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Size-induced segregation of granular materials during filling a conical hopper

T.F. Zhang [a], J.Q. Gan [a], D. Pinson [b], Z.Y. Zhou [a,*]

[a] Laboratory for Simulation and Modelling of Particulate Systems, Department of Chemical Engineering, Monash University, Clayton, VIC 3800, Australia
[b] Steelmaking Technology and Planning, BlueScope Steel Ltd., P.O. Box 202, Port Kembla, NSW 2505, Australia

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ABSTRACT

Granular materials often experience segregation due to the differences of particle size, density and shape. In this work, particle size-induced segregation is investigated for one typical device – conical hopper which is widely used in the storage and processing of granular materials. In particular, the fundamentals governing particle size segregation during the hopper filling process are revealed by the analysis of DEM data such as particle velocities, trajectories, coordination number (CN) and mixing index. The results show that during the central charging process, particles with large velocities easily bounce to the side wall region while particles with small velocities are obstructed by their neighbours and stop moving quickly. Large particles tend to roll along the free surface and accumulate in the side wall region. Particle scale mixing index decreases with the increase of hopper height and the distance from the centre, indicating the effect of charging height and segregation occurrence along the radial direction. Further, the effect of friction coefficients is examined, and a contour plot is drawn, illustrating that a combination of sliding friction coefficient larger than 0.5 and a moderate rolling friction coefficient in a range of $0.01d_p$ to $0.1d_p$ leads to pronounced segregation. The concentration distribution of small particles for various feeding mixtures is analysed, and general trends are observed to demonstrate the segregation extent at different hopper radial locations.

1. Introduction

Granular materials are prone to segregate due to the differences of particle size, density, shape or particle resilience [1]. Generally speaking, particle size difference is by far the most important cause of segregation, and consequently extensive attention has been paid in the past to this research direction. This is also a commonly encountered problem in a variety of industries including pharmaceutical, food and agricultural processing, chemical and metallurgical industries. Segregation might render undesirable blend quality and also induce flow problems. For example, in an ironmaking blast furnace, multiple hoppers, conveyors and transfer points are involved in the charging process. Granular materials such as ore and coke in such process may experience significant segregation, which directly affects the blast furnace burden distribution and smooth operation of the process.

In the past, many studies have been conducted to understand the segregation of particles in the free-surface flow. For example, Fan etal. [2] summarized the heap formation process and identified three flow regimes depending on the flow rate: discrete avalanching flow, continuous flow with a flat free surface and continuous flow with a concave free surface. Most of the segregation studies during heap formation process are related to the former two types flow regimes, such as sandpile formation [3–5], free surface flow [6,7], the bounded heap flow [8,9] with solid static bed and flat free surface. Regarding the flow of granular materials in conical hoppers, most of previous studies focus on its industry application, for example, the charging process into ironmaking blast furnaces from two parallel hoppers [10–15]. However, the detailed analysis and further understanding of segregation occurrence of granular materials in conical hoppers with non-flat free surface and non-steady bed is still lacking, and need further investigation.

For the segregation studies of conical hoppers, over the preceding decades [16–20], many researchers studied the size-induced segregation experimentally during the hopper filling process. Different materials and various vessel shapes have been examined, and macroscopic results such as flow and segregation patterns have been analysed. Meanwhile, several models including the minimal model [21], screening model [22] and void filling model [23] and other theoretical analyses using continuous

* Corresponding author.
E-mail address: zongyan.zhou@monash.edu (Z.Y. Zhou).

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Table 1
Components of forces and torque acting on particle *i*.

Forces and torques	Symbols	Equations
Normal elastic force	$\mathbf{f}_{cn,ij}$	$-4/3E^* \sqrt{R^*}\delta_n^{3/2}\mathbf{n}$
Normal damping force	$\mathbf{f}_{dn,ij}$	$-c_n(8m_{ij}E^*\sqrt{R^*\delta_n})^{1/2}\mathbf{V}_{n,ij}$
Tangential elastic force	$\mathbf{f}_{ct,ij}$	$-\mu_s\lvert\mathbf{f}_{cn,ij}\rvert(1-(1-\delta_t/\delta_{t,\max}{}^{3/2})\hat{\boldsymbol{\delta}}_t, (\delta_t < \delta_{t,\max})$
Tangential damping force	$\mathbf{f}_{dt,ij}$	$-c_t(6\mu_s m_{ij}\lvert\mathbf{f}_{cn,ij}\rvert\sqrt{1-\lvert\mathbf{v}_t\rvert/\delta_{t,\max}}/\delta_{t,\max})^{1/2}\mathbf{V}_{t,ij}, (\delta_t<\delta_{t,\max})$
Coulomb friction force	$\mathbf{f}_{t,ij}$	$-\mu_s\lvert\mathbf{f}_{cn,ij}\rvert\hat{\boldsymbol{\delta}}_t, (\delta_t \geq \delta_{t,\max})$
Torque by tangential forces	$\mathbf{M}_{t,ij}$	$\mathbf{R}_{ij} \times (\mathbf{f}_{cn,ij} + \mathbf{f}_{dt,ij})$
Rolling friction torque	$\mathbf{M}_{r,ij}$	$\mu_{r,ij}\lvert\mathbf{f}_{n,ij}\rvert\widehat{\boldsymbol{\omega}}_{t,ij}\, n$

where R* is the reduced radius of the particle *i* and *j* at the contact point. $1/m_{ij} = 1/m_i + 1/m_j$, $E^* = E/2(1-\nu^2)$, $\widehat{\boldsymbol{\omega}}_{t,ij} = \boldsymbol{\omega}_{t,ij}/\lvert\boldsymbol{\omega}_{t,ij}\rvert$, $\hat{\boldsymbol{\delta}}_t = \boldsymbol{\delta}_t/\lvert\boldsymbol{\delta}_t\rvert$, $\delta_{t,\max} = \mu_s(2-\nu)/2(1-\nu)\cdot\delta_n$, $\mathbf{V}_{ij} = \mathrm{V}_j - \mathrm{V}_i + \omega_j \times \mathrm{R}_{c,ji} - \omega_i \times \mathrm{R}_{c,ij}$, $\mathrm{V}_{n,ij} = (\mathrm{V}_{ij}\cdot \mathrm{n})\cdot \mathrm{n}$, $\mathrm{V}_{t,ij} = (\mathrm{V}_{ij} \times \mathrm{n}) \times \mathrm{n}$. Note that tangential forces ($\mathbf{f}_{ct,ij} + \mathbf{f}_{dt,ij}$) should be replaced by $\mathbf{f}_{t,ij}$ when $\delta_t \geq \delta_{t,\max}$.

methods [9,24] were proposed to predict segregation. However, the models generally have assumptions to simplify the initial conditions and complex flow processes. Therefore, they could predict the concentration distribution under certain conditions only with approximate results. Most of the experimental and theoretical analyses could not capture the microscopic properties of granular flow such as particle scale flow and force structures, which however are significant in developing understanding the size-induced segregation.

Hence, more recently, computer simulation using discrete element method (DEM) has become a popular tool to examine hopper charging processes. Many articles [25–31] have been published on the flow of mono-sized particles in hoppers. However, only a few researchers focused on binary and ternary mixture charging. For example, Rahman etal. [32] used DEM to validate the screening model proposed by Shinohara etal. [23] in forming a conical piles. They examined the mixing ratio at different distances from the centre along the pile line at different initial size ratios and feed rates. Wu etal. [33] utilised relative particle size to examine the effect of the small particle mass fraction, the burden apex and the lower hopper slope on segregation. Mio etal. [13] built a DEM model for blast furnace bell-less type charging process, showing that large particles are located in the wall boundary during the hopper filling process. Although the efforts made as shown above, the microscopic properties such as particle velocities, particle-particle contact informaiton and particle mixing index are not fully analysed for a further understanding of segregation mechanisms. The effects of some key variables such as sliding friciton and rolling friction are not well addressed in the literature, which however is important as they are closely related to particle properties such as particle shape and particle surface roughness.

Therefore, the objective of this paper is to analyse the segregation details of binary mixtures during the hopper filling process. The model is validated first, and then particle mixing index is used to quantify the segregation degree. The velocities and trajectories of large and small particles in binary mixtures are traced for understanding the segregation. In addition, effects of parameters such as sliding friction coefficient and rolling friction coefficients are examined and shown by a contour plot. Finally, the segregation extent for various volume fraction of small particles is given.

2. Model description

2.1. Discrete element modelling

In DEM, granular materials are modelled based on a finite number of discrete, semi-rigid particles interacting by contact or non-contact forces. The translational and rotational motion of every particle in a system is described by Newton's law of motion. For simplicity, we only consider spherical particles and the most dominant forces and torques. Therefore, the governing equations for the translational and rotational motion of a particle i interacting with another particle j can be written as:

$$m_i\frac{d\mathbf{v}_i}{dt} = \sum_{j=1}^{k_i}\left(\mathbf{f}_{c,ij} + \mathbf{f}_{d,ij}\right) + m_i\mathbf{g} \tag{1}$$

$$I_i\frac{d\omega_i}{dt} = \sum_{j=1}^{k_i}\left(\mathbf{M}_{t,ij} + \mathbf{M}_{r,ij}\right) \tag{2}$$

where $\mathbf{v}_i$ and $\boldsymbol{\omega}_i$ are the translational and angular velocities respectively of particle i with mass m_i and moment of inertia $\mathbf{I}_i$. The forces considered are gravitational and particle-particle interaction forces including elastic contact force $\mathbf{f}_{c,ij}$ and viscous damping force $\mathbf{f}_{d,ij}$ in both normal and tangential components at the contact point. The torque acting on particle i by particle j includes two components. One is generated by tangential force and causes particle i to rotate, $\mathbf{M}_{t,ij}$, and rolling friction torque $\mathbf{M}_{r,ij}$ generated by normal force that acts to oppose the relative rotation between the contacting particles. For a particle

Table 2
Materials properties and parameters range used in DEM simulation.

Variables	Base value	Parameters range
Particle properties		
Particle shape	Spherical	
Particle number	81,283	
Particle diameter, d_p	5 mm (large) 2 mm (small)	
Diameter ratio of large particles to small particles, φ	2.5	
Small particle volume fractions, χ	50%	(25%–95%)
Particle density, ρ_p	900 kg/m^3	
Young's modulus, E	1.0×10^7 Pa	
Poisson ratio, ν	0.3	
Time step, Δt	2.25×10^{-5} s	
Interaction parameters		
Particle-particle sliding friction, $\mu_{s,pp}$	0.6	(0.1–0.8)
Particle-wall sliding friction, $\mu_{s,pw}$	0.6	(0.1–0.8)
Rolling friction coefficient, $\mu_{r,pp}$ and $\mu_{r,pw}$	0.025 d_p	(0.001–0.2 d_p)
Damping coefficient	0.3	
Dimensionless hopper geometry		
Width, W	40 d_p	
Depth, Z	4 d_p	
Upper hopper outlet orifice shown in Fig. 3	2 d_p	