Axial segregation in 3D rotating drums with spherical particles: Experiments

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Abstract. Despite the wide research of powder and solid mixing in science and industry, a majority of researches focus on numerical simulation. Theory on the actual mixing of solid particles in 3D rotary drums is needed. In this work, the axial segregation of binary spherical granular particle is studied experimentally in a 3D tumbler to find the effect of key outer parameters on the mixing results. Experiment results indicate the outer parameter-rotational speed will have significant effect on axial segregation and there is some kind of competition between axial segregation and radial segregation. In addition, The initial loading method has noting to do with axial segregation. These results will provide guidance for particle mixing in cylinder mixer.

1. Introduction
Granular materials are macroscopic systems composed of a large number of discrete solid particles larger than one micron in size, and are the second largest raw materials on earth[1]. In agriculture, ceramics, pharmaceutical, civil construction and many other industrial processes occupy an important position. The annual production of particulate matter in the world exceeds one trillion kilo, and particulate matter plays an important role in the development of national economy [2]. For macroscopic granular matter, classical mechanics can be used to describe the motion state of individual particles in seconds. However, the system consisting of a large number of particles will have some special properties and motion laws. For example, they can remain stationary like a solid or flow like a fluid, depending on external conditions. Their motion will also trigger random flows of constituent particles, such as molecular diffusion. More interestingly, a mixture of two different particles can separate itself as it moves due to differences in size or density [3]. The dynamic behavior of granular material is very complicated due to its sensitivity to external action, nonlinear response and self-organization behavior.

Rotating tumblers have been widely used in solid particle mixing due to its unique advantages,
including simple structure and high mass transfer efficiency[4]. The application of particulate matter requires it to reach the corresponding mixing state, but on account of the unique characteristics of particle system, segregation phenomenon will occur in the mixing process. There are two kinds of segregation phenomena, one is radial segregation, the other is axial segregation. Segregation is influenced by particle properties and equipment. Both radial segregation and axial segregation in rotary drums occur, for example, when particles differ in density, frictional properties or size and the equipment has different diameter and length. However, axial segregation is rarely studied because of its complexity.

Axial segregation is a meta-stable sluggish segregation phenomenon which consists in the separation of particles system in bands approximately perpendicular to the axis, it is initiated on the end walls[5]. Maiione (2017) stated that granular particles differ in shape will form axial segregation in mixing process and the DEM can reproduce the experimental results[6]. Recently, some work reported the formation of a streak pattern in a mixture of spherical and non-spherical particles in rotating tumblers. At present, most studies mainly use numerical simulation method to study the effect of particle properties on segregation, but there are few experimental studies on particle mixing.

Maiione et al. made use of a binary mixture system consisting of small wood rods and steel balls, and the experiment showed that the shape of the material would also have an important influence on axial segregation. The experimental results show that the small wooden strips are mainly distributed in the axial endwall, while the steel balls are mainly concentrated in the inner region of the cylinder. In this work, we use a 3D rotating drum to study the effects of operating parameters on binary granular.

2. Experimental setup

![Fig. 1. Experimental apparatus, rotating drum, ccd camera, electric motor](image)

Fig. 1. shows the relevant experimental setup used in this experiment. This rotating drum made of transparant plexiglass for the sake of observe the mixing process. It has a diameter of 20cm and a length of 80cm. There are two CCD high-speed cameras to keep a record of the particle mixing process. The rotating drum is connected to an electric motor which can accurately adjust its rotating speed by a speed adjusting device. The electric motor can provide a precise rotating speed in the range
of [4rpm, 100 rpm]. Two types of particles with different size and same shape were used in the experiments: larger glass ball and glass sand. Table 1 gives the relevant properties of the particles.

| Property       | larger | smaller |
|----------------|--------|---------|
| Diameter(mm)   | 5      | 1       |
| Density(kg/m³) | 2500   | 2500    |

3. Results and discussion

3.1 Reroducing the axial segregation

It is noted that in previous reports on the mixing of spherical particles, the mixing process of larger particles is mainly studied, while the mixing process of smaller particles (Millimeter-scale particles) is rarely studied. In addition, mixing can be also affected by the parameters of the rotating cylinder, and a longer cylinder was used in this experiment. Therefore, a typical mixing experiment is conducted and the parameters are presented in Table 2.

Figure 2. show the axial view of the granular material bed for a filling degree of 30% after 30 rotations at the speed of 10 rpm. Compared with the previous experimental results, it is found that there are several alternating segregation bands of large and small particles along the axial direction. Large particles gather on the side walls of the cylinder and alternate with bands of smaller particles. In addition, radial segregation usually occurs in a two-dimensional cylinder with small length, but the experimental results show that there is no inner core of smaller particles in the bed of the three-dimensional cylinder after the mixing reaches stability, indicating that radial segregation disappears. The effect of rotating speed, filling degree, particle mass ratio and initial loading method on segregation were investigated.

| Property   | value |
|------------|-------|
| Drum diameter(cm) | 20    |
| Drum length(cm)   | 80    |
| Filling level(%)  | 30    |
| Rotational speed(rpm) | 20    |
| Mass ratio       | 1:1   |
| Total mass(Kg)   | 12.2  |

Figure 2. Photographs of the granular materials after 30 rotations. The dark areas are belts of smaller particles and the bright is the areas of larger particles.
3.2 Different rotational speed, experimental results

On the basis of the above typical experiment, the effect of rotational speed on particle mixing was investigated. Table 3 shows the corresponding parameters.

| Experiment number | Velocity (rpm) | Loading method | Fill level | Mass ratio |
|-------------------|----------------|----------------|------------|------------|
| A                 | 4              | top-bottom     | 30%        | 1:1        |
| B                 | 10             | top-bottom     | 30%        | 1:1        |
| C                 | 20             | top-bottom     | 30%        | 1:1        |
| D                 | 30             | top-bottom     | 30%        | 1:1        |
| E                 | 40             | top-bottom     | 30%        | 1:1        |

(A) 30 rotations

Axial view

Radial view

Figure 3. The image of axial and radial granular bed
Fig. 3. shows the image of the particle mixing after 30 revolutions at different rotational speeds. At lower speeds (below 10rpm), there are only small particle segregation bands on both sides of the endwall. At the same time, there will be obvious inner core in the radial position. When the rotational speed exceeds 20rpm, the axial segregation bands of small particles also appear in the middle position of the rotating drum. There is no doubt that the radial inner core will disapper. It can be seen that with the increase of rotational speed, there will be a transition from radial segregation to axial segregation.

4. Conclusion

In this paper, the effects of different rotating speed on the mixing process of different sizes of binary spherical particle system were studied by three-dimensional cylinder particle mixing experiment. The following conclusions can be drawn:

(1) When particles are mixed in a 3D cylinder, both radial and axial segregation will occur. Rotational speed will affect axial segregation. The higher the rotational speed, the lower the filling rate, and the higher the proportion of small particles, the greater the axial segregation.

(2) Radial segregation is stronger in a two-dimensional cylinder. In 3D drums, when started to mix, particles near the end-wall move away from the end-wall at the upper part of the flow layer. Then, particles will return at the bottom part of the flow layer in order to keep mass balance. However, smaller particles which pass through the gaps between the larger particles, fall into the interior of the liquid layer. This phenomenon results in the relative axial motion of smaller particles. Then the axial segregation occurs.

This work has fully studied the mixing of spherical particles under different rotational speed and its influence on the mixing effect, which provides important guidance for the design of cylindrical mixer and the selection of particle mixing conditions. Due to the limited experimental conditions, it is impossible to investigate the mechanism of axial segregation during particle mixing. In future studies, the axial segregation can be studied by changing the initial loading methods, filling level of particles in the experiment. Alternatively, it can be studied by numerical simulation under corresponding conditions to study the mechanism of axial and radial segregation.

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