Effect of Chute Angle on Segregation of Granular Particles

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***Abstract*—The segregation of uniform granular mixtures is a common problem in pharmaceuticals, food processing, 3D printing, and cosmetic industries, due to quality control considerations. This is a common phenomenon for granular mixtures due to inherent differences among the individual particles such as size, density or shape. However for industrial purposes it may not be possible to change the granular mixture itself, and therefore we need to consider other ways to minimize segregation. Here, we study the flow of granular particles in a chute inclined at different angles using discrete element modelling in LIGGGHTS with the aim of investigating the significance of inclination angle on segregation.**

***Index Terms*—Segregation, chute angle, granular flow, Discrete element method**

I. Introduction

Segregation is an undesirable separation of different particles in the mixture. Even if the particles are mixed initially, there is a tendency for the mixture to un-mix – that is, separate into clusters of similar particles based on differences in size, shape or density - when it becomes excited through moving, pouring, conveying, or processing etc. From an industrial point of view, this segregation of particles may give rise to non-uniformity in products and ultimately affecting the product quality.

Granular flow, and segregation of such flows, has been studied widely through both numerical and physical experiments. Campbell and Brennen [1] developed a computer code to study the flow of dry granular material down inclined chutes and found that granular temperature is also a quantity on which the flow behavior depends. Hsiau S.S. and Yu H.Y. [2] observed that the segregation of particles first increases to a maximum and then decreases with vibrational acceleration. Sadjadpour and Campbell [3] studied the effect of chute geometry and inclination on the flow of cohesionless granular particles. An axial segregation of particles was investigated by Santomaso et al. [7] in a rotating drum, where they showed that the segregation can be controlled by modifying the geometry and roughness of the mixer. Yu and Saxén [8] found that the average velocity at the chute tip depends only on the chute angle for the uniform spherical particles flow. Kuo et al. [9] investigated the changes in flow characteristic in a chute due to a small fixed semi-cylindrical obstacle. Xiao et al. [10] proposed that segregation in industries could be reduced by controlling the feed rates and feed cycle durations in a heap flow.

From literature, it is widely agreed that the difference in size, shape and density of constituent particles in a mixture are the main factors affecting the segregation. However, it is not always easy or possible to change the material properties of particles. As such, we need to consider how the segregation can be minimized by controlling external factors. In this paper, we present the results of our numerical investigation into one such factor - the effect of chute angle on segregation.

II. Experimental Setup

The experimental setup is shown in Fig. 1, that consists of semicircular shaped chute made of Perspex glass and a open box to collect the glass beads from chute. In this case, 49 number of particles (28 small and 21 big size) are inserted with small initial velocity and the behavior of particles are studied. The glass beads are allowed to flow down the chute and the segregation intensity shown in Fig. 2 is calculated using the formula in Eq.1.

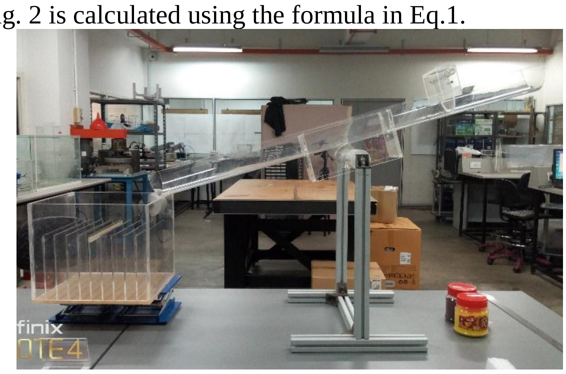

Figure 1. Experimental set up.

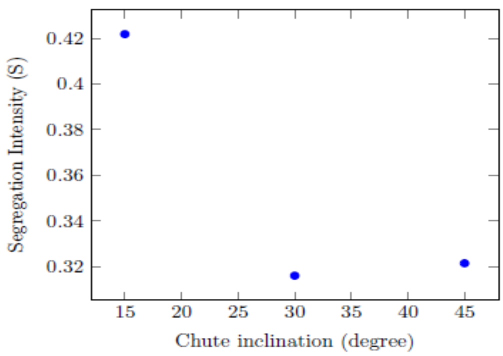

Figure 2. Segregation Intensity of particles in an inclined chute from experiment.

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The segregation intensity for each species is given by

$$S_{expt} = \sqrt{\frac{\Sigma_{i=1}^{n}(\phi_i - \bar{\phi}_i)^2}{n}} \quad (1)$$

where 'n' is the total number of samples; ϕ_i is the volume fraction of particles in i partition of the collection bin; $\bar{\phi}_i$ is the initial volume fraction.

III. Numerical Simulation

The numerical simulation is performed using an open source discrete element method (DEM) particle simulation software called LIGGGHTS i.e. LAMMPS improved for general granular and granular heat transfer simulations in Kloss et al. [4]. The repulsive contact force between a pair of over-lapping granular particles in Eq.2 are modeled based on Hertzian contact theory ([5],[6]).

$$\mathbf{F} = \mathbf{F}_n + \mathbf{F}_t = (k_n\, \boldsymbol{\delta}_n - \gamma_n\, \mathbf{v}_n) + (k_t\, \boldsymbol{\delta}_t - \gamma_t\, \mathbf{v}_t) \quad (2)$$

where **F**n and **F**t are the components normal and tangential to the plane of contact.

$$\mathbf{F}_t \leq \mu \mathbf{F}_n$$

μ = coefficient of friction

k_n = elastic constant for normal contact

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

δ_n = overlap distance of two particles

v_n = normal component of the relative velocity of the 2 particles

γ_n = viscoelastic damping constant for normal contact

$= -2\sqrt{\frac{5}{6}}\beta\sqrt{S_n m^*} \geq 0$

k_t = elastic constant for tangential contact

$= 8G^*\sqrt{R^*\delta_n}$

δ_t = tangential displacement vector between two particles which is truncated to satisfy a frictional yield criterion

v_t = tangential component of the relative velocity of the two particles

γ_t = viscoelastic damping constant for tangential contact

$= -2\sqrt{\frac{5}{6}}\beta\sqrt{S_t m^*} \geq 0$

$$S_n = 2E^*\sqrt{R^*\delta_n}$$

$$S_t = 8G^*\sqrt{R^*\delta_n}$$

$$\beta = \frac{\ln(e)}{\sqrt{ln^2(e) + \pi^2}}$$

$$\frac{1}{E^*} = \frac{1-\nu_1{}^2}{E_1} + \frac{1-\nu_2{}^2}{E_2}$$

$$\frac{1}{G^*} = \frac{2(2-\nu_1)(1+\nu_1)}{E_1} + \frac{2(2-\nu_2)(1+\nu_2)}{E_2}$$

$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{m^*} = \frac{1}{m_1} + \frac{1}{m_2}$$

G = Shear Modulus

The subscripts 1 and 2 in above definition refer to the two contacting particles.

Specifically, we model the flow of a fixed volume of binary granular mixture (composed of spheres) down a chute with semi-circular cross-section. The only external force in the simulation is gravity. The chute shown in Fig. 3 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 100 g/s mass-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 I. The flow of particles in the chute inclined at different angles to the horizontal axis (from 15◦ to 60◦) are observed. The simulation. From the number of different size particles exited from the chute at a particular time, the solid fraction and segregation is calculated.

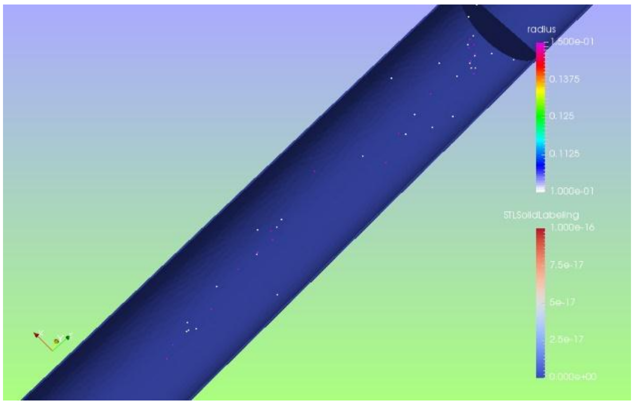

Figure 3. Flow of particles in an inclined chute.

A. *Average Velocity*

The average velocity of particles present in the whole chute are shown in Fig. 4 for different inclination of chute with respect to time. It can be observed that the velocities increase with time for all four inclinations, with greater acceleration at higher inclinations. It is noted that for the larger inclinations (30° to 60°), the particles have completely left the chute after 1.5s, and hence there is no data point beyond then. Average velocity of particles in different direction is individually studied in Figs. 5-7. The velocity in x-direction (cross-stream) and y-direction (normal to chute direction) in Fig. 5-6 is small compared to the overall velocity (from Fig. 4) and the particles do not move in a particular direction, which shows that there is no bulk cross-stream motion as expected. The average velocity in z-direction i.e. in the direction of flow is shown in Fig. 7. It is observed that the velocity increases as inclination increases.

TABLE I. MATERIAL PROPERTIES OF PARTICLES

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

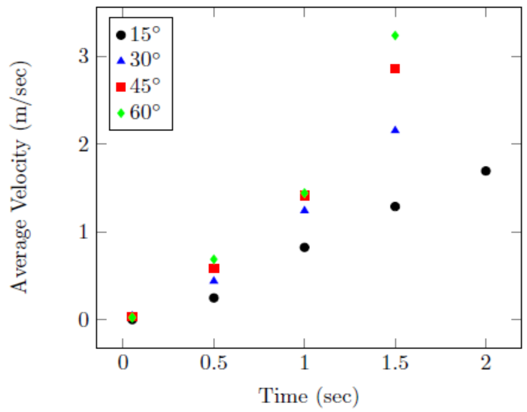

Figure 4. Average velocity of particles in inclined chute over time for different inclination angles

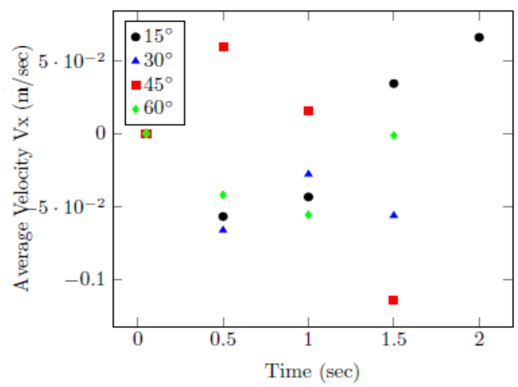

Figure 5. Average velocity of particles in x-direction in an inclined chute

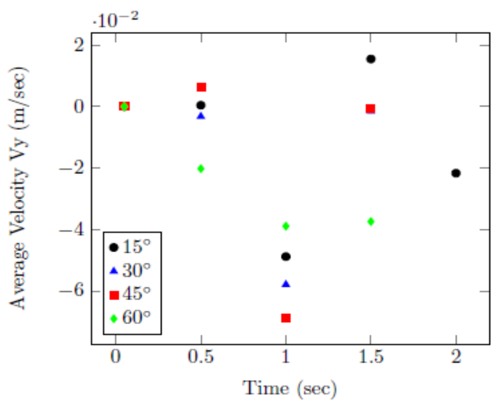

Figure 6. Average velocity of particles in y-direction in an inclined chute

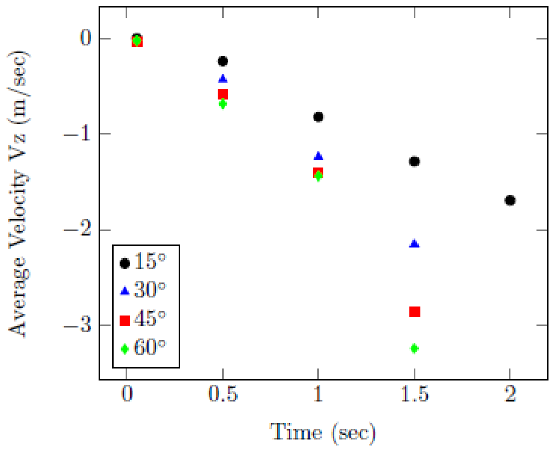

Figure 7. Average velocity of particles in z-direction in an inclined chute

B. *Average Velocity of Each Species*

The average velocity of different size particles in different direction is shown in Fig.8-10 at different chute angles. The velocity of larger particles in cross stream direction in Fig.8 is found to be more than the smaller particles. The velocity of larger particles in y-direction in Fig.9 is found to be more than the smaller particles and it increases with chute inclination. The larger particle velocity is more than the smaller one in direction of flow. From Fig.10, it can be concluded that 3mm particles exited the chute faster than 2mm particles.

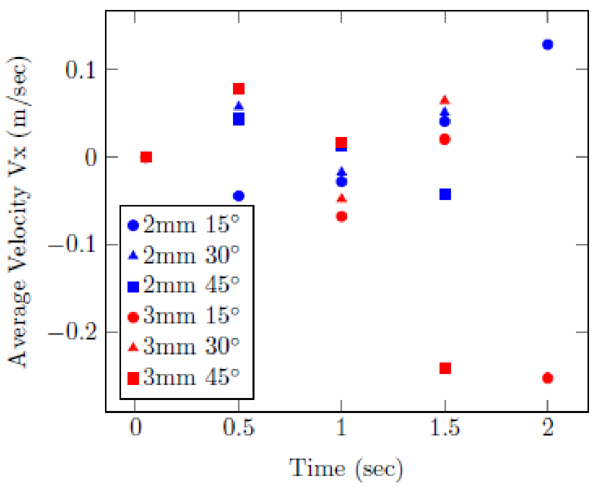

Figure 8. Average velocity of different particles in x-direction in an inclined chute

C. *Volume Fraction*

The relative solid volume fraction of small (2mm diameter) particles is given by

$$\phi_1 = \frac{N_1 \times V_1}{N_1 \times V_1 + N_2 \times V_2} \qquad (3)$$

and for the larger (3mm diameter) particles it is

$$\phi_2 = 1 - \phi_1 \qquad (4)$$

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. Using this definition, a ϕ_2 value of '0' would indicate that the sample only contains small particles; conversely, a value of '1' would indicate that the sample only contains large particles. The volume fraction for large particles ϕ_2 exiting from chute at different time interval is plotted in Fig.11. This gives us an indication of the respective exit flow-rate of each species in the mixture.

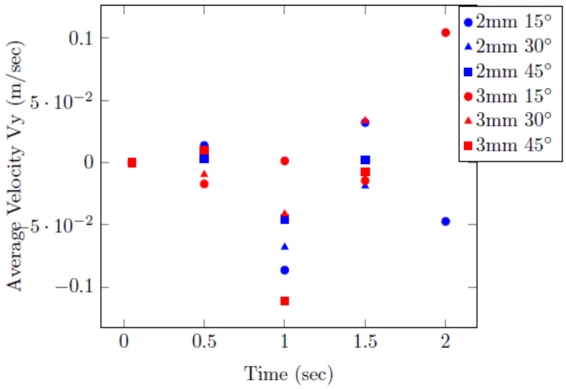

Figure 9. Average velocity of different particles in y-direction in an inclined chute

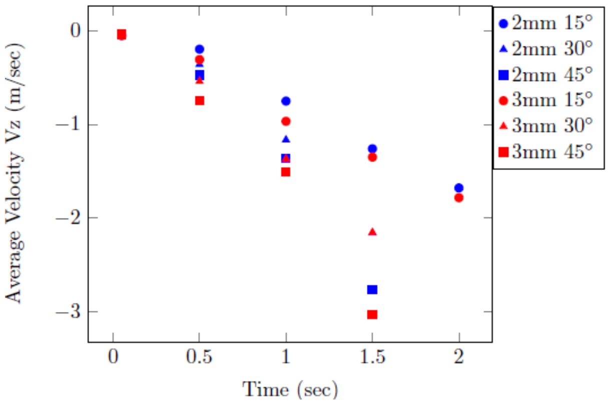

Figure 10. Average velocity of different particles in particles in x-direction in an inclined chute

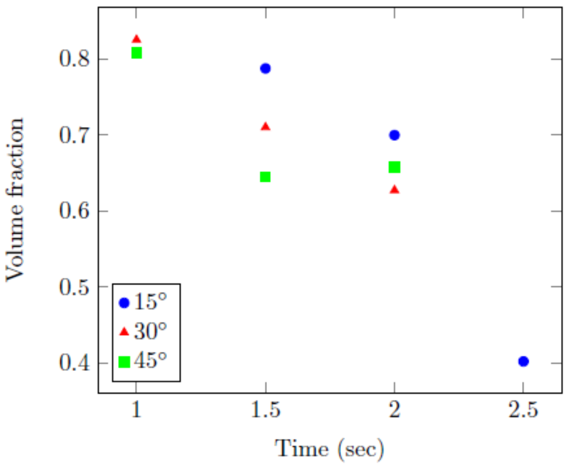

Figure 11. Volume fraction of larger particles in an inclined chute

D. Segregation Factor

The segregation intensity of each species shown in Fig.12 can be calculated from the standard deviation which quantifies the extent of mixing. From numerical results, the segregation intensity for each species is given by

$$S = \sqrt{\frac{\sum_{i=1}^{n}(\phi_i - \bar{\phi}_i)^2}{n}} \quad (5)$$

where n is the total number of samples; $\phi_i$is the volume fraction of particles in particular time step i exited; $\bar{\phi}_i$is global (or initial) relative solid volume fraction (=0.3 for 2mm and 0.7 for 3mm).

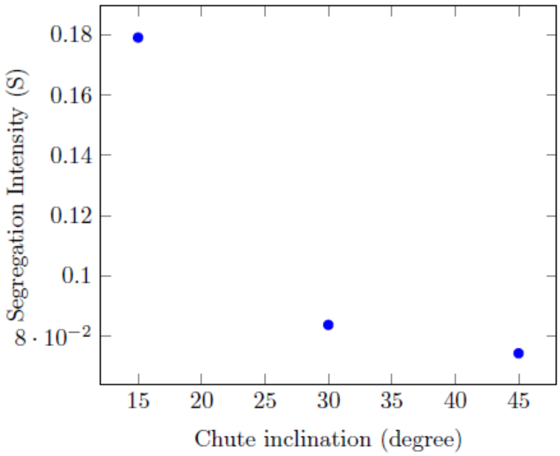

Figure 12. Segregation Intensity of particles in an inclined chute

IV. Conclusion

In this paper, we investigated the effect of the inclination angle on segregation. Specifically, we modelled a binary granular mixture of small volume traveling down a semi-circular chute at different inclination angles under gravity. From the experiment, it is found that the segregation intensity increases with increase in chute inclination. From our simulations, we observed that: the average velocity in cross-stream and normal to chute is negligible. With increase in inclination, the average velocity in chute flow direction increases. The segregation intensity calculated over time from numerical simulation is found to decrease with increase in inclination angles. It must be noted however, that this is a preliminary work, a more detailed investigation will follow, on more inclination angles with a higher volume of particles.

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