OPEN ACCESS

Kashf Journal of Multidisciplinary Research
Vol: 02 - Issue 06 (2025)
P-ISSN: 3007-1992 E-ISSN: 3007-200X
https://kjmr.com.pk

INFLUENCE OF NUMBERS OF PARTICLE-CONTACT ON VERTICAL SEGREGATION OF BINARY GRANULAR MIXTURES

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Article Info

Abstract

We present a simulation study dealing with segregation in vertical shaking by extending our previous works using the so-called Brazil-nut effect (BN) and Reverse Brazil-nut effect (RBN) phenomena. We consider same layer-size of granular beads of various diameters and materials. We investigate the impact of contact dynamics of particles for various parameters of two particles species. We illustrate the potential functionality of these concepts and their key physical principles for different size and density of the two particles species. Our results show that the granular segregation is highly affected by the contacts of particles demonstrating thereby that the most plausible explanation reposes on the fact that the particles having higher contacts per particle will go to the bottom while having lower contacts per particle will accumulate on the top. By employing discrete element method, we show that larger particles have lower contacts per particle as compare to the smaller ones. Likewise, the particles with higher densities have higher contacts per particle.

Keywords:
granular media, segregation, Brazil Nut Effect, vertical shaking, DEM, Simulation.

Introduction

Over the years, the usage of winnowing basket is a common practice to separate wheat grains in entire rural Asia. This method is traditionally connected with Indus Civilization for separating cultivated grains from chaff [1,2]. One of the consistently found discrepancy involves the accumulation of large and light chaff stuff while shaking the winnowing basket at the top of heavy and large wheat grain [3–5]. Such type of size separation of granular particles in a container subjected to shaking is known as the Brazil Nut Effect (BN) [6]. Researchers have also narrated the reverse of this effect in which larger particle sinks to the bottom of the container leads to the process known as Reverse Brazil Nut Effect (RBN) [7–9]. Understanding particle segregation is of paramount importance to make it possible to tune, avoid or invert the segregation patterns of granules under various conditions [4,10–12]. Earlier examinations have summarized two effects that were proposed to explain BN phenomenon: dynamic effect and geometric percolations [13–15]. Processes under dynamic effect such as convection and inertia have found to be responsible for trapping the large beads at the top surface of the pile [16]. However, geometric percolations have shown small beads percolate through larger ones to sink at the bed [13].

Hong et al. predicted different conditions for the crossover from BN to the RBN by considering comparative analysis of percolation effect and the condensation of particles [17]. Properties such as same-sized layer, coefficient of friction □, proper diameter ratio r_d, and density ratios r_ρ of the two different particles, where $r_d^2 \geq r_\rho$ and $r_d^2 \leq r_\rho$ have been observed for RBN and BN respectively. This means that the square of the diameter ratio is greater than the density ratio, the system should show RBN and vice versa. But many experimental and numerical findings challenged the conditions of RBN [18] suggesting that when the granular system is shaken, the particles at bottom layer get highest granular temperature than the top one. The problem of variation in granular temperature can be resolved by choosing same layer thickness of granular beds [19].

Several issues raised with the findings of Hong et al. which lead the researchers to continue and examine the evidences for the proposed criterion. Preliminary studies have analyzed the states in which the larger particles found to be on the top with low densities, however, the mixed states were shown when the density of such larger particles was up surged than the smaller particles [8,20,21].

Moreover, Breu et al. [7] have experimentally inspected parameters of Hong's theory further down which the larger particles shown tendency to sink at the bottom. They observed three-dimensional distributions reliant on the density ratio r_d as well as on external conditions. Additionally, the effect of frequency and the effect of normalized acceleration □ were reported along with diagrams as function of density and diameter ratio. They explored the experimental validation of Hong's theory as provided several conditions including factors such as utilizing rigid particles and selection of intermediate vibration amplitude which were implemented carefully [7].

Unswervingly, same-sized layers of binary particles did not consider for analysis and therefore, no steady assumptions can be concluded for the validation of the condensation model from the published data [7,18]. It has been shown that during investigating BN and RBN phenomena, most of the existing experiments have not gained attention towards the control parameters such as same layer size, diameter ratio r_d, density ratio r_ρ, amplitude A, frequency f , normalized acceleration □ and so on [19,22]. Therefore, experimental results have seen as controversial [8,20,23]. In order to investigate Hong's model, we run series of experiments by making same layer-thickness of binary mixture of particles of different diameters and densities [24]. We found that Brazil Nut Effect (BN) takes place only in the region of low-density ratio and is independent of layer-thickness. While, Reverse Brazil Nut Effect (RBN) occurs in the region of larger density ratio and is sensitive to both the layer-thickness and frequency. We further explain these experimental results (by comparing with the simulation results) that both BN and RBN are highly related to the contacts among granular particles which have not been studied yet. The more the particles make contacts more they transfer granular temperature; in this way they segregate. The particles having higher contacts per particle will go to the bottom while having lower contacts per particle will accumulate on the top. Experimentally, it is difficult to get contact profiles of all particles, therefore, we choose discrete element method (DEM) simulation.

The aim of the present article is to point out the by the explanation of segregation phenomena in vertical shaking of granular system in terms of their contact dynamics and mainly answering the following questions: "Are segregations in granular system could be explained by their contacts rather than the mechanisms of percolation and condensation? Is the contacts per particle parameter, able to capture the whole segregation phenomena?".

The structure of the paper is as follows: In next section we will deal with DEM simulation model and settings. In following sections, we present and discuss the results of our simulations, and concluding remarks are made in the last section.

Discrete Element Method Simulations

Discrete Element Method (DEM) Model

As it is difficult experimentally to extract contact profiles of all particles, we therefore employ in the present study the Discrete Element Method (DEM). This method, which is rationalized initially by Cundall and Strack [25], has been widely used for granular dynamics investigations [26]. Over the years there has been much interest in DEM to study granular materials prevalent in many fields spanning powder metallurgy, chemical engineering, and many others. It is a very powerful tool extensively applied to diverse problems in granular processes and it is mainly based on the description of the contacts between discrete particles. The numerical simulations presented herein are conducted using commercially available DEM code known as EDEM Academic 2.6.1 (DEM Solutions Ltd. United Kingdom) [27]. EDEM comes with many built-in models. However, we shall employ the so-called Hertz-Mindlin model which is well suited to the non-cohesive interactions. This non-linear elastic model is the most commonly used model within EDEM simulations due to its accurate and efficient force calculation [28], [29]. The model is mainly based on Hertzian contact theory [30] while the tangential forces between particles are modelled according to Mindlin-Deresiewicz theory [31]. We should emphasize that Hertzian normal forces and Mindlin's tangential forces have damping components. The proposed expression of the normal damping coefficient, initially described by Tsuji at.al. gives a constant restitution coefficient.

It is important to note that in the approach presented herein, the particle motion as well as the different interactions are calculated by Newtonian equations of motion. The net force on each spherical particle (i) is determined by the sum of gravitational and inter-particle components:

$$\sum F_i = m_i g + F_n + F_t$$

where F_n and F_t are normal and tangential components of force respectfully. The torque τ on each particle is the sum of the moment of the tangential forces (F_t) arising from inter-particle contacts :

$$\sum \tau_i = r_i \times F_t$$

The normal force (F_n) is given by:

$$F_n = \frac{4}{3} E^* \sqrt{R^*} \delta_n^{\frac{3}{2}}$$

Where δ_n a function of normal overlap, E^* is the equivalent Young's Modulus, and R^* the equivalent radius which are defined by:

$$\frac{1}{E^*} = \frac{1-\nu_i^2}{E_i} + \frac{1-\nu_j^2}{E_j}$$

$$\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j}$$

with E_i,ν_i,R_i and E_j,ν_j,R_j are the Young's Modulus, Poisson ratio and radius of particle i and j in contact. More description of the code is given in the EDEM User Manual [27].

Table 1. Properties of materials of spherical particles used in DEM simulation.

Property	Value
Statics friction coefficient between particle & particle	0.5
Statics friction coefficient between particle & wall	0.5
Coefficient of Restitution (particles)	0.99
Coefficient of Restitution (wall)	0.98

Simulation Settings

The DEM spherical particles and the container are made of the same materials as defined in the Table 1. The container is modelled as vertical cylindered. The particles are spherical in shape with a size range from 1mm to 10mm in their radii and density range from 1.5g/cm^3 to 18g/cm^3 We label smaller particles as A (and corresponding radius as r_A)and larger particles as B (and corresponding radius as r_B). We create same layer of thickness of two granular species A and B. First we will initialize mixing of both species of spherical particles randomly by pouring from injector. After pouring the cylinder with binary mixer of particles for specific mixing, the shaker is then allowed to shake vertically for some period of time until we achieve the segregation.

Segregation Patterns Deduced from Particle Contact Profiles

In order to measure the segregation patterns in the mixture, we use contact dynamics of particles. We geometrically divide the system in two equal portions. As can be seen from Fig. 1, two different regions can be depicted, a bottom region where smaller particles will be observed for BN effect and a top region brief description where larger particles will be observed for BN effect. In these two regions, the reverse will occur for RBN effect. Once the segregation is achieved, we stop the vertical shaking and extract the number of contacts profiles for A−A and B−B systems by defining a function variable of EDEM. We calculate the contacts per particle (c_p) value according to:

$$C_p = \frac{N_p}{N_c}$$

where N_p is the total number of same species of particles in specific region about which C_p is required and N_c is the total number of contacts between the particles in that region. We first calculate C_p for different sizes of particles individually. The contacts per particle C_p of particles for different values of densities is also calculated in the same way.

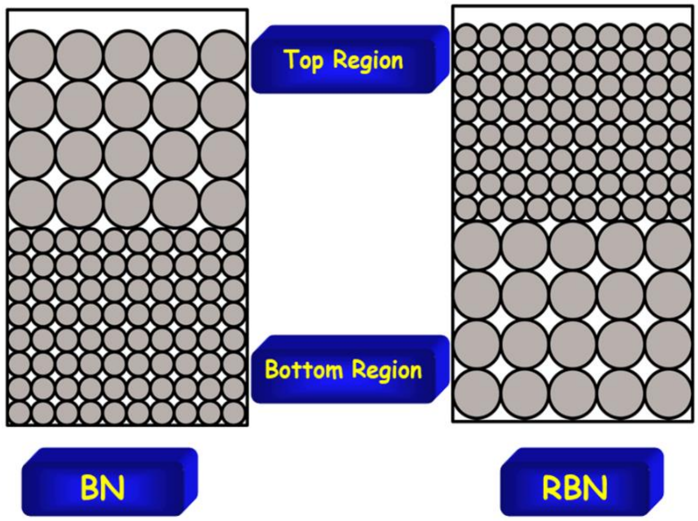

Figure 1. The system is geometrically divided into two regions: Top Region and Bottom Region. In BN, the top region has more larger particles than smaller ones while in RBN, the effect is reversed.

Segregation Patterns Deduced from Segregation Ratios

All segregation patters of vertically shaken granular systems are obtained from their corresponding segregation ratios. The procedure consists to disentangle larger particles having larger ratios to the smaller ones in specific region of interest. We should pay our attention to top region as it is the region of interest for Brazil Nut and Reverse Brazil Nut phenomena. The segregation ratio is determined by two different methods namely the visual method and the analytical method [29,32,33]. The analytical method is defined as the population of larger or smaller particles in the bi-disperse mixture for specific region (for example top region) and it is calculated automatically during the simulation run with EDEM's built-in function. In parallel, it is important to observe the segregation of particle visually during simulation in order to confirm that segregation is fully achieved. For Brazil Nut effect, the top region is observed for the population of larger particle to the smaller ones while for Reverse Brazil effect, the population of smaller particle to the larger ones. We compare our visual results with their corresponding analytical results obtained by means of EDEM. Once a suitable segregation ratio for each trial is reached, we stop the simulation and run with next parameters.

Results and Discussion

The modelling of vertical segregation of granular shaking, leading to size segregation where the larger grains rise to the top, is still a challenge in many industrial domains since the homogeneity of a mixture is essential for obtaining good product quality. Many theories like convection, percolation and reorganization have been published to explain size segregation phenomena, but no solid explanation is achieved so far. Herein, we provide for the first time a new approach dealing with segregation in vertical shaking by extending our previous works using the so-called Brazil-nut effect (BNE) and Reverse Brazil-nut effect (RBNE) phenomena. The numerical simulations, resulting from the theoretical predictions of the present approach, are conducted using particles with different sizes and densities in a specific container allowing thereby for the calculations of the (C_p)values of the particles individually. Hence, the simulations carried out, using EDEM built-in function, are capable to provide us with the C_p values for each particle size and its density. This could help us to explain the segregation patterns in binary mixture. We extract the whole data, showing the total particle counts as well as their contacts. This data is used for calculating the contacts per particles C_p for each species of particles using the contacts per particle (C_p) equation.

Figure. 2 and 3 illustrate the effect of the size and the density of granular particles on C_p. The inspection of these figures allows to observe that C_p value is more and more smaller for larger particles and for those particles having lower density. We should emphasize that if the size of spherical particle is increased, the contacts between surrounding particles become weak. This suggests that the weakness of the particles contacts is caused mainly by its spherical shape, as will be further explained below. These arguments are based on the fact that when the density of the particles is increased, a maximum of contacts can be detected due to the effect of the gravity. We further divide the system into top and bottom regions and calculate, thereby, their corresponding C_p individually. The results are shown in Figure 2. It is observed that the bottom layer make more C_p than the top layer even the same size of particles is used. This is primarily due to the gravitational force and stresses from the top layer which makes the particles to achieve their maximum C_p. Therefore, one can make a connection between C_p and the bottom layer, suggesting that the particles having higher C_p must always accumulate to the bottom layer.

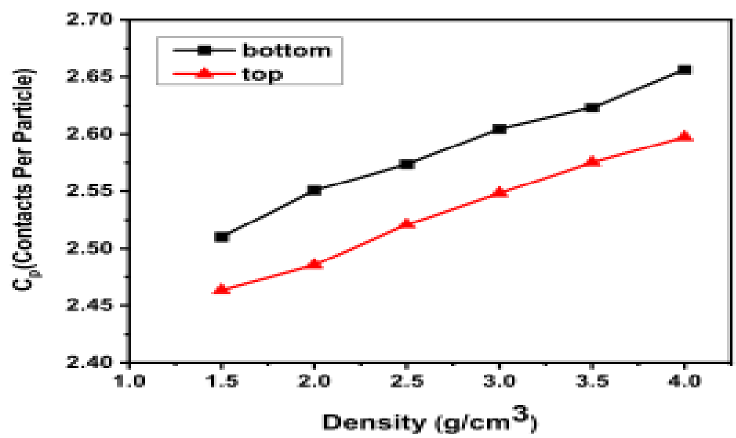

Figure 2. Simulation results for monodispersed spherical particles in container showing the contact profiles (C_p) for various densities. The result shows that bottom region has more C_p than top region.

Let us now consider the simulations of binary mixture of particles in the same container in order to observe different segregation patterns as we did experimentally somewhere else [24]. Following the trials, we observed five kinds of segregation patterns, namely Brazil Nut (BN), Light-BN (LBN), Mixed, Reverse Brazil Nut (RBN) and Light-RBN (LRBN) [24]. Our numerical simulations, plotted in Figure 4, are superimposed with the experimental ones (of [24]) in order to provide a strong support for the explanation of the obtained experimental results on the basis of their contact profiles (Cp). As can be seen from Figure 4, we notice that BN state is dominant at the region giving rise to the following conditions, that are $\frac{\rho_L}{\rho_S} < 1, \frac{d_L}{d_S}$ >1.2, while RBN occurs at the region: $\frac{\rho_L}{\rho_S} > 5, \frac{d_L}{d_S}$ <1.5. It is important to note that, Breu et al. [7] have observed both states BN and RBN, at the region satisfying the condition $\frac{\rho_L}{\rho_S}$ <4, while our numerical results as well as those provided by Canul-Chay et al. [8] have demonstrated only the BN state suggesting that the BN phenomena are independent of layer-thickness. For the regions $\frac{\rho_L}{\rho_S}$ >4, occurrence of RBN is well observed even with same layer-thickness. We should emphasize that there is wider region, namely the mixed state region, which is situated between RB and RBN regions. Moreover, this region is further divided into three regions, namely the low BN (LBN) region, the mixed region and then the low RBN (LRBN) region [24]. As plotted in Figure 4, our simulations results capture the same segregation patterns which can be easily explained on the basis of C_p.

Also, the inspection of Figure 4 leads to clearly observe that the BN state occurs at low density ratio and depends considerably on the size ratio. This can be explained by the fact that because at low density ratio the contacts per particle value increases as the size ratio increases. Hence, the plausible explanation of this phenomenon repose accurately on C_p value than percolation effect. In percolation effect, the void filling mechanism becomes stronger with increasing diameter ratio [21] while RBN is attributed to the condensation mechanism which is initially introduced by Hong et al. [17]. Instead of explaining the different segregation patters with different mechanics, we can explain all segregation patters by just one mechanics i.e., contacts per particle effect.

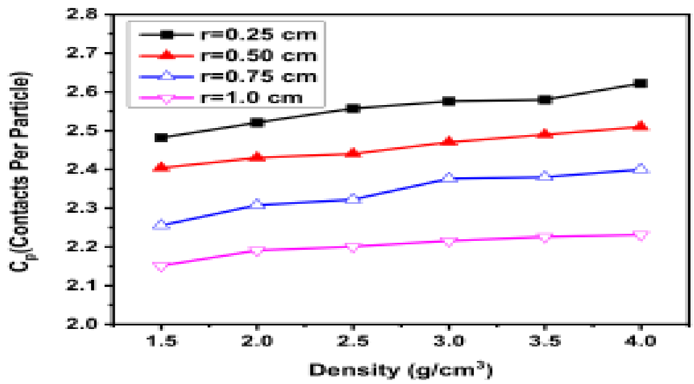

Figure 3. Simulation results for monodispersed spherical particles in container showing the contact profiles (C_p) for various densities and radii. The result shows that smaller particles have more C_p than larger ones.

Now, let us discuss the effect of increasing the densities ratio (ρ_B/ρ_A). Our simulations give rise to the observation of the RBN state because higher density in larger particle produces more stress and consequently, C_p value increases. This is consistent with the fact that larger particles having higher density accumulate at the bottom. In addition, our numerical simulations shows that the segregations patterns can be well explained by only one control parameter C_p. We should underline that the segregation index may changes if the value of C_p is changed. Finally, we should note that the C_p values are highly effected with the particle size and its density.

Conclusions

In this paper, we studied the influence of particle contacts on vertical segregation of granular systems. We carried out DEM simulations of binary spherical particles packed in a cylinder container. The dynamic flow of two layers having same thickness but constituted with particles of various sizes and densities, are conducted by means of comparing the simulations results and our corresponding previous experiment on the basis of contacts per particle C_p. The validity of explaining the segregations phenomena is very clearly proved with their C_p values rather than percolation and condensation mechanism suggesting that the contact profiles could constitute a strong support for developing a better model for the segregation mechanism as well as the mixing mechanism in granular systems.

Owing the decent results obtained herein, we will continue in the future work using the present approach to investigate the behaviors and the treatment processes of binary particles and non-spherical granular materials in horizontally rotating drums. The introduction of fluid with particles to elucidate the effect of fluid on C_p values may also constitute a further step of the present work.

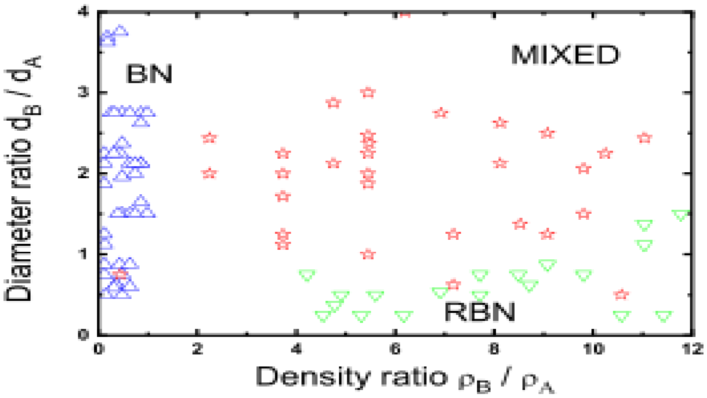

Figure 4. Simulation results for segregation patterns of binary mixture: BN, RBN and the mixed state. Subscripts A stands for smaller particles and B for larger ones.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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