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Original Research Paper

Density segregation of dry and wet granular mixtures in vibrated beds

Eldin Wee Chuan Lim *

Department of Chemical and Biomolecular Engineering, National University of Singapore, 4 Engineering Drive 4, Singapore 117585, Singapore

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ABSTRACT

The Discrete Element Method was coupled with a capillary liquid bridge force model for computational studies of density segregation in dry and wet binary granular mixtures in vibrated beds. Due to the presence of capillary liquid bridge forces between wet particles, relative motions between particles were hindered. Agglomerates were observed to form in the wet vibrated granular beds due to the cohesive nature of the capillary liquid bridge forces. The rate and extent of density segregation decreased with increasing amount of liquid present in the wet binary granular mixtures. The average orders of magnitudes of particle-particle collision forces and capillary liquid bridge forces were similar for both types of particles for all wet binary granular mixtures considered and this explained the difficulty for individual particles to be removed from one agglomerate and be transferred onto another agglomerate for density segregation to occur.

1. Introduction

Segregation or mixing occurs in granular materials that are subjected to vibrations. In particular, it is well-established that granular mixtures are capable of undergoing segregation by virtue of a variety of physical property differences such as particle size, density, or inelasticity. Many experimental and computational studies have been devoted towards investigations of segregation or mixing of granular mixtures in general [1] and vibrated granular bed systems in particular. Shi et al. [2] investigated segregation of binary granular mixtures consisting of particles of the same size but different densities and observed lighter particles rising to form a layer at the top while heavier particles formed a mixture with some lighter particles near the bottom of the vibrated bed. The behaviors of granular materials in vibrated beds with a bumpy base was investigated computationally and subsequently extended to studies of density segregation as well as the granular Leidenfrost effect [3–5]. Density segregations could be induced by vertical or horizontal oscillations of a bumpy base and higher granular temperatures were observed to be more effective in inducing density segregations in binary mixtures in such systems. Tai et al. [6] investigated experimentally the phenomenon of density segregation in vibrated granular bed systems by a particle tracking method and image processing technology. The granular temperature and bulk convection motion were found to play significant roles in causing density segregation when the number of layers of granular materials present was low and high respectively. More recently, Windows-Yule and Parker [7] reported the first experimental study of density segregation in ternary granular beds. They applied Positron Emission Particle Tracking to study steady-state particle distributions in both binary and ternary granular mixtures and established the causal relationship between convection and segregation in such systems. Windows-Yule et al. [8] subsequently addressed the issue of the effect of particle shape on density segregation behaviors by considering vibrated granular bed systems consisting of particles differing in both shape and density. They concluded that the effects of particle geometry were secondary to those resulting from density differences.

It is well-known that the behaviors of granular materials can change significantly in the presence of small amounts of liquids [9]. Although vibrated beds of dry granular materials have been the subject of a large number of studies reported in the literature, the study of vibrated beds of wet granular materials has received much less attention. In one of the first studies reported on this subject, Yang and Hsiau [10] applied the Discrete Element Method (DEM) for investigation of convection cells in vibrated beds of wet granular materials. They subsequently investigated the phenomena of self-diffusion and mixing in such systems and observed that granular temperatures and self-diffusion coefficients were highly anisotropic while mixing was strongly dependent on self-diffusion [11]. The effects of moisture content on convection

* Fax: +65 6779 1936.
E-mail address: chelwce@nus.edu.sg

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strength in a vibrated bed system were investigated experimentally and moisture content was found to have both a lubrication effect and a viscous effect [12]. Both the amount and viscosity of liquid present in a wet vibrated granular bed system were found to have significant effects on the segregation process [13]. More recently, Hsiau et al. [14] applied a particle-tracking technique to investigate the dynamic properties of convection rolls in a 2D wet vibrated granular bed and observed that convection rate and granular temperature decreased with increasing liquid content, surface tension and viscosity. Other than vibrated granular bed systems, the behaviors of wet particles in spouting fluidized beds have also been investigated numerically using DEM [15]. The effect of liquid addition on density segregation of wet granular materials in a rotating drum has also been investigated experimentally recently [16].

The study of vibrated beds of wet granular materials is an important complement to that of their dry counterparts and has the potential to contribute towards the advancement of the field of granular physics in general. However, most studies of mixing or segregation behaviors of dry or wet granular materials in vibrated bed systems that have been reported in the literature to date have focused largely on the kinematic aspects of motions, mixing and segregation. To gain deeper insights to the fundamental mechanisms responsible for such mixing or segregation behaviors, examinations of the dynamics are essential. In other words, analyses of the various forces present during vibration, mixing or segregation are required. Lim [17] applied a modified DEM for simulations of shear aggregation of colloidal nanoparticles and analyzed the time evolution of the various forces present to provide a more mechanistic understanding of the shear aggregation process. In the present study, the conventional DEM model was coupled with a capillary liquid bridge force model to investigate density segregation of dry and wet solid particles of different densities in vibrated granular beds. Mixing efficiencies were compared quantitatively via a mixing index and dynamic force data at the individual particle scale were extracted from the simulations and analyzed with a view towards advancing current understanding of the mechanisms involved in density segregation of wet granular mixtures in such systems. In the following section, the computational model and physical system of interest will be described. The simulation results obtained for the various physical conditions considered in this study will then be discussed and a summary of the conclusions derived will be presented in the Section 4 of this paper.

2. Model

2.1. Discrete Element Method

The Discrete Element Method (DEM) was developed by Cundall and Strack [18] for modeling the behavior of assemblies of discs and spheres. With the advent of computational power in recent years, it has been applied for studies of various types of granular systems. In this section, a brief description of the method and corresponding governing equations will be presented.

The governing equations in DEM for describing translational and rotational motions of individual solid particles are basically Newton's laws of motion:

$$m_i \frac{d\mathbf{v_i}}{dt} = \sum_{j=1}^{N} (\mathbf{f_{c,ij}} + \mathbf{f_{d,ij}} + \mathbf{f_{cap,ij}}) + m_i \mathbf{g} \tag{1}$$

$$I_i \frac{d\boldsymbol{\omega_i}}{dt} = \sum_{j=1}^{N} \mathbf{T_{ij}} \tag{2}$$

where m_i and $\mathbf{v_i}$ are the mass and velocity of the ith particle respectively, N is the number of particles in contact with the ith particle, $\mathbf{f_{c,ij}}$ and $\mathbf{f_{d,ij}}$ are the contact and viscous contact damping forces respectively, $\mathbf{f_{cap,ij}}$ is the capillary liquid bridge force between wet particles, I_i is the moment of inertia of the ith particle, $\boldsymbol{\omega_i}$ is its angular velocity and $\mathbf{T_{ij}}$ is the torque arising from contact forces which causes the particle to rotate. As will be seen later, the capillary liquid bridge force is assumed to act in the normal direction at the point of contact between two particles and so does not contribute towards the torque.

Contact and damping forces were calculated by applying a linear spring-and-dashpot model as closure. The normal ($\mathbf{f_{cn,ij}}$, $\mathbf{f_{dn,ij}}$) and tangential ($\mathbf{f_{ct,ij}}$, $\mathbf{f_{dt,ij}}$) components of the contact and damping forces were calculated as follows:

$$\mathbf{f_{cn,ij}} = -(\kappa_{n,i}\delta_{n,ij})\mathbf{n_i} \tag{3}$$

$$\mathbf{f_{ct,ij}} = -(\kappa_{t,i}\delta_{t,ij})\mathbf{t_i} \tag{4}$$

$$\mathbf{f_{dn,ij}} = -\eta_{n,i}(\mathbf{v_r} \cdot \mathbf{n_i})\mathbf{n_i} \tag{5}$$

$$\mathbf{f_{dt,ij}} = -\eta_{t,i}\{(\mathbf{v_r} \cdot \mathbf{t_i})\mathbf{t_i} + (\boldsymbol{\omega_i} \times \mathbf{R_i} - \boldsymbol{\omega_j} \times \mathbf{R_j})\} \tag{6}$$

where $\kappa_{n,i}$, $\delta_{n,ij}$, $\mathbf{n_i}$, $\eta_{n,i}$ and $\kappa_{t,i}$, $\delta_{t,ij}$, $\mathbf{t_i}$, $\eta_{t,i}$ are the spring constants, displacements between particles, unit vectors and viscous contact damping coefficients in the normal and tangential directions respectively, v_r is the relative velocity between particles and R_i and R_j are the radii of particles i and j respectively. Following Coulomb's law of friction, if $|\mathbf{f_{ct,ij}}| > |\mathbf{f_{cn,ij}}| \tan\phi$, then $|\mathbf{f_{ct,ij}}| = |\mathbf{f_{cn,ij}}| \tan\phi$, where $\tan\phi$ is analogous to the coefficient of friction. Further, when the Coulomb's criterion is enforced, the displacement between particles is not adjusted.

2.2. Rolling friction model

It is well recognized that rolling against a contacting surface is a common state of motion of solid particles in addition to pure translational or rotational motions. This arises when the translational velocity of a particle is exactly equal but opposite in direction to the tangential velocity due to rotation at the point of contact such as to give rise to a 'no-slip' condition between the two surfaces. In the presence of only sliding frictional effects simulated by the Coulomb friction law, a particle in such a state of motion tends to preserve its kinetic energy for unrealistically long traveling times and distances. As such, a rolling friction model which simulates resistances against rolling motion in terms of a torque which opposes this 'no-slip' rotation of a particle may be essential for an accurate representation of such motions. The following angular velocity-independent rolling friction model due to Beer and Johnson [19] was incorporated into DEM in this study to ensure realistic simulations of particle motions and dynamics:

$$\mathbf{M}_i = \mu_r \mathbf{f_{cn,ij}} \tag{7}$$

where $\mathbf{M}_i$ is the torque which opposes rotation of the particle and is opposite in direction to that of its angular velocity, μ_r is the coefficient of rolling friction.

2.3. Capillary liquid bridge force

Various models for describing the behavior of liquid bridges between solid particles have been reported in the literature and several such models have been coupled with DEM and Computational Fluid Dynamics (CFD) for numerical simulations of various granular systems [20–25]. In this study, following Mikami et al. [26] and Seah and Lim [24] the capillary liquid bridge force