Density segregation of granular material in a rotating cylindrical tumbler

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ABSTRACT

Many mining operations use large quantities of water to separate valuable minerals from less valuable gangue. This dependence on liquid separation has an environmental impact in terms of energy and water use and also implies a cap on production due to the availability of water. To address these problems, the CSIRO has developed the CSIRO Rotational Classifier, which – by using the phenomena of rotational segregation - can quickly separate dry granular material in terms of size and/or density without the use of any liquids.

The purpose of this paper is to obtain a deeper understanding of how rotational segregation can separate particles of different densities in a rotating cylinder, free from any interstitial fluids. This was accomplished by analyzing a cross section at the 20% fill level in a 50% full classifier, which contained a 50-50 ratio of glass and lead beads. The granular bed was sampled at different time intervals over a 60 second period with a classifier rotation rate of 2 rpm. These experiments resulted in a high segregation level of 0.9 in 20 seconds and 0.95 by 60 seconds (where a level of 1 implies full segregation). The results then underwent image analysis and were subsequently compared to results from a discrete element method (DEM) model where similar segregation ratios, albeit at longer timescales, were obtained. This study gave a further insight into the segregation process particularly in terms of axial formation of the segregated core which may one day be used in the separation of minerals.

Keywords: Granular Materials, Density Segregation, Discrete Element Model, Rotational Classification

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1. INTRODUCTION

In many industrial applications, efficient particle separation in terms of size and/or density is central in making the process profitable. Separation of different materials is a common practice in mineral mining applications. Current separation processes can have detrimental environmental implications ranging from energy usage with resulting greenhouse gas production through to using increasingly scarce water resources [1]. With environmental concerns ever increasing, the need to come up with more environmentally friendly ways of material separation is paramount.

Minerals of different size and density in nature are commonly found in a dispersed state, for example, silicates in coal, heavy minerals in minerals sands, bauxite mixed with soil. Certain grade qualities are then required so that the end product meets a desired specification. As such, the separation of the minerals from the gangue is a central process in the minerals processing industry. Common methods that industry uses to separate mineral from gangue are, for example, vibrating screens, mechanical classifiers and hydro-cyclone classifiers [2].
Vibrating Screens (Fig. 1a) work by having a flat porous bed which vibrates, where the finer particles fall through the apertures whilst retaining the larger particles. Separation of dry materials can be attempted down to 75\mu m. Finer particles may cause blinding of the sieve. One way to help sieving is to use water to wash the screen, although fine particles may still cause problems. A way to get around this is by using classifiers. There are 2 main kinds of classification processes used; these are mechanical and hydro classification [2].

Mechanical classifiers such as a spiral classifier (Fig. 1b) operate with an inflow of slurry which is fed half way along the length of the settling tank. In some spiral classifiers, the tank has a slope of approximately 15°. The solids then settle on the bottom of the tank which is conveyed away with a screw thread, while the water and finer particles are washed into an overflow and dispatched. A common problem with this method is that the spirals impede the downward slurry movement which can result in some build up [2].

Hydro-cyclones (Fig. 1c) work by feeding the slurry in to a conical shape cylinder. Tangential feeding of the slurry into the device produces a vortex, which results in the heavy particles flowing around the outside and falling down while the lighter particles flow closer to the middle and get caught in the vortex and flow out the top [2].

A common characteristic of all these methods is the use of an interstitial fluid to separate granular materials of different size and density. Such a requirement may lead to difficulties in more arid areas where the availability of water is an issue. Alternatively, it may turn out that water is not dense enough to separate the materials efficiently, in which case chemicals are often used to enhance the separation process. The addition of processing chemicals, for this and other reasons, may lead to problems when the waste material is sent to tailings dams or when the effluent has to be treated before it can be released to the environment. Such storage and processing adds additional costs to the processing system, costs that may be avoided if an interstitial fluid is not required in the first place. One potential method for obtaining efficient separation of dry granular materials is to use the phenomenon of rotational segregation, which we shall discuss in the next section.
2. ROTATIONAL SEGREGATION

Suppose that we place granular material in a cylinder, where the central axis of the cylinder is approximately horizontal. A characteristic criterion for the motion of solids in the cylinder is given by the Froude number, \( Fr \), which is the ratio of angular acceleration to gravitational acceleration:

\[
Fr = \frac{L\omega^2}{g},
\]

with \( \omega \) being the angular velocity, \( L \) is a characteristic length scale, e.g., the radius of the cylinder, and \( g \) is gravitational acceleration. This dimensionless number enables a classification of the flow conditions of the particles, over a range of different classifier parameters (e.g. radius and angular velocity).

![Diagram of rolling regimes](image)

Fig. 2: A schematic depiction of four different rolling regimes, where the Froude number increases from left to right [3].

In Fig. 2 we show a schematic depiction of the different rolling regimes as a function of the Froude number [3], where, in this case, the relevant length scale, \( L \), is the half length of the free surface. In semi-quantitative terms, these rolling regimes are:

- **Avalanching**: \((0 < Fr \leq 10^{-3})\) when a thin layer of particles shear, whilst the rest is in solid rotation.
- **Rolling/Cascading**: \((10^{-4} < Fr \leq 10^{-2})\) at higher speeds, material rotates with the cylinder as a solid body until it reaches its dynamic angle of repose \( \beta \) and a steady flow is obtained with a thin cascading layer at the free surface of the rotating bed.
- **Cataracting**: \((10^{-2} < Fr < 1)\) at still higher speeds, inertial effects cause the particles to become airborne.
- **Centrifuging**: \((Fr > 1)\) the particles are forced against the wall of the rotating cylinder.

It is observed that, for the rolling regime, the granular material often segregates in terms of size and/or density. For material of the same density, the smaller particles go to the centre of the granular bed, and the larger particles go to the outside. Similarly, for particles of approximately the same size, denser material goes to the centre of the granular bed, while less dense material moves to the outer regions of the granular bed. In Fig. 3, we show a schematic representation of this segregation. This segregation has the nearly unique capability of size or density separation without using any form of fluid.
Fig. 3: (a) Size segregation produced by rotational motion, where the granular material has approximately the same density. (b) Density segregation also occurs when the material has approximately the same size, but different densities.

The CSIRO has developed a fully automated device that uses this segregation behaviour to separate granular material (Fig. 4). This device, known as the CSIRO Rotational Classifier is currently undergoing commercialization trials with the minerals equipment manufacturer RCR Tomlinson. In this study, we wish to determine the degree of separation that occurs within the granular bed.
3. EXPERIMENTAL AND DEM RESULTS

3.1 Equipment

The classifier used in this study is shown in Fig. 5. This classifier was constructed out of mild steel with an inside diameter of 110 mm and a length of 100 mm; it was designed so it would separate at a fill level of 20%. The circular part of the classifier was lined with an abrasive sanding paper with a grit size of 36. This lining was used to stop the granular bed from slipping in the classifier during rotation. The front of the classifier was covered with Perspex. Jacking screws were used so that the top of the classifier could be removed with as little disruption to the bed as possible.

![Fig. 5: The Classifier used in the experiments](image1)

The classifier was mounted to a test rig shown in Fig. 6. The test rig consisted of a variable speed motor which had a key on the shaft to lock the classifier into place. The variable speed motor was controlled by a control panel that could adjust the rotational speed and the direction of rotation. The lines on the backing plate were used to line up the classifier’s starting and finishing positions, as well as a guide to setting the rotational speed of the classifier.

![Fig. 6: Test rig used to conduct the experiments](image2)
Other equipment needed in the experiment were: a stop watch to measure the rotation time as well as to calculate the rotational speed of the classifier, a freezer capable of -50°C which was used to freeze the samples, and a bottle with a plastic hose that was used to insert water into the classifier.

3.2 Procedure

For these experiments, glass and lead beads of 2 mm diameter were placed in equal volumetric quantities into the classifier until the classifier was 50% full. This was done to ensure no particle dominated the segregation process and the fill ratio was chosen so that the observed segregation would be consistent with experimental results that are available from the literature [4]. Equal volumes (237 ml) of both glass and lead beads were placed into the classifier, where the beads were randomly mixed by hand. The degree of initial mixing was evaluated in a semi-quantitative manner, where it was determined that there were no groups of one particular type of particle larger than approximately 10 particles. Other procedures could have been used to obtain a, possibly, more constant starting point, but, due to significant time constraints, implementing more complex mixing procedures were not practical.

The classifier was then placed on the test rig (Fig. 6), the test rig was set to a predetermined angular rotation frequency of 2 rpm and spun clockwise for periods of 5, 10, 20, 30, 40 and 60 seconds. Rotation of the classifier always finished with the split of the classifier and the angle of repose being parallel to one another - to ensure the sample would cut through at the 20% level of the classifier when it was placed on a flat, horizontal surface.

After the experiment was completed, the sample was removed from the test rig and placed on a horizontal surface. A plug was removed from the Perspex window, through which the plastic hose was inserted until it rested against the side wall of the classifier (to minimize the affect of the water added on the beads). Water was then added to fill the classifier to 20%; the amount of water added was set at 53 mL. The whole classifier was then placed into a freezer for 4 hours, freezing the beads in the classifier up to the 20% fill level. The classifier was then split open and the non-frozen beads were removed to expose the core of the classified material. The results were then photographed with a digital camera at a set height on a tripod with two photography lamps on either side of the sample, this ensured that the same resolution and picture quality was achieved each time and the results were recorded.

3.3 Image Analysis

A Matlab program was written to analyse each photo. The program took the original picture, converted it into a gray scale image, where the gray scale image was converted into a binary (black for lead and white for glass) image. The image was subsequently filtered to clear parts of the photo where the pixel size was too small, e.g., at the extremities of joining beads. Next, three masks of a chosen image were created. The first mask was used to remove all parts of the image that were not required for the analysis (e.g., the classifier drum). The second mask involved isolating the segregated regions of black and white particles, while the third mask traced the segregated core isolated in the second mask. This allowed the image to be broken up into regions of black and white, which could be used to calculate how much area was occupied by lead and glass beads in each segregated region. The results of this process were then calculated to find the percentage error of where the masks overlapped. The areas of black and white particles in each mask were calculated and the results normalized by dividing through by the total area of the particle region to find the ratio of segregation.

Two calculations were carried out using the Matlab program, the first of these involved using the 60 second segregated image and transplanting it on to every other image. We then calculated the ratio of black particles in the black region (BB), the amount of white particle in the white region (WW) and the amount of intruder particles in both regions (BW black in white region, WB white in black region). This gave the segregation ratio as a function of time which allowed an assessment of the amount of segregation that had occurred.
To calculate the errors in the tracing during the creation of the masks, four trials were conducted for each analysis. The average and standard deviation were calculated. These quantities were then used to determine the 95% confidence interval to determine the range of values expected from the experiments. A part of the image analysis program which generated some analysis errors was the “im2bw” function which converted the original image to a black and white image. Trial and error was employed in finding the appropriate settings for identifying a particle correctly. Unfortunately, such programs sometimes produce errors in identifying the correct particle. To test the potential for error, the resolution number was changed by one unit on the same image. The error that was calculated between these images was found to be around ± 2%.

3.4 DEM Analysis

Due to the discrete, possibly irregular, nature of the granular medium, it is not always possible to describe a granular system via a set of continuous differential equations. As such, researchers have developed the Discrete Element Method (DEM) as a means of computationally describing the behaviour of granular materials. The DEM model uses Newton’s equations of motion (rotational and translational motion) to determine the position of the particles as a function of time. Collisions between particles are modeled via the agency of springs and dampers, which, in turn, provide values for coefficients of restitution and friction between particles. This is shown schematically in Fig. 7.

![Fig. 7: Schematic depiction of particle interaction in the DEM model.](image)

For this study, all collisions were deemed to be elastic, i.e., the coefficient of restitution was set equal to 1. The coefficient of inter-particle friction was set at 0.5, while the coefficient of friction between the particles and the cylinder walls was set to 1.5. The forces, velocity and position involved with each particle were calculated by explicit numerical integration with respect to neighbouring particles. The forces were then resolved and stored for that instant in time. The classifier was then rotated to the next time step \(10^{-3}\) seconds), while the neighbour list was updated. This process was continued until the classifier has been rotated for 60 seconds. The particles and classifier dimensions were identical to that of the experimental classifier. The DEM model calculated the segregation ratio by removing a small area of the classifier bed and individually counting every particle that is in that area. This was then averaged over the whole of the segregated region, giving the segregation ratio. The results of this were then compared against the image analysis to validate the DEM model.

4. RESULTS

Although we start the experiments with equal number of glass and lead beads, the axial and radial movement of the lead beads during the experiment produces a final result where there are relatively few lead beads at the front face of the classifier. This is illustrated in Fig. 8 which shows a front view of the classifier after 60 seconds of rotation. In Fig. 9, we
show the axial segregation within the classifier as a function of time. The rotational frequency of the classifier was set to 2 rpm and the initial state of the glass and lead beads was "well mixed". As can be seen, segregation occurs quite rapidly with significant segregation occurring by 20 seconds. The experimental results are, qualitatively, very similar to the results obtained from the DEM model, as can be seen in Fig. 10.

![Image](image_url)

**Fig. 8:** Front view of the classifier after segregation has taken place. The inward axial and radial movement of the lead (black) beads relative to the glass (grey/white) beads is apparent.

**Fig. 9:** Axial view of segregation within the rotational classifier using lead (black) beads and glass (white) beads, where the classifier was rotated with a rotational frequency of 2 rpm. The lead beads move to the centre of the bed. The granular bed was sampled at a depth of 22mm (20% of the classifier).
The segregation ratio (i.e., the proportion of lead beads in the lead bead region) obtained from the experiments is shown in Fig. 11, where it should be noted that the initial value at zero time was, accidentally, not measured, but was set to 0.5. As can be seen, the classifier becomes nearly fully segregated within twenty seconds, which, at 2 rpm, is two thirds of the rotational period of the classifier. The segregation ratio as obtained from the DEM model for three rotational frequencies (1, 2 and 4 rpm) is shown in Fig. 12. The DEM results suggest that the system becomes fully segregated after sixty seconds or two revolutions of the classifier. This discrepancy will be subject to further study.
5. CONCLUSION

This study analyzed the segregation of particles of different densities in a rotational classifier. This was done to determine the feasibility of using a dry rotational classifier in the separation of minerals in the mining industries. Dry separation technologies have a major advantage over current separation techniques which either use a large quantity of water or use chemicals, both of which can have an impact on the environment.

We examined the segregation obtained at the 20% fill level of a classifier in the axial direction. The results of this experiment show that at a rotational frequency of 2 rpm a high segregation percentage of 90 to 95% occurs in a core region after about 20 seconds. The speed and quality of this segregation would suggest that rotational classification may have some commercial potential in the mining and other relevant industries, with the caveat that differently sized particles and moisture content have not been considered. The effects of such parameters on the segregation would need to be evaluated before the technology could be used in a commercial setting.

Comparing the experimental results to those obtained from the DEM model indicated qualitative agreement between the two data sets. However, the experimental results appear to indicate faster separation relative to the DEM results. The source of this discrepancy needs to be determined before we can be fully confident that the DEM model is replicating reality in a reasonably accurate manner.

REFERENCES


