**In this section of *Resonance*, we invite readers to pose questions likely to be raised in a classroom situation. We may suggest strategies for dealing with them, or invite responses, or both. "Classroom" is equally a forum for raising broader issues and sharing personal experiences and viewpoints on matters related to teaching and learning science.**

# Segregation of Granular Material in Two and Three-Dimensional Units

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**Segregation of particulate materials in mixtures is controlled by differences in density, shape, and size. Experiments on segregation were performed in two and three-dimensional demonstration units. The results conclusively indicated that the segregation of solids is affected by the shape, size and density of granular particles.**

## 1. Introduction

Granular materials are ubiquitous in nature and are encountered in several industrial processes such as biotechnological processes, processing of agro-products, chemicals, detergents, food, pharmaceuticals, cosmetics, paints, plastics, mineral beneficiation, metallurgical operations, power generation through coal combustion, etc. Two-third of the industrial products use granular materials in the form of crystalline solids, flakes, powders, dispersions, pastes, etc., at one stage or the other. Their impact on industrial economy is enormous. For example, the impact of particulate products on US economy is estimated to be equivalent to 1 trillion USD (Rs 65 lakh crore) [1]. Operations like stirring, shaking and vibrating, often used for mixing two or more materials, result in size segregation of mixture of free flowing particulates of different sizes. Similarly, when a steel ball or disc is placed at the bottom of a

**Keywords**
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container filled with sand and the container is vibrated in the vertical plane, the steel ball or disc rises to the surface of the sand bed.

The special behavior of particulate matter is often ignored or overlooked at the design stage in industries, resulting in disruption of production processes. Thus, it is necessary for all engineers concerned with handling and use of granular materials to have a clear understanding of the behavior of granular materials [2].

### 1.1 *Applications of Segregation of Granular Materials*

There are several examples of practical uses of particulate segregation in the pharmaceutical, food, chemical, ceramic and metallurgical operations [2]. In many applications, particle separation based on size or density is central to making the process profitable, the most preferable state for free flowing granular material like powders is to segregate by size and density.

Separation of minerals from gangue is a central process in the mineral processing industry. Minerals of different sizes and densities are commonly found in a dispersed state in Nature. For example, silicates in coal, heavy minerals in mineral sands, bauxite mixed with soil.

### 1.2 *Basic Concepts of Segregation*

When the average energy of the individual particle is low and the particles are fairly stationary relative to each other, the granular materials behave like a solid. The particulate systems handled in industries usually consist of heterogenous components and their physical properties such as size, density, shape, and surface roughness vary over a wide range. *Figure* 1 shows the arrangement of the granular particle in a 2D lattice. When the motion of individual particles differ, segregation occurs according to their characteristic size, shape, composition, etc. Grains of rice and wheat, seeds, coal, sugar, sand and fine powders used in the pharmaceutical industry, all tend to segregate. Common methods used to separate minerals from gangue using vibrating screens, mechanical classifiers and hydrocyclone classifiers, all take advantage of segregation properties. The flow of a granular

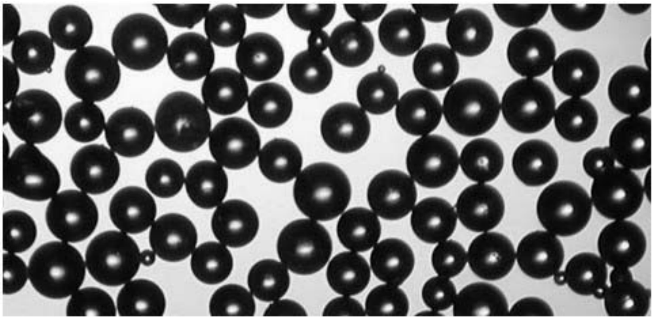

**Figure 1.** Arrangement of granular material in a 2D lattice.

material is dependent on physical properties such as the angle of repose and the bulk density. Hence the granular flow quite often results in the segregation of the constituent granular material.

### 1.3 *Mechanism of Segregation of Granular Materials*

Depending upon the physical characteristics and flow conditions, segregation of granular materials can be classified as trajectory segregation, percolation segregation, elutriation segregation and segregation due to shaking or vibration of particles [1].

**Trajectory segregation:** Due to inertia, particles of smaller diameter tend to fall away from the larger particles of the granular mixture falling from a container or a conveyor belt. This type of segregation is also observed when a gas stream is used to carry away the granular mixture (*Figure* 2a).

**Percolation segregation:** Percolation of fine particles might be caused by generation of shear forces through forced rotation of particles in a drum. The rearrangement of particles occur due to continuous movement of individual particles, when a moving mass of particles get interrupted. The particles suffer a free fall because of creation of a void, whereas some of the particles at different locations tend to move upwards. However, it becomes easier for smaller particles to fall down in case the powder consists of particles of different sizes and this leads to segregation. A significant segregation is likely to occur even with a very small difference in size. During the process of stirring, shaking and vibration, segregation mediated by percolation of particles of small

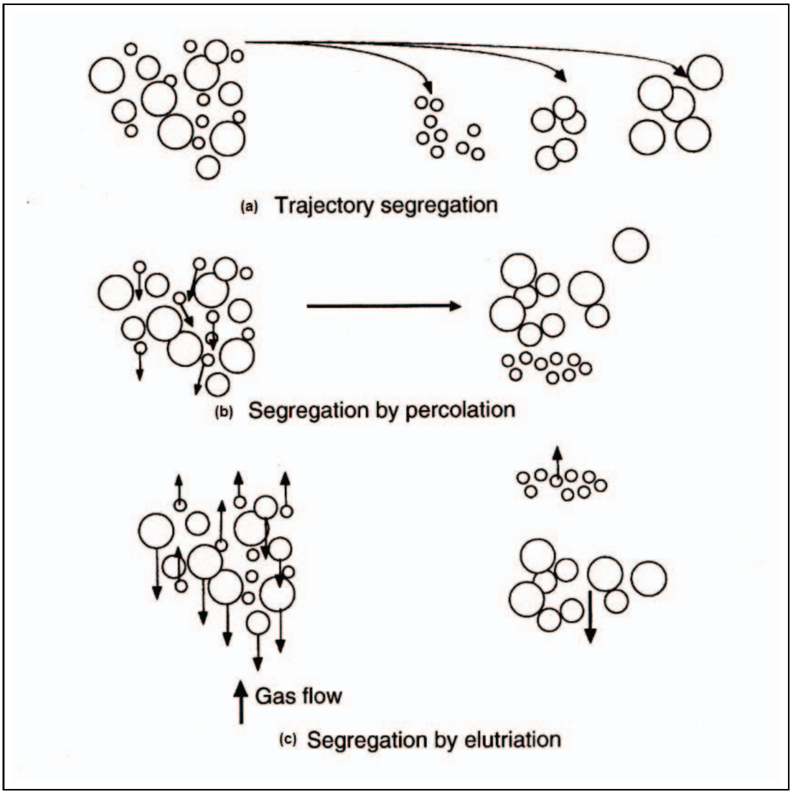


**Figure 2.** Mechanism of segregation: (**a**) Trajectory segregation (**b**) Percolation segregation (**c**) Segregation by elutriation shaking and vibrating (Ref: Rhodes, 2008).

size takes place (*Figure* 2b).

**Elutriation segregation:** Air is displaced in upward direction when large number of particles of size less that 50 mm are present in a powder loaded into a storage vessel or hopper in such a way that some of the finer particles achieve higher terminal free fall velocity and continue to remain in suspended sate even though they get settled in the hopper. This results in achieving the terminal velocity of the order of few cm/s. The particles get elevated as a function square of the diameter of the particle. For e.g., terminal velocity of 7 cm/s may be obtained with 30 mm particle size (*Figure* 2c).

**Segregation of coarse particles on vibration:** It has been observed that larger particles undergo circulation akin to convection process of fluids when a mixture of particles with different diameters is subjected to vibration. Thus larger particles reach the surface of the granular mixture; the phenomenon is commonly known as 'Brazil nut effect'. This can be easily observed when a large ball (steel ball, pebble) is placed at the bottom of a sand bed in a beaker. The steel ball moves upward and reaches the surface when the beaker is shaken up and down [3]. Spector [4] conducted several experiments to observe the influence of a particle's size range, and density on segregation and proposed the model, as shown in (1).

$$\frac{d_1}{d_s} = \left(\frac{\rho_1}{\rho_s}\right)^{-1} , \tag{1}$$

where, $d_1$ and $d_s$ are the size of granular particles and the sphere, and $\rho_1$, $\rho_s$ are the density of granular particles and the sphere, respectively. It can be seen that if the diameter ratio - $(d_1/d_s)$ is smaller than the inverse of the density ratio - $(\rho_1/\rho_s)^{-1}$, the particle mixture would exhibit Brazil nut effect. But if the diameter ratio is larger than the inverse of the density ratio, the particle mixture would show the reverse Brazil nut effect [4].

Simple demonstration set-ups and their results are presented here in support of the physical concepts of segregation described above.

## 2. Demonstration Experiments

### 2.1 *Materials*

Pulses (black moong and yellow arhar dal grains), puffed rice, plastic disc, white peas, dice, steel ball and glass ball were used as different particulate solids.The average size of the moong grain was around 2–4 mm, arhar dal grain was 3–5 mm and that of puffed rice was 13 × 4 mm. *Table* 1 presents the densities of

| Material | Density ($g/cm^3$) | Material | Density ($g/cm^3$) |
|---|---|---|---|
| Puffed Rice | 0.09 | Metal ball | 7.07 |
| Moong grains | 1.98 | Glass ball | 2.34 |
| Arhar grains | 0.84 | Disc | 0.76 |
| White peas | 0.63 | Disc | 1.13 |

**Table 1.** Densities of various particulate materials used in the present work.

various materials used in the present work and *Figure* 3 shows the photographs of grains and large solid objects used in the present work.

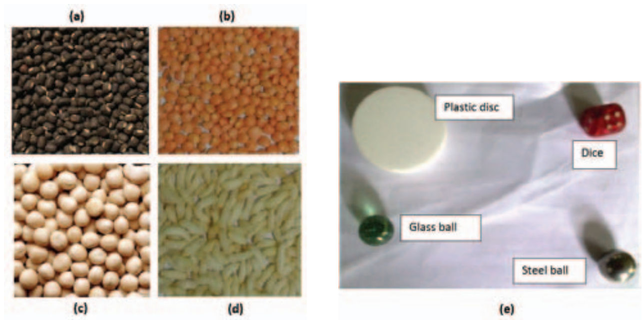


**Figure 3.** Photographs of granular materials used. (**a**) Moong grains (**b**) Arhar grains (**c**) White peas (**d**) Puffed rice (**e**) Large solid particles (dice, glass ball, steel ball and plastic disc).

## 2.2 *Experimental Set-up*

Any one type of grain can be used for this experiment. In the present experiment moong dal, arhar dal and rice grains were used as particulate matter. A 2D vessel made up of perspex sheet (thickness = 5 mm) was used. The length of the unit was 20 cm and width was 15 cm. The gap between the front and back walls were 25 mm. The 3D unit used was made of perspex sheet with an outer diameter of 6 cm and length 55cm. The units were mounted on a rigid rubberized base. The details of the demonstration set-ups are shown in (*Figure* 4–5).

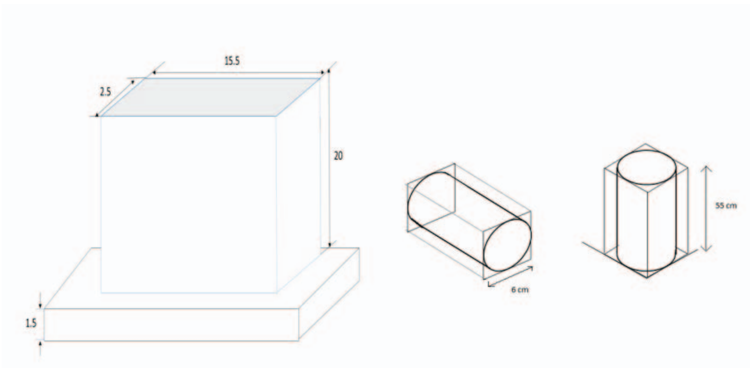


**Figure 4.** Engineering drawing of 2D and 3D experimental set-ups (isometric views; all dimensions are in centimeters).

**Figure 5.** 2D and 3D units.

## 2.3 *Procedure*

**Segregation of particulate matter in a 2D vessel:** A large plastic disc (diameter = 41 mm) was placed at the bottom of the 2D unit which was then filled alternatively with known amount of black moong dal grains and yellow arhar dal grains to form a layered structure with good visibility. The unit was then vibrated (amplitude 9 cm and frequency 2 vibrations per second) vertically. The movement of the plastic disc was observed and recorded as shown in *Figure* 6 (a–e). It is seen that the disc first moves to the top and then starts moving back to the bottom. The alternate layers of the two pulses disappear and a less homogeneous mixture is obtained at the end. The size and density of the pulses are nearly similar, hence mixing of pulses took place. The plastic disc, on the other hand, is much larger in size and has a density of 1.138 g/cm$^3$.

To re-verify the movement of pulses, the plastic disc was removed and black moong dal was vibrated with white peas in the 2D unit (amplitude 9 cm and frequency 2 vibrations per second) vertically. The size and density of white peas and black moong dal are significantly different hence mixing of white peas and moong

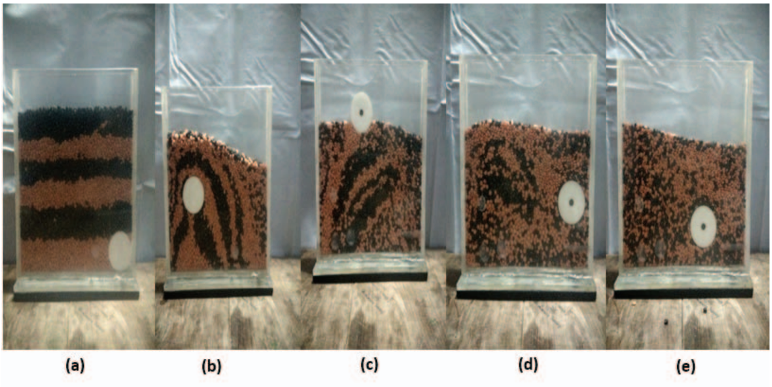


**Figure 6.** 2D unit for showing segregation (**a**) at time t = 0s (**b**) at time t = 14s (**c**) at time t = 20s (**d**) at time t = 30s (**e**) at time t = 50s.

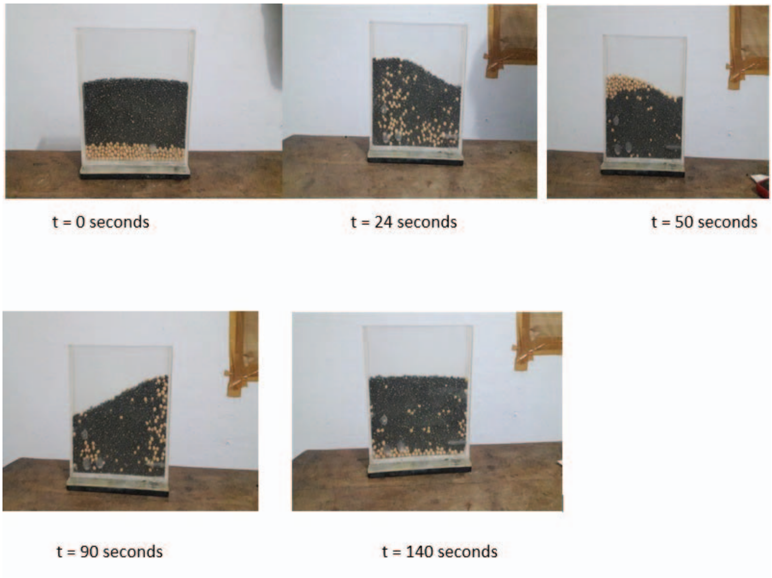


**Figure 7.** 2D unit for showing segregation (**a**) at time t = 0s (**b**) at time t = 24s (**c**) at time t = 50s (**d**) at time t = 90s (**e**) at time t = 140s.

dal did not take place. It is evident from *Figure* 7 (a–e) that white peas reached the top and then moved back to the bottom of the 2D unit.

*Figure* 6 (a–e) and *Figure* 7 (a–e) shows the suitability of a simple 2D device for demonstrating circulation of grains. From the above observations, it is evident that when large sized particles, whose density is different from the granular material is vibrated in a 2D vessel, then larger sized particles show circulation of grains.

**Segregation of particulate matter in a 3D vessel:** A large plastic dice (diameter = 16 mm) was placed at the bottom of the 3D unit which was then filled with known amount of puffed rice. The unit was then vibrated (amplitude 10 cm and frequency 3 vibrations per second) vertically. The movement of the plastic dice was observed and recorded as shown in *Figure* 8 (a–c).

It is seen that the dice moves to the top and then remains on the top after several vibrations. Since the sizes and densities of puffed rice and dice are appreciably different hence only Brazil nut effect has been observed. This is also in accordance with the model given by Spector [4].

The same experiment was performed with a metallic ball having a diameter of 16 mm and density $7.07\,\mathrm{g/cm^3}$ and a glass ball having diameter of 15.9 mm and density $2.34\,\mathrm{g/cm^3}$. Frequency, amplitude and time taken for the balls to reach the top of the cylinder were noted down. *Table* 2 presents the comparative analysis of time required by the dice, the glass ball and the metal ball to reach the top at a fixed amplitude and frequency.

It has been observed that as the density difference increases, no reverse Brazil nut effect is seen. This experiment demonstrates the segregation of particulate matter in a 3D vessel. The time taken by a small metallic ball is less as compared to a larger metallic ball, which shows that size is an important factor in the process of segregation [5].

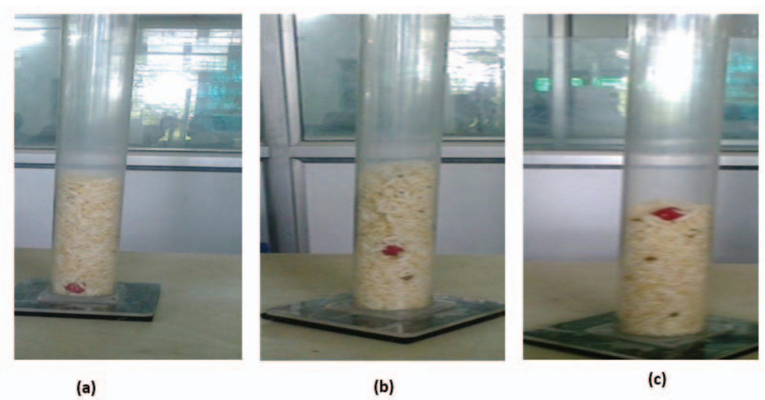


**Figure 8.** 3D unit for showing segregation 3D unit (**a**) at time t = 0s (**b**) at time t = 20s and (**c**) at time t = 50s.

**Table 2.** Time required by dice, glass and metal ball to achieve top position

| Material | Time (sec.) | Amplitude (cm) | Frequency (vibration per sec.) |
|---|---|---|---|
| Dice | 50 | 10 | 3 |
| Glass ball | 27 | 10 | 3 |
| Metal ball | 7 | 10 | 3 |

## 3. Conclusion

Using simple experimental set-ups it has been shown that in the process of segregation, apart from the size of the particles, density difference plays a more significant role compared to the shape of the particles. In case of 2D vessels, only circulation of grains was observed. However, in case of 3D cylindrical units, as the density difference between particles increased, no reverse Brazil nut effect was seen.

## 4. Acknowledgements

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## Suggested Reading

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