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Significance of Chute-Related Factors on Segregation of a Granular Chute Flow

S. Panda and D.S. Tan

Department of Mechanical Engineering,
National University of Singapore, Singapore-119077

Abstract

Granular segregation is a common occurrence in the pharmaceutical and food industries, although typically it is undesirable as segregation leads to non-uniformity in end products and thus lowers the overall product quality. It is well-known that segregation occurs due to differences in the species composing the mixture such as particle size, shape or density; unfortunately, this is often an unchangeable quality. The question is then how to minimize (or enhance, depending on the application) the segregation, given a mixture that cannot be changed; thus, the focus of this work is on external factors that can be controlled. Specifically, considering a dry granular chute flow, we focus on chute-related factors such as the inclination angle, surface roughness, fill volume, cross-sectional profile, and base profile of the chute. We present here, the investigation results (to date) into some of these factors, for a mixture comprising two species of different size. The numerical simulations were conducted using the discrete element method (DEM) specifically using the open-source code LIGGGHTS developed for granular simulations. A small-scale table-top experiment consisting of an acrylic chute, approximately 1m in length with variable inclination angle, was used to obtain results both for obtaining a preliminary understanding, as well as to validate the numerical simulations. Monitoring the rate and extent of segregation when varying each investigated factor, unsurprisingly we find that the segregation dependency is not straightforward, due to the sensitivity of the granular flow's velocity profile. Formulation of a general guideline or optimal set of conditions, will thus require further investigation using other granular compositions as well.

Introduction

Granular materials can be seen in processing industries of food, pharmaceuticals, detergents, chemicals, paints, cosmetics, etc. During handling of these products, stirring, shaking or vibrating can cause segregation which is sometimes a problem in these industries. Segregation is the separation of different particles in the mixture. Even if the particles are mixed initially, the mechanical processes lead to separation that is, they separate into clusters of similar particles based on differences in size, shape or density. In industries, this segregation of particles may give rise to non-uniformity in products and ultimately affects the product quality. Although the root cause of segregation is differences of the particles making up the mixture, oftentimes we have little to no control over the mixture composition. As such the overarching goal of this research is to study how the segregation process can be affected by external parameters such as the inclination of the chute transporting the chute, as this affects the flow velocity and therefore the segregation, indirectly.

Segregation aside, the flow of granular particles have been studied widely through both numerical and physical experiments. Bi et al. [2] investigated experimentally the influence of bottom roughness on monodisperse disks flowing down an inclined chute. They studied the positions, velocities, and rotations with respect to different inclinations. Tai and Lin [16] presented results of granular flow in an inclined chute into the horizontal run-out zone. They studied the motion of granular masses and evolution of deposition heaps. Sheng et al. [15] conducted experiments to study the characteristics of quasi two-dimensional granular flows down in an inclined straight rectangular chute. Zhou and Sun [18] used particle flow code (PFC) to numerically model the solid particles. They studied the effect of channel confinement, shear rate and variation in flow regime. Šalinić et al. [12] used the optimal control theory to find the optimum chute profile at maximum exit velocity of granular material. Brodu et al. [3] studied the flow of the granular material in an inclined plane with flat base. They varied the material parameters and basal conditions and found a new pattern in high speed flows of granular material.

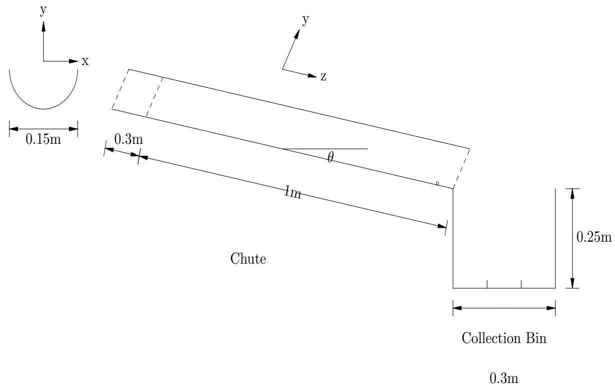

Figure 1: 2D sketch of experimental setup

Deng et al. [5] discussed the segregation of tridisperse granular materials flowing down a chute. They made a continumm transport model and studied the effects of relative particle size, diffusion and velocity profile on segregation characteristics. Much previous works are either on developing a new model [10, 14, 17] on predicting the segregation or controlling the particle properties [13, 1, 11] in heap flow and rotating drum mixers. From literature, many numerical simulations and experiments are carried out to study the behavior of granular particles flowing through chutes. There are also numerous studies on segregation and its underlying mechanisms, but none on how the segregation can be minimized by controlling external factors. In this paper, we present the preliminary results of our numerical and experimental investigation into one such factor - the effect of fill volume on segregation.

Experimental Setup

We study the flow of different volume of two-sized particle mixture down an inclined semicircular chute. The experimental setup is shown in Fig.1, where a Perspex pipe of 0.15m diameter is cut into semicircle to simulate in a chute of length 1.3m. First, the chute is adjusted to a predetermined angle, and an acrylic stopper is placed at the 0.3m mark of the chute to signify the starting position of the glass beads. Then, depending upon the percentage of fill volume, the number of small and big particles will be evenly mixed and placed before the stopper. This percentage of fill volume is calculated as per the initial

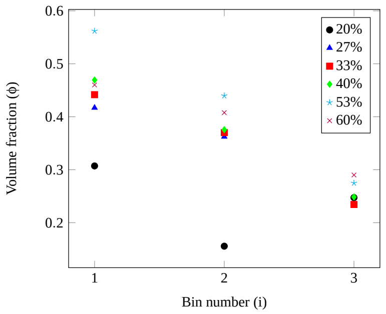

Figure 2: Volume fraction of small particles in bin

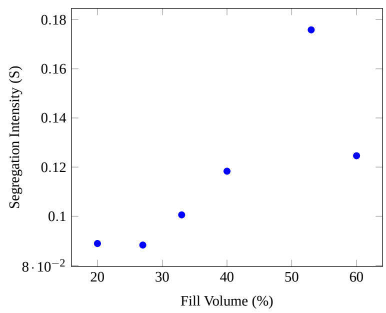

Figure 3: Segregation Intensity of particles in bin

height at the chute entry gate to which it is filled. The collection bin is placed at the bottom near the exit of the chute. We have used three partitions in the collection bin made of perspex. The two sizes of glass beads - 2mm and 3mm diameter have identical density. They are allowed to flow down the chute inclined at 30° to the horizontal.

Relative solid volume fraction for 2mm particles is given by

$$\phi = \frac{N_1 \times V_1}{N_1 \times V_1 + N_2 \times V_2} \tag{1}$$

where N_1 and N_2 are the number of small and larger particles respectively. V_1 and V_2 are the volume of small and larger particles respectively. We measure the mass of beads in each partition and use it to determine the degree of segregation, as follows.

$$S = \sqrt{\frac{\sum_{i=1}^{n}(\phi_i - \bar{\phi})^2}{n}} \tag{2}$$

where ϕ_i is the relative solid volume fraction of small particles in i partition of the collection bin and $\bar{\phi}$ is the initial solid volume fraction, i.e. 0.3 as for small particles.

Using this standard deviation expression, ‘0’ would correspond to a uniform mixture. Thus the larger the value of S, the more segregation has occurred.

Results of Physical Experiments

The relative solid volume fraction of small particles in each bin for different fill volume is shown in Fig. 2. Bin 1 is the closest to the bottom of the chute, while bin 3 is the furthest. Generally we expect that particles near the top of the granular flow will fall into bin 3, while particles near the bottom of the flow will fall into bin 1.

From Fig. 2, we find that for the lowest initial fill volume (20%), the relative solid volume fraction of the small particles is close to 0.3 (the initial relative volume fraction of small particles) in all 3 bins, which implies that not much segregation has occurred. For the higher initial fill volumes, we observe that the relative solid volume fraction of small particles is greatest in bin 1, and lowest in bin 3. This implies that the small particles have segregated towards the bottom of the flow. Comparing within each bin, it appears that the segregation is increased with higher initial fill volume. This is seen more clearly from the plot of segregation intensity for different fill volumes, shown in Fig. 3.

There is a clear increase in segregation intensity with initial fill volume up to 53%, followed by a sharp drop. We theorise that this is because at low initial fill volumes, the layer of particles is small (sometimes only 1 layer), which makes it difficult for segregation (via percolation or kinetic sieveing) to occur. As the initial fill volume increases, the number of layers increase and so more segregation can occur. However beyond a critical fill volume (around 50%), there are enough particles such that segregation along the length of the granular flow (that is, larger particles move towards the front of the flow) becomes more significant, and therefore the ‘vertical’ segregation as measured by the bins is no longer as distinct.

Aside from this, the absolute mass of particles falling in each bin is also not uniform — this could lead to misleading interpretations of the physical experiment results. While finer divisions could remedy this issue slightly, we believe that using numerical simulations would shed more light on both this as well as the segregation process within the chute itself.

Numerical Setup

Cundall and Strack [4] first proposed the discrete element method (DEM) in 1979. It calculates and updates the positions and velocities of every single particle at each incremental timestep. The numerical simulation is performed using an open source discrete element method (DEM) particle simulation software called LIGGGHTS [9]. The repulsive contact force between a pair of overlapping granular particles in Eq.3 are modeled based on Hertzian contact theory [6, 7].

$$\mathbf{F} = \mathbf{F_n} + \mathbf{F_t} = (\mathbf{k_n}\delta_\mathbf{n} - \gamma_\mathbf{n}\mathbf{v_n}) + (\mathbf{k_t}\delta_\mathbf{t} - \gamma_\mathbf{t}\mathbf{v_t}) \tag{3}$$

where $\mathbf{F}_n$ and $\mathbf{F}_t$ are the components normal and tangential to the plane of contact. The subscripts 1 and 2 in the formulae mentioned in Table 1 refer to the two contacting particles.

$$\begin{aligned}
\mathbf{F}_t &\leq \mu \mathbf{F}_n \\
\mu &= \text{coefficient of friction} \\
\delta_n &= \text{overlap distance of two particles} \\
\delta_t &= \text{tangential displacement vector between 2 particles} \\
v_n, v_t &= \text{normal and tangential component of the relative velocity} \\
&\quad \text{of 2 particles} \\
G &= \text{Shear Modulus}
\end{aligned}$$

Specifically, we model the flow of a fixed volume of binary granular mixture (composed of spheres) down a rigid wall chute with semi-circular cross-section. The only external force in the simulation is gravity. Just as in the physical experiment, the chute used is of length 1.3m, and the granular particles are inserted at 0.3m from the end. In the present simulation, 3mm and 2mm diameter particles at 100g/s mass flow-rate distributed with mass ratio of 0.3:0.7 are inserted. The other material properties used for the numerical simulation are listed in table 2. The flow of particles in the chute inclined at 30° to the horizontal axis are observed.

Variable	Formulae
k_n	$\frac{4}{3}E^*\sqrt{R^*\delta_n}$
k_t	$8G^*\sqrt{R^*\delta_n}$
γ_n	$-2\sqrt{\frac{5}{6}}\beta\sqrt{S_n m^*} \geq 0$
γ_t	$-2\sqrt{\frac{5}{6}}\beta\sqrt{S_t m^*} \geq 0$
S_n	$2E^*\sqrt{R^*\delta_n}$
S_t	$8G^*\sqrt{R^*\delta_n}$
β	$\frac{\ln(e)}{\sqrt{\ln^2(e) = \pi^2}}$
$\frac{1}{E^*}$	$\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$
$\frac{1}{G^*}$	$\frac{2(2-\nu_1)(1+\nu_1)}{E_1} + \frac{2(2-\nu_2)(1+\nu_2)}{E_2}$
$\frac{1}{R^*}$	$\frac{1}{R_1} + \frac{1}{R_2}$
$\frac{1}{m^*}$	$\frac{1}{m_1} + \frac{1}{m_2}$

Table 1: Formulae for calculating force components for a pair of particles in contact

Youngs Modulus (E)	5×10^6 Pa
Density (ρ)	2500 kg/m^3
Particle-particle restitution coefficient (e)	0.9
Particle-particle friction coefficient (μ)	0.3
Poissons ratio (ν)	0.45
Time step (dt)	0.01 millisecond

Table 2: Material properties of particles

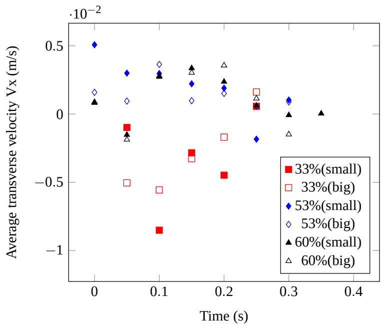

Figure 4: Evolution of average transverse velocity Vx of particles at midpoint of chute, for different initial fill volumes

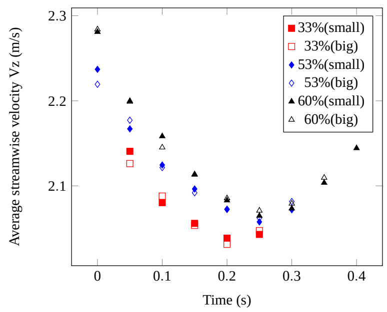

Figure 5: Evolution of average streamwise velocity Vz of particles at midpoint of chute, for different initial fill volumes

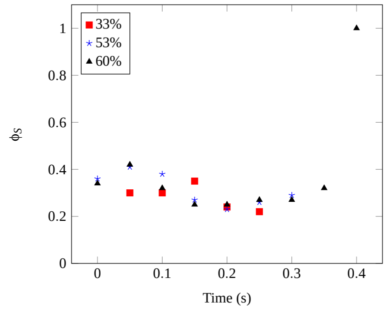

Figure 6: Evolution of relative solid volume fraction of small particles at midpoint of chute, for different initial fill volumes

Results of Numerical Simulation

Figures 4 shows the time evolution of average cross-stream wise velocities of small particles for a small section halfway down the length of the chute. From Fig. 4, we see that the average normal velocities of the small particles are more than the larger ones. This means that the larger particles are flowing at center and small particles are flowing at edges. As the fill volume increases, the cross-stream velocity Vx decreases, which implies there is little movement of particles from the center, i.e. the particles are moving together. Thus, the segregation in cross stream direction decreases with an increase in fill volume.

Figures 5 and 6 show the time evolution of average streamwise velocities as well as the relative solid volume fraction of small particles for a small section halfway down the length of the chute. Only a portion of the initial fill volumes investigated are presented here for clarity. Note that due to the small volume of particles, the flow height was typically not very high and thus vertical profiles of solid volume fraction and velocity were not measured.

We observe a general decrease in the downstream velocity of small particles in Fig. 5. This is in keeping with reported literature observations of segregation along the granular flow, where the large particles are generally faster than the small particles [8]; it also supports our hypothesis regarding the drop in segregation intensity observed in Fig. 3 for the highest initial fill volume. . Figure 6 shows three different stages:

1. For the first ≈0.1s, the particles are still evenly mixed. This is reflected by the relative solid volume fraction being close to 0.3 (the initial relative volume fraction).

2. Over the next ≈ 0.2s, the relative solid volume fraction of small particles decreases. This indicates that large parti-

cles have moved faster than the small particles, implying segregation along the chute.

3. Finally, the relative solid volume fraction of small particles increases again, which is due to the decreasing number of large particles left in the chute.

It must be noted, however, that while these changes can be observed the magnitude is relatively small. This implies that segregation along the chute flow is relatively low. The only exception is at the highest initial fill volume investigated (60%), for which the changes occur both earlier and more sharply — this implies that near 60% initial fill volume, the total mass of particles has become large enough that segregation along the chute flow is now starting to be significant.

Conclusions

Considering observations from both the physical and numerical investigations, we conclude that even in a chute as short as 1m in length, segregation occurs in both the transverse (normal) and streamwise directions. The extent of vertical segregation increases with initial fill volume. Segregation along the chute flow, however, is not significant until at higher initial fill volumes. Thus to maximise segregation, initial fill volumes should be as high as logistically possible. Conversely to minimise segregation, low initial fill volumes would be better, although this is not preferable in terms of (industrial process) efficiency.

We acknowledge, however that in an industry it is unlikely for granular flows to involve only such low volumes of material. Our logical next step is thus to investigate the effect of fill volumes using simulations with periodic boundary conditions. Other aspects currently under investigation include other inclinations as well as the surface roughness of the chute.

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