35mm)</td>
<td>2.20%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (2.00-4.00mm)</td>
<td>-</td>
<td>57.83%</td>
<td>49.64%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (1.00-2.00mm)</td>
<td>-</td>
<td>23.03%</td>
<td>10.65%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (&lt; 2.00 mm)</td>
<td>0.16%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size distribution (&lt; 1.00 mm)</td>
<td>-</td>
<td>0.22%</td>
<td>0.14%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle Length (mm)</td>
<td>4.54</td>
<td>3.38</td>
<td>13.15%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle Width (mm)</td>
<td>3.62</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle Thickness (mm)</td>
<td>3.84</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size (minimum)</td>
<td>2.36</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle size (maximum)</td>
<td>4.75</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle Mass (g)</td>
<td>0.043</td>
<td>0.276</td>
<td>0.132</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle Volume (cm³)</td>
<td>0.047</td>
<td>0.101</td>
<td>0.107</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle Poisson Ratio</td>
<td>0.45</td>
<td>0.41</td>
<td>0.35</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>Particle Shear Modulus (Pa), ( G )</td>
<td>1.17E+8</td>
<td>1.92E+9</td>
<td>9E+8</td>
<td>1E+9</td>
<td>7.75E+10</td>
</tr>
<tr>
<td>coefficient of restitution on material plate ( CR_{pp} )</td>
<td>0.654</td>
<td>0.258</td>
<td>0.55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coefficient of restitution on stainless steel ( CR_{pw} )</td>
<td>0.650</td>
<td>0.269</td>
<td>0.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coefficient of restitution on the Perspex plate ( CR_{pw} )</td>
<td>0.659</td>
<td>0.449</td>
<td>0.58</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coefficient of static friction on material plate ( \mu_{s(pp)} )</td>
<td>0.200</td>
<td>0.580</td>
<td>0.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coefficient of static friction on stainless steel ( \mu_{s(pw)} )</td>
<td>0.277</td>
<td>0.600</td>
<td>0.40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coefficient of static friction on the Perspex plate ( \mu_{s(pw)} )</td>
<td>0.300</td>
<td>0.348</td>
<td>0.43</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coefficient of rolling friction on material plate ( \mu_{r(pp)} )</td>
<td>0.10(0.10)</td>
<td>0.15(0.10)</td>
<td>(0.10(0.05)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coefficient of rolling friction on stainless steel ( \mu_{r(pw)} )</td>
<td>0.15(0.05)</td>
<td>0.30(0.10)</td>
<td>(0.30(0.10)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coefficient of rolling friction on the Perspex plate ( \mu_{r(pw)} )</td>
<td>0.15(0.05)</td>
<td>0.30(0.10)</td>
<td>(0.30(0.10)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

PP: polyethylene pellets ; IO: Iron Ore ; Co: Coal ; PA: Perspex Acrylic, SS: Stainless steel SS304-2B

Particle length, particle width, particle thickness, particle size, particle mass and particle volume were based on 50 particles average.

The coefficient of rolling friction are presented as: spherical shape (non-spherical shape)
Appendix B

Drawings of Dustiness Testers

Figure B1 Schematic of five bins analysis of International standard dustiness tester
Note: 1 is bin1; 2 is bin2; 3 is bin3; 4 is bin4 and 5 is bin5

Figure B2 Schematic of five bins analysis of Australian standard dustiness tester
Note: 1 is bin1; 2 is bin2; 3 is bin3; 4 is bin4 and 5 is bin5

Figure B3 Schematic of calculated the angle of the vanes rotated for IS tester
## Appendix C

### Experimental Data

#### Table C1: Solid Density of Polyethylene Pellets Materials

<table>
<thead>
<tr>
<th>Material: Polyethylene pellets</th>
<th>Date: 17/12/2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client:</td>
<td>Moisture: Dry materials</td>
</tr>
<tr>
<td>Project No.:</td>
<td>Tested By: Sathaphon</td>
</tr>
<tr>
<td>Approved By:</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Large Ball Calibration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample + Cell wt</td>
<td>49.66</td>
</tr>
<tr>
<td>Cell wt</td>
<td>20.48</td>
</tr>
<tr>
<td>Sample wt</td>
<td>29.18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test number</th>
<th>P2 (g)</th>
<th>P3 (g)</th>
<th>P2/P3</th>
<th>Vp (cc)</th>
<th>g/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.362</td>
<td>10.029</td>
<td>1.615</td>
<td>32.0933</td>
<td>0.9092</td>
</tr>
<tr>
<td>2</td>
<td>16.195</td>
<td>9.924</td>
<td>1.6319</td>
<td>32.1786</td>
<td>0.9068</td>
</tr>
<tr>
<td>3</td>
<td>16.663</td>
<td>10.21</td>
<td>1.6320</td>
<td>32.2031</td>
<td>0.9061</td>
</tr>
<tr>
<td>4</td>
<td>17.064</td>
<td>10.459</td>
<td>1.6315</td>
<td>32.1021</td>
<td>0.9090</td>
</tr>
<tr>
<td>5</td>
<td>16.274</td>
<td>9.974</td>
<td>1.6316</td>
<td>32.1274</td>
<td>0.9083</td>
</tr>
<tr>
<td>6</td>
<td>16.365</td>
<td>10.03</td>
<td>1.6316</td>
<td>32.1202</td>
<td>0.9085</td>
</tr>
</tbody>
</table>

**Average grams per cc =** 0.9080

#### Table C2: Solid Density of Iron Ore Materials

<table>
<thead>
<tr>
<th>Material: Iron Ore</th>
<th>Date: 11/07/2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client:</td>
<td>Moisture: Dry materials</td>
</tr>
<tr>
<td>Project No.:</td>
<td>Tested By: Sathaphon</td>
</tr>
<tr>
<td>Approved By:</td>
<td></td>
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**Average grams per cc =** 3.8782

#### Table C3: Solid Density of Coal Materials

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**Average grams per cc =** 3.8782
Appendix C: Experimental Data

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Average grams per cc = 1.4224

**Table C4** Loose pound bulk density of polyethylene pellets.

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**Table C5** Loose pound bulk density of iron ore.

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<td>1439.33</td>
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**Table C6** Loose pound bulk density of coal

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**Table C7** Shows the angle of repose from the experiment for the three materials.
### Table C7.1 Angle of Repose: Experiment of polyethylene pellets using Swing Arm

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### Table C7.2 Angle of Repose: Experiment of iron ore particle using Swing Arm

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### Appendix C: Experimental Data

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### Table C7.3 Angle of Repose: Experiment of coal particle using Swing Arm

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Appendix D

Particle Distribution Using DEM-CFD

Figure D1 Iron ore model segregation in the IS tester (a) 2 mm diameter (b) 4 mm diameter (c) 5.6 mm diameter and (d) 6.3 mm diameter
Appendix D: Particle Distribution Using DEM-CFD

Figure D2 Coal model segregation in the IS tester (a) 2 mm diameter (b) 4 mm diameter (c) 5.6 mm diameter and (d) 6.3 mm diameter

Figure D3 Iron ore model segregation in the AS tester (a) 2 mm diameter (b) 4 mm diameter (c) 5.6 mm diameter and (d) 6.3 mm diameter
Figure D4 Coal model segregation in the AS tester (a) 2 mm diameter (b) 4 mm diameter (c) 5.6 mm diameter and (d) 6.3 mm diameter
During the course of this PhD study, various papers were published by the author as a result of the study. They are listed as follows:

**Conference Papers**


**Journal Papers**
