Chapter

Flow and Segregation of Granular Materials during Heap Formation

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Abstract

Segregation during flow of granular materials is important from an industrial point of view. Granular materials segregate during flow due to their physical properties (such as size, shape, and density). A considerable work has been done on granular segregation in the past (two decades). This chapter is divided into three parts. In the first part, a review of work done on heap formation is presented. Experimental work during heap formation by intermittent feeding is reported in the second part. The system used is a simplified model for the feeding of raw materials to a blast furnace, which is widely used for the manufacture of iron and steel. Experiments carried out using 2-D system and steel balls of size 1 and 2 mm are used as model granular materials. Image analysis is done to detect the position of each particle using an in-house computer code. Accuracy and efficiency of image analysis techniques were found to be good enough as we have used 1 and 2 mm spherical steel balls for all the cases studied. The chapter ends with concluding remarks.

Keywords: granular materials, segregation, heap, granular flow, blast furnace

1. Introduction

Granular materials are a collection of solid particles in the size range of a few millimeters to a few centimeters. They are present everywhere in nature and are the second most manipulated materials after water [1]. Commonly used granular materials are salt, sugar, coffee, and rice in day-to-day life and sand, gravel, coal, powders, fertilizers, and pharmaceutical pills in various industries. They are made up of different constituents, ranging from 1 μm to 1 km (theoretically) and having various shapes. Here, we are mainly interested in the above-mentioned size range as most of the materials used in the industry are in this range. Coke and sinter particles used in the blast furnace are also in the above-mentioned size range. Electrostatic charges and surface forces are negligible for such particles. The properties of granular materials are very different from the properties of constituent particles. They primarily depend on the nature of interstitial fluid (air, water, etc.) and forces acting between the particles. The important forces are van der Waals forces, interaction forces, frictional forces, and capillary forces when some interstitial fluid is present. If the influence of the interstitial fluid (like air) is neglected, then we called it as dry granular materials. Otherwise, the system will become more complex. Granular materials behave like a solid when they are packed in a container or in case of a heap. They can also withstand strong shear force as they can support our body weight while walking on the beach. They can flow through a hopper and can take the shape of a container like liquids. But unlike liquids, the pressure at the base of a bin filled with granular materials does not increase after a certain height of filling. In each of the states (both solid and liquid), they exhibit different properties that are unique in nature. This dual behavior made them an interesting and complicated system to study the basic of granular materials. For the size range of millimeters to few centimeters, we can ignore electrostatic forces. Also, the focus of this study is on simple system (quasi-two-dimensional rectangular bin: heap formation) where particles are uniform in shape (spherical) and air (whose viscosity and density are very less as compared to those of SS balls) is the interstitial fluid that has negligible effect.

The flow of granular material is encountered in various industries during transportation of materials, mixing of rotary kiln, storage of materials in hopper and silos, crushing and grinding, mechanical separations, etc. It is also encountered in nature during transportation at river bed, during formation of sand dunes, in lava flows, and in avalanches. The properties of granular materials during flow are different, which gives problems in various industries. Granular materials have a tendency to segregate. Segregation occurs due to small differences in either size or density when they flow or are shaken or vibrated. But this is not true with liquids and gases. Fluids often mix with each other after agitation in industrial processes. Segregation of granular materials during transport and handling is an important problem in the chemical, pharmaceutical, and food industry wherever mixing is required. Segregation is the fundamental characteristics of granular flow. During flow, granular matter segregates.

Segregation mechanisms have been studied experimentally [2–6] as well as by simulations [7–9]. Particle dynamics [10, 11] or discrete element method [12] and Monte Carlo simulations [10, 13] are used as computational techniques. If a bed of grains of different sizes is sheared parallel to the top surface, the larger grains segregate to the surface of the bed and the smaller ones to the bottom. Brazil nut effect is the most celebrated example to understand the mechanism of segregation where large particles remain at the top.

In this chapter, the problem of segregation has been studied during flow in a blast furnace using a simplified system. A binary mixture of spherical particles of different sizes is used in a quasi-two-dimensional system, with a finite mass of the mixture poured periodically. Although this problem has not been studied in detail previously, some works have reported a related system in which the material is poured continuously. The objective of the present work is to study the segregation of a binary mixture of different diameter spheres in a quasi-two-dimensional rectangular bin (two vertical glass plates separated by a gap of 10 mm) during heap formation by intermittent pouring of a finite mass of the mixture at one edge of the bin. The concentration distribution in the system is obtained by image analysis for different system parameters including the mass of the material poured, the initial concentration of the mixture, the height of pouring, and the size ratio of particles in the mixture. The experimental details are presented next followed by the results and conclusions.

1.1 Blast furnace

The blast furnace is charged with coke and sinter particles by means of an inclined chute rotated about its vertical axis (**Figure 1**). For each rotation of the chute, the particles on the sloping burden surface form a circular ring. The particles in the ring then flow along the burden surface and form a new surface profile. These particles are distributed over a range of sizes. During the flow, the particles have a tendency to separate due to differences in size and density as shown in **Figure 2**.

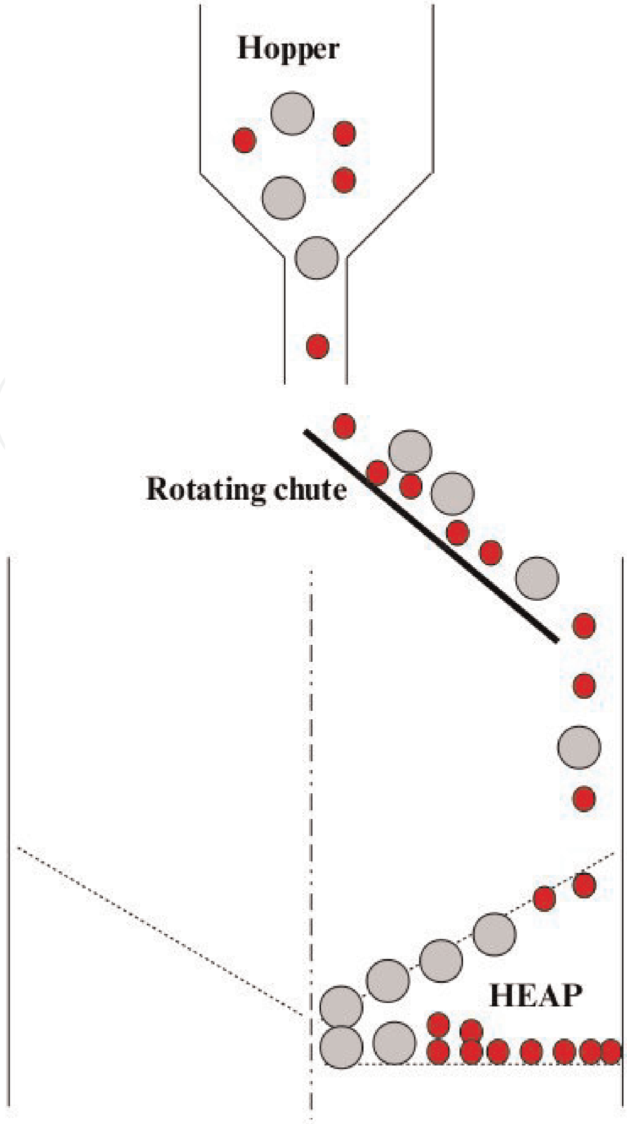

Figure 1.
Schematic view of blast furnace.

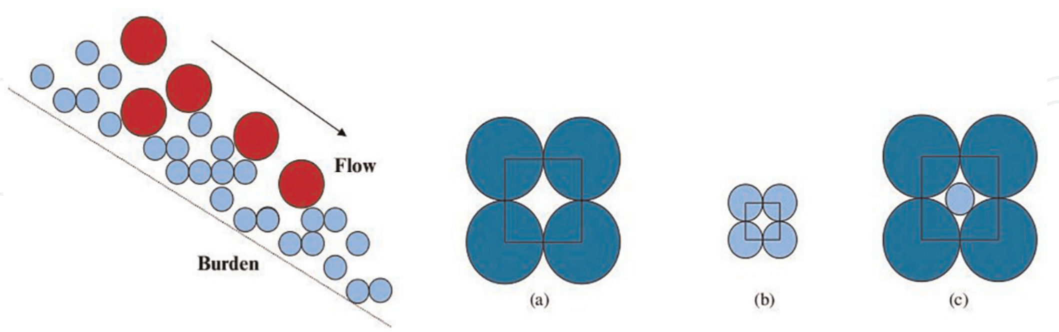

Figure 2.
Schematic view of a partially segregated mixture of particles flowing down along the burden surface (left). Packing of particles: (a) monosize large, (b) monosize small, (c) mixed.

This results in smaller particles being deposited first and larger particles rolling more distance before they stop. According to this mechanism, larger particles should be concentrated near the center of the blast furnace and smaller particles closer to the radius at which the material stream impinges on the burden surface.

Due to limited time of flow, segregation of granular material is generally not complete. This affects the packing of particles and thus the gas flow resistance and distribution of gas through blast furnace. In the case of complete segregation, the void fraction in the region containing only large particles is roughly the same as void fraction in the small particle region (**Figure 2**). However, the region with larger particles has a large average interstitial pore diameter and thus a lower flow resistance. In a mixed region, the void fraction is lower than that of pure component case and the average pore diameter is lower than the larger particle case. Thus, the extent of segregation affects both void fraction and average pore diameter; both affect flow resistance and consequently gas distribution through the blast furnace.

2. Experimental details

2.1 Experimental setup

Experiments are carried out in quasi-two-dimensional rectangular bins (two vertical glass plates separated by a gap of 10 mm). Stainless steel (SS 316) balls of different size of diameters (1 and 2 mm) are used as model granular materials. The images taken are analyzed using computer code to detect the particles. Image analysis technique is used to detect the position and size of the particles. The profiles of the number fraction of big (2 mm) particles along the flow direction across the depth in the layers are plotted separately for the top and bottom regions of the heap. Flowing layer decreases toward the end. We have assumed flowing depth constant for simplicity. A schematic view of heap formation is shown in **Figure 3**.

The experimental setup consists of two glass plates (52 cm × 29 cm), L-shaped aluminum divider, and an auxiliary hopper. The side walls (glass plates) are transparent to facilitate imaging. The gap between two vertical glass plates is 1 cm, and the L-shaped aluminum spacer is placed. The L-shaped divider is a chute used in the blast furnace with the angle of the chute close to 40°. Aluminum divider forms an inclined chute so that materials will easily flow and then settle at the bottom to form a heap. The auxiliary hopper is placed on the top of the bin for supplying granular materials as a feed. The exit of the chute is designed so as to provide minimum

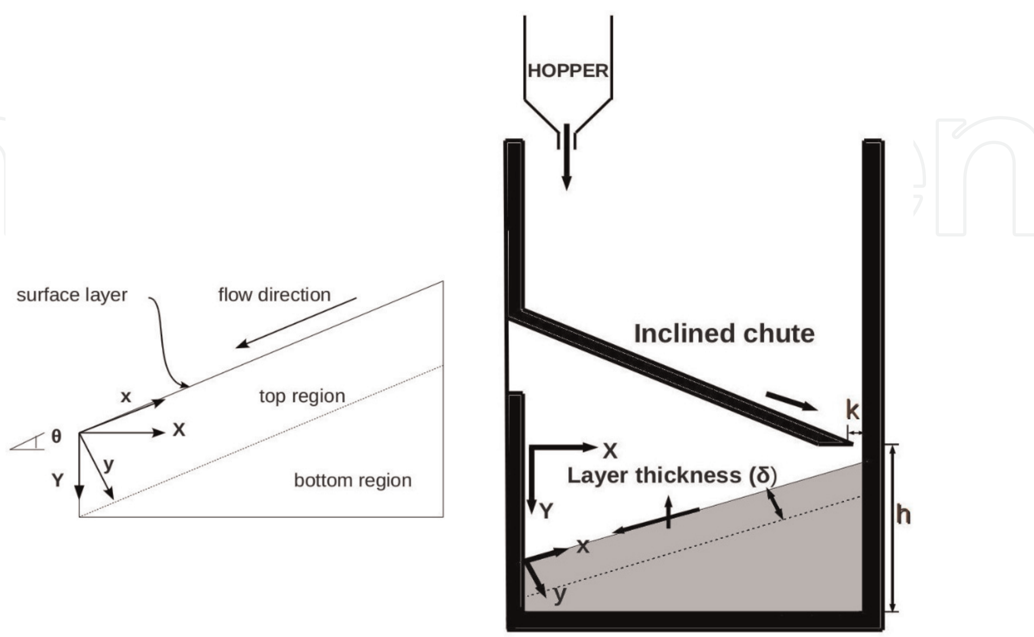

Figure 3.
Schematic view of heap formation, comprising top and bottom regions (left) along with setup used (right). The coordinate system shows x = 0, y = 0 at the low end of the top surface of the pile. The coordinate system employed in the analysis is shown (left).

disturbance to the flow. The tip of the chute is smoothened by reducing the sharpness of the exit (the point at which materials fall from the gap k and then fall onto the heap), which in turn reduces the disturbance to the flow. A black paper is placed at the back of the glass plate so as to ensure good-quality images after experiments. The position of the aluminum divider can be adjusted to control the flow rate and the height of fall to the top of the heap. Halogen lamp (1000 W) is used as light source for better image analysis. The setup is leveled properly to ensure that side walls are vertical and the base is horizontal. The distance between divider exit and heap (forms at the bottom after experiments) is sufficient so that materials will flow easily and get enough time to settle at the bottom.

2.2 Experimental method

A known weight of the binary mixture of a specified composition is poured intermittently into the auxiliary hopper and then allowed to pass through the gap (k) between the divider and the plate and finally settle onto the heap. This forms a layer on the surface of the heap. The process is repeated to form a number of layers until the top of the heap is close to the end of the chute. The heap thus formed is imaged to determine the concentration distribution of the different size particles in the heap. To obtain a sufficiently high resolution, the heap is imaged in eight parts. A transparency of known scale is placed while capturing images for each part. Images taken with and without transparency give more accuracy and also help in combining all parts of the heap. A source of light is placed parallel to the camera and in front of the heap so that each particle has a single reflection of the light, the size of which depends on the particle diameter. Each part is captured using a digital camera (Nikon D3100) at 1/100 shutter speed and intensity of 800/1600. Captured images have a resolution of 4608 × 3072 pixels; one pixel is equal to 0.020616 mm. Data (in terms of pixel) obtained for the detected images are converted into mm. The images are analyzed to determine the position of each particle (small and big) and number fraction of big particles across the layer. Each experiment is repeated eight times to get average data. The details of image analysis are explained in the next section.

2.3 Image analysis technique

Image analysis technique is used to detect the position and size of the particles from captured images using an in-house computer code (*c programming*). The detection of particles (small and big) is done based on the number of pixels obtained in each cluster (white spots in **Figure 4**). As we have used binary mixture (1 and 2 mm) particles while performing experiments, analysis became easy. Therefore, the detection of particles is accurate and efficiency is high. These data are used to plot profiles of the number fraction of big particles vs. component x (flow direction) with depth y (mm) in the layer. This will be useful to develop the segregation model based on it.

2.3.1 Detection of particles

The images (4608 × 3072 pixels) are captured using Nikon D3100 camera. In all images, particles appear as tiny bright spots on a black background. The typical captured image is shown in **Figure 4**.

Thresholding is used to convert gray scale images into black and white images. The threshold value is chosen such that the less illuminated particles from the inner layers are eliminated and particles from the front layer appear as clusters of white pixels on a black background. During the thresholding process, individual pixels in

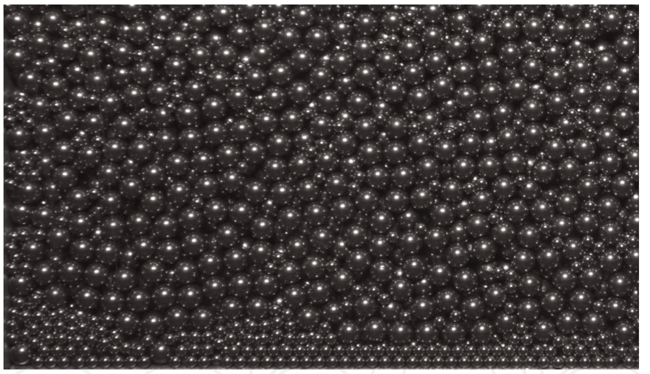

Figure 4.
Typical captured image: the particles are seen as bright spots.

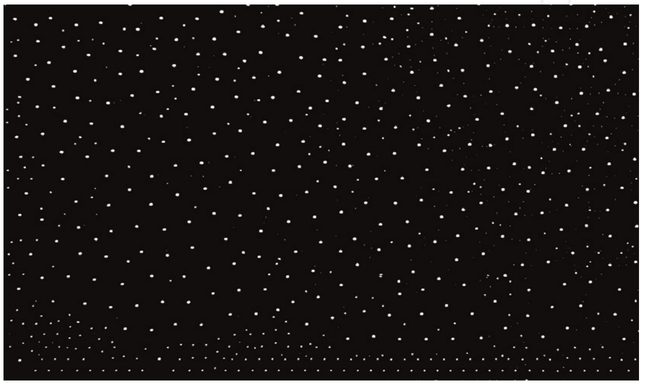

Figure 5.
Detected particle as a white cluster after thresholding.

an image are marked as "object" pixels if their value is greater than some threshold value (assuming an object to be brighter than the background) and as "background" pixels otherwise. This convention is known as threshold above. If the chosen threshold value is 200, it means all the pixel value (range 0–255) that are above 200 will be marked as white (255) and less than 200 will be marked as black (zero value). Also, we can use threshold below, which is opposite of threshold above. In this way, the binary image is created by coloring each pixel white or black, depending on a pixel value. We next scan the thresholded image for a white pixel, starting from top left corner, in both right and downward directions. Once a white pixel is found, then the neighboring pixel should be scanned to detect all the white pixels that form the cluster. Similarly, all the white clusters are identified in that image. The captured image after thresholding shows individual white clusters of pixels (**Figure 5**).

2.3.2 Position and size of particle

The position (X and Y coordinates) of individual cluster is determined based on mean position of all the pixels present in that cluster. The radius of gyration (R_g) is used to calculate the size of the cluster. It is calculated as the root mean square distance of the object's parts from either its center of mass or an axis. Here, we have used this parameter to characterize the size of individual particle (cluster) based on center of mass.

$$\text{Radius of gyration}\left(R_g\right) = \sqrt{\frac{\sum_{i=1}^{N}\left[(X_i - X_0)^2 + (Y_i - Y_0)^2\right]}{N}} \tag{1}$$

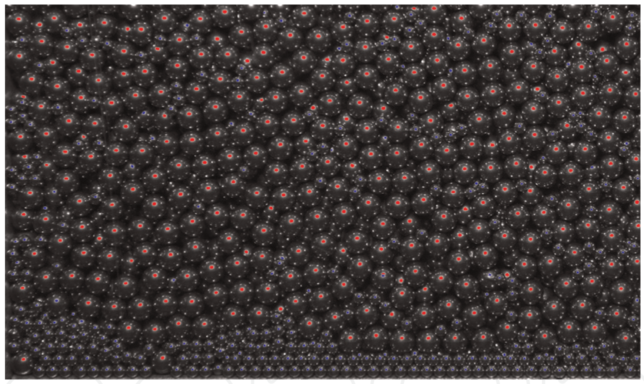

Figure 6.
Detected particle: red (2 mm) and blue (1 mm).

where X_i and Y_i are the X and Y coordinates of each pixel in the cluster. X_0 and Y_0 are center of mass of each cluster of X and Y coordinates, respectively, and they are calculated as

$$X_0 = \sum_{i=1}^{N} \frac{X_i}{N} \tag{2}$$

$$Y_0 = \sum_{i=1}^{N} \frac{Y_i}{N} \tag{3}$$

The particles detected in **Figure 5** as a white cluster are marked as red and blue based on the radius of gyration. The values of R_g greater than or equal to 3.5 are marked as red or as blue. Detected particles are shown in **Figure 6** in red (big particle—2 mm) and blue (small particle—1 mm).

For analysis, we have chosen a coordinate system with its origin (x,y) at the top left corner of the free surface layer, such that the +ve x-axis is opposite the flow direction and + ve y-axis is in the downward direction. The default and transformed coordinate axis is shown in **Figure 3**. The new position of the particles is calculated using the following transformation:

$$x = X\cos\theta + Y\sin\theta \tag{4}$$

$$y = Y\cos\theta - X\sin\theta \tag{5}$$

where x, y and X, Y are the position according to the new and old coordinate system respectively and θ is the angle the free surface makes with the horizontal.

3. Results and discussion

3.1 Heap formation and layer thickness

Figure 7 shows a schematic view of the layers formed due to repeated pouring of the mixture. There is no time internal between two pouring. Once the first layer settles and forms a heap, then another layer is poured over the heap form in earlier layer. In each pouring layer, the upper particle (mostly large in size) gets eroded in the next layer cycle. Several repeated pouring (7–8 layers) forms a heap, which is analyzed to get the data. One pouring corresponds to layer thickness (δ). The initial layers formed do not reach the edge of the bin since a fixed amount of material is poured and the angle of repose is fixed. As more layers are poured, the height of the heap increases and the layer spans the bin. When there is no movement of particles

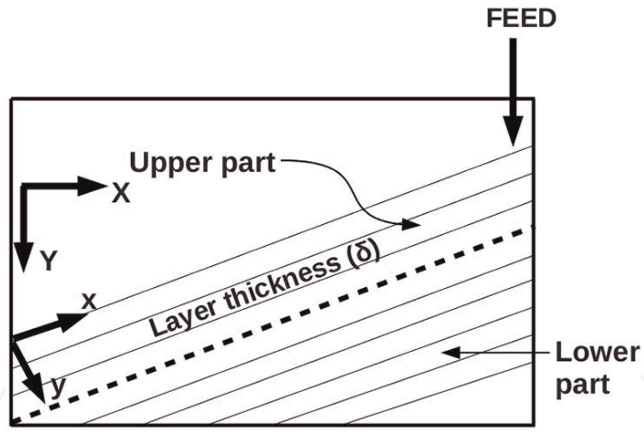

Figure 7.
Schematic diagram of layer formation showing top region, bottom region, and layer thickness.

in the heap form, then stable state heap is achieved. We denote the region in which the layer spans part of the bin as the bottom region and the region with the full layers the top region. The regions are demarcated by a dashed line in **Figure 7**. The layer thickness (δ) is measured experimentally as well as estimated theoretically using measured bulk densities of the mixtures.

The parameters varied in the experiments are the volume (mass) of mixture and height of the divider from the bottom for fixed gap (k = 5 mm) between the plate and the divider. Therefore, results presented below are based on these parameters. The profiles of the number fraction of big (2 mm) particles along the flow direction across the depth in the flowing layer for top and bottom regions are shown below. Each flowing layer is divided into bin of size (layer thickness $\times$ 10 mm). Layer thickness depends upon the amount of volume poured in each step. Layer thickness is calculated experimentally as well as theoretically for known volume (mass) of mixture, which is explained below. Practically, thickness of layer reduces with distance but here we assumed as same from initial (pouring point) to the end point. Experimentally, it is measured before and after pouring using Image J software in terms of pixels and then converted to mm. Theoretical calculations are done as follows: amount of material poured (i.e., mass) converted into volume using density of material. Then using setup geometry, the distance of one layer in x-direction (flow direction) is known, which is typically the distance of the surface profile. The gap between two glass plates is known as 10 mm (1 cm). Finally, the following formula is used: volume of material (mm^3) = layer thickness (δ) $\times$ gap (k) $\times$ distance in flow direction (x). We have found that the obtained values of theoretical layer thickness and experimental are the same. In **Figure 9**, we have obtained layer thickness of 10 mm for 150 g of mixture and average layer thickness taken for each layer is 5 mm (in the middle of layer which is half of 10). Therefore, the depth of layer from surface of heap is 15 mm (we have neglected top layer in all cases studied), which is consider as sampling depth in **Figure 9**, and similar calculation is done for subsequent layers. We also checked number fraction profile at the back side of heap (opposite to front side) and found similar results compared to front plate/side. The error bars denote the standard deviation over eight experiments.

3.1.1 Effect of mass of pouring

Figure 8 shows the profile for 50% mixture of small (1 mm) and big (2 mm) particles with equal density for different volume of pouring for top region (**Figure 8a–c**) and bottom region (**Figure 8d–f**). Equal percent of small and big particles is used for all cases of mass of pouring. All other parameters (composition,

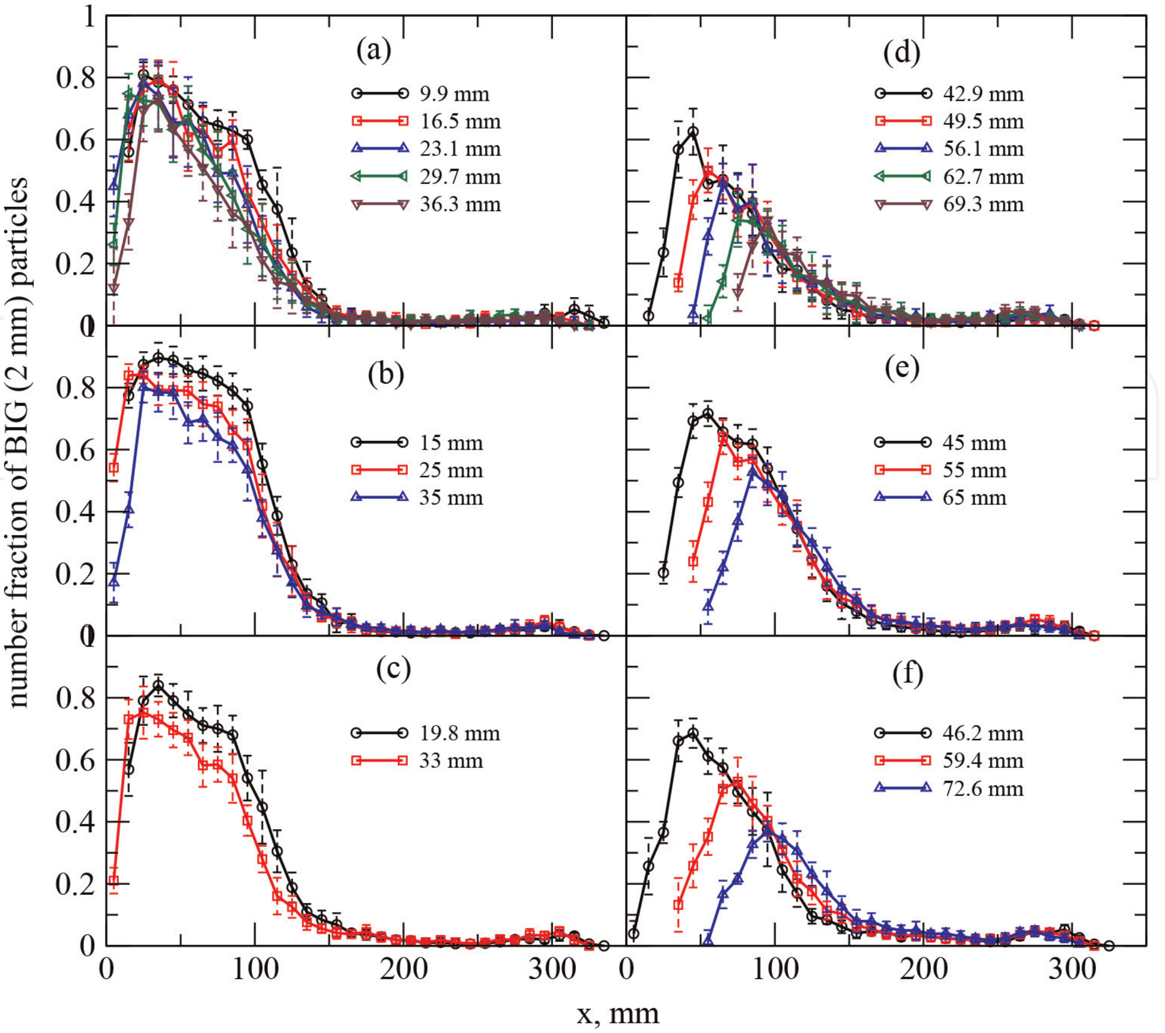

Figure 8.
Profiles of number fraction of big (2 mm) particles along the flow direction, x (mm) across the depth in the flowing layer, y (mm) for equal % of mixture. Volume of pouring (a) 100, (b) 150, and (c) 200 g for top region and similarly for bottom region (d), (e), and (f). Height of the divider from the bottom (h) is: 22 cm. Error bars show the standard deviation over eight experiments.

height, and size ratio) are the same. The number fraction profiles of big particles for bottom region overlap with each other and are almost identical for all the cases of volume of pouring (**Figure 8d–f**). The pattern formation for three different pouring is somewhat similar and is apparent. The profiles of top region **Figure 8a–c** do not show significant variation in the number fraction across the depth in flowing layer, and it indicates that segregation in flowing layer is independent of volume of pouring. Though we increase the mass of particles (i.e., number of particles), percent fraction of small and big particles in the mixture remains the same (i.e., 50%). Also corresponding value of layer thickness varies with the mass of pouring, which is calculated theoretically as well as experimentally. Therefore, in each bin, the variation in number fraction of particles along the flow direction and flow depth is less for all three cases studied (i.e., 100, 150, and 200 g). The data indicate segregation (partial) with big particles at the far end of the heap and small particles settle near the heap. The nature of number fraction profile is almost equal and will overlap with each other if we combined all the plots for top region as well as bottom region.

3.1.2 Effect of height variation

Figure 9 shows profiles of 50% by volume of mixture of small and big particles with equal density for different height of the divider from the bottom. The top

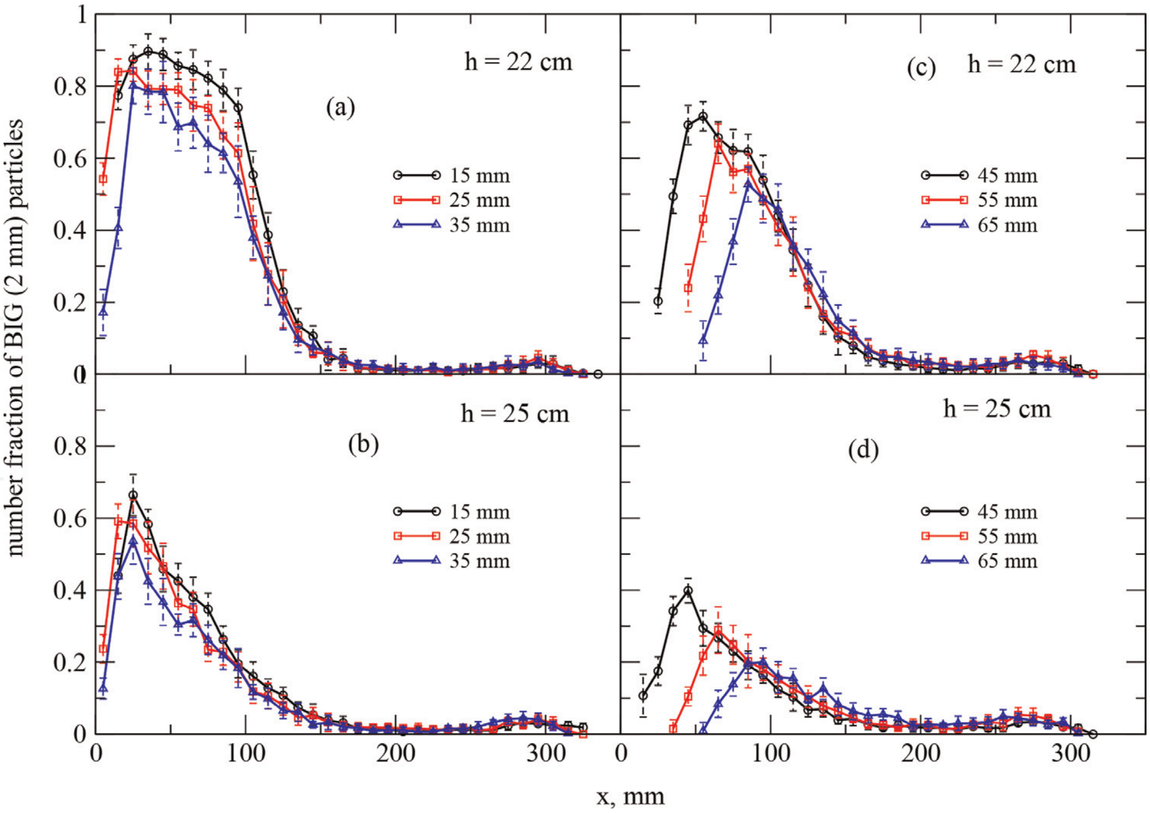

Figure 9.
Profiles of number fraction of big (2 mm) particles along the flow direction, x (mm) across the depth in the flowing layer, y (mm) for equal % of mixture. The height of the divider from the bottom is (a) 22 and (b) 25 cm for top region and similarly for bottom region (c) and (d). The volume of pouring is 150 g. Error bars show the standard deviation over eight experiments.

region (**Figure 9a** and **b**) and bottom region (**Figure 9c** and **d**) show large variations in number fraction profile plotted for different layer thickness. This indicates that mixing is more in flowing layer if height of the divider from the bottom increases. Also increase in height creates more energy for particles during flow due to which small particles may bounce and settle at the far end of the heap. This variation in mixing/segregation pattern also depends on the height of the heap and other working parameters, which have to be studied further. Here, we have considered only two values of height while studying the effect on segregation pattern. Also, the system studied here is 2D; therefore, the effect of wall also plays a vital role in heap formation and mixing/segregation pattern. Wall effect will be neglected if we perform similar study in 3D heap formation setup.

4. Concluding remarks

Segregation of binary granular mixtures, differing in size and equal density, during heap formation by intermittent feeding in a quasi-two-dimensional rectangular bin has been investigated. Experiments were performed by varying the mass (volume) of the mixture and the height of the feeding point above the bottom of the bin. Data show large particles travel more distance than small particles as smaller ones can easily fit into void spaces created during flow of materials. The profiles of the number fraction decreases along the flow path with depth in the deposited layer for both the parameters studied (mass of pouring and height). During heap formation, the small particles concentrate near the upper part of the heap and large particles travel more distance and settle at the bottom. The profiles for different volumes of pouring do not show significant variation and this indicates that segregation in flowing layer is independent of volume of pouring. This is due to mere increase in mass (volume) of pouring, but number fraction in each layer remains the same. Therefore, they overlap with each other as observed. In all cases studied, there is a peak in number fraction profile near the pouring end. Increase in height (h) decreases the number fraction of big particles, which in turn affects the extent of segregation. This indicates that mixing is more in flowing layer if we increase height of the divider above the bottom of the bin for 22 and 25 cm height. Also increase in height creates more energy for particles during flow due to which small particles may bounce and settle at the far end of the heap. The impact for height of fall is clearly apparent near the pouring point of the heap. We have investigated size segregation of particles during heap formation. It has direct implications in engineering applications, and one of the examples of such granular process is blast furnace. These findings may be useful for the optimization of the design of blast furnace and its accessories. Also, the methodology followed in this chapter can be implemented to minimize particle segregation in an actual blast furnace.

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References

[1] Patrick R, Nicodemi M, Delannay R, Ribiere P, Bideau D. Slow relaxation and compaction of granular systems. Nature Materials. 2005;**4**:121-128

[2] Ding YL, Forster R, Seville JPK, Parker DJ. Segregation of granular flow in the transverse plane of a rolling mode rotating drum. International Journal of Multiphase Flow. 2002;**28**:635-663

[3] Khakhar DV, Orpe AV, Hajra SK. Segregation of granular materials in rotating cylinders. Physica A. 2003;**318**: 129-136

[4] Makse HA, Havlin S, King PR, Stanley HE. Spontaneous stratification in granular mixtures. Nature. 1997;**386**: 379-382

[5] Ottino JM, Khakhar DV. Fundamental research in heaping, mixing, and segregation of granular materials: Challenges and perspectives. Powder Technology. 2001;**121**:117-122

[6] Savage SB, Lun CKK. Particle size segregation in inclined chute flows of dry cohesionless granular solids. Journal of Fluid Mechanics. 1988;**189**:311-335

[7] Shinbrot T, Zeggio M, Muzzio FJ. Computational approaches to granular segregation in tumbling blenders. Powder Technology. 2001;**116**:224-231

[8] Tripathi A, Khakhar DV. Rheology of binary granular mixtures in the dense flow regime. Physics of Fluids. 2011;**23**: 113302

[9] Yaowei Y, Saxen H. Experimental and dem study of segregation of ternary size particles in a blast furnace top bunker model. Chemical Engineering Science. 2010;**65**:5237-5250

[10] Khakhar DV, McCarthy JJ, Ottino JM. Radial segregation of granular mixtures in rotating cylinders. Physics of Fluids. 1997;**9**:3600-3614

[11] Vargas WL, Hajra SK, Shi D, McCarthy JJ. Suppressing the segregation of granular mixtures in rotating tumblers. AIChE. 2008;**54**: 3124-3132

[12] William RK, Curtis JS, Wassgren CR, Hancock BC. Modeling granular segregation in flow from quasi-three-dimensional, wedge-shaped hoppers. Powder Technology. 2008;**179**: 126-143

[13] Rosato A, Prinz F. Monte Carlo simulation of particulate matter segregation. Powder Technology. 1986; **49**:59-69