Characterization of motion modes of pseudo-two dimensional granular materials in a vertical rotating drum

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Abstract. The aim of this work is to characterize the modes of motion of pseudo-two dimensional granular materials in a vertical rotating drum. The granular materials are 4 mm diameter marbles, which are put in a flat drum with 16 cm diameter and 5 mm thickness. Rotation axis of the drum is always perpendicular to the direction of gravity. Granular materials in a vertical rotating drum usually have six modes of motion i.e. slipping, slumping, rolling, cascading, cataracting, and centrifuging. Those modes depend on number of granular particles, rotation speed, and types of materials of granular particles. Characterization of modes of motion in this work has been conducted by varying number of particles, rotation speed, and types of materials. Rotation speed is varied from 15 rpm to 125 rpm, while number of granular material is varied from 50 to 600. Each steel and plastic granular materials has five modes of motion with centrifuging mode is absence in observation of steel materials and slipping mode is absence in observation of plastic materials, both for the same parameter ranges used in the experiments. Parameters room of number of particles against rotation speed for both types of materials are presented.

1. Introduction

There are many usages of rotating drum or kiln, e.g. granular mixers, dryer, gas solid reactor, and granular segregation, since granular materials in a vertical rotary drum can be used for segregation [1] and mixing processes [2]. Segregation and mixing in rotary drum depend on mode of motion of granular particles. Generally, types of granular materials (bed) motion in rotary drum can be differentiated in six basic mode i.e. slipping, slumping, rolling, cascading, cataracting, and centrifuging [3]. Granular materials motion in these different modes is influenced by many parameters such as rotational speed of drum, granular material depth, filling degree, and kind of materials [4].

A lot of studies about modes of granular material motion in vertical rotating drum have been conducted, but they reported only the three dimensional system. The modes have been observed only through their cross-section behavior at the drum end. In this study modes of motion of pseudo-two dimension granular materials in vertical rotating drum are observed in order to characterize their dependence to number of particles, rotation speed, and types of materials. The system is referred as pseudo-two dimension since the particles are actually three dimensional but they can move freely only in two-dimension.
2. Theory

Modes of motion of granular materials in a vertically rotating drum depend on types of granular materials, rotational speed of the drum, and amount of granular materials placed in the drum. There are six reported modes, where each can be specified as [5]

1. Slipping: occurs when the bulk material, as a whole, slips against the wall;
2. Slumping: occurs when a segment of bulk material at the shear wedge becomes unstable, yields and empties down the incline;
3. Rolling: occurs when there is a steady discharge onto the bed surface causing its renewal;
4. Cascading: occurs at high rates of rotation, where the particles cascade or shower down the free surface;
5. Cataracting: occurs in between and centrifuging mode; and
6. Centrifuging: occurs at critical and high speeds, all the material rotates with the drum wall.

Illustration of these modes used as modes of operation in the transversal mixing plane of rotary kilns is given in figure 1.

![Modes of operation in a rotary kiln](image)

**Figure 1.** Different modes of operation (modes of motion) in the transversal mixing plane of rotary kilns [4].

Slipping mode occurs when less friction between granular material and drum wall [6]. When drum wall is very smooth granular material will be sliding. Slipping mode occurs when rotational speed of the drum is low and filling degree of drum is also low.

Slumping mode occurs when rotational speed increase from previous mode and amount of particle increases a little bit. In slumping mode, granular or bed particles experiences a cyclical process of avalanche and solid body motion. When the bed reaches the maximum angle of the bed inclination $\alpha$, a slum and avalanche occurs. Particles from the upper part of the bed slide rapidly down to the form of lower wedge so that the bed surface is approximately flat. The angle when avalanche occurs is $\beta$ [7].

Rolling mode occurs when granular particle alternately up and down in all particle surface (see figure 2). Particle surface in drum is flat and make an angle with horizontal direction. Particles bed in rolling mode consists of three parts, *i.e.* active layer, passive layer and boundary line [8]. The active layer is located on the top of bed surface. On this layer, particles rotate and fall into the lower part. The bed particles move parallel to the surface of the bed at a relatively high speed. Passive layer is located the bottom or near the wall and the boundary line is located between active and passive layer. Particles in this layer moves up to the same speed as the rotation speed of the drum. These particles will move to boundary lines and then get into the active layer.
With the increase of rotational speed, bed surface become curve. That curve looks like kidney. Transition of cascading also depends on particle size. In this cascading mode, there is no bed particle slip. Cascading condition prospers for transfer heat energy in high temperature process and unsure uniformity [4].

![Figure 2](image)

**Figure 2.** Rolling mode in granular motion.

![Figure 3](image)

**Figure 3.** Cataracting mode with granular filling fraction 40 % [9].

Cataracting mode occurs when many particles from the bed flung into the gas space. With incensement of the rotational speed, the number of particle thrown off and length of particle trajectories increase until a uniform trickling veil forms along diameter [6]. An example of this mode with granular filling factor 40 % is given in figure 3.

Changing from cataracting to centrifuging occurs with increase of rotational speed. Particles in outer cataracting trajectories will contact with drum wall and move together with wall. Centrifuging mode only occur in high rotational speed.

![Figure 4](image)

**Figure 4.** Characterizations of bed motion in a 0.4 m diameter rotary drum [10].

A type of graph is developed with experimental data in order to characterize the modes of operation depending on operating parameters and geometry aspects of rotary drum [3]. For the studied kiln the Froude number $Fr$ is in the order of $10^{-4}$. Froude number value is influence by rotational speed $\omega$, rotation radius $R$, and gravitational acceleration $g$ as in
Fr = \frac{\omega^2 R}{g} . \quad (1)

Then, this Froude number was compared with operational conditions (modes of motion) and shown in the graph (figure 4). Figure 3 is for Fr = 0.25.

Based on the graph, forms of particles bed when rotate in drum depends on four factors, i.e. rotational speed, particles bed depth, filling degree, and Froude number. Particle depth and filling degree depend on number of particles in the drum, while Froude number depends on rotational speed. So that, generally form of particles bed in rotation drum depend only on particles bed depth and rotational speed, since the two other factors are dependent to the former two.

Characterization of previous granular materials motion has done in three dimensions. In this study, characterization is performed for pseudo-two dimension system, since granular materials have spherical shape (three-dimensions), but it is observed in one layer (two-dimensions).

3. Experiment
The experiment has been conducted with a vertical rotation drum and the drum could be filled one layer granular materials (one layer in the direction of rotation axis). This system is equipped with rotational speed gauge for measuring the rotational speed. Two types of granular materials, i.e. plastic and steel, are used. Both of them have 4 mm diameters. Rotational speed is varied from 15 rpm to 120 rpm with 5 rpm difference

\[ \omega_i = 15 + 5(i-1), \quad i = 1, 2, \ldots, 21, 22 \quad (2) \]

and number of particles varied from 50 to 600 with difference of 50

\[ N_j = 50 + 50(j-1), \quad j = 1, 2, \ldots, 11, 12 \quad (3) \]

Number of the particles converse to height of granular material \( h \) in drum from lower margin wall as in figure 5 below. Observations of the granular modes have been done visually in two ways. The former way is a life observation, while the later is with a help of recorded images which is taken using a photo camera.

![Observation equipments (left) and the definition of height of granular particles in rotating drum (right).](image)

Rotation speed \( \omega_i \) is controlled through the given input voltage \( V_{in} \) which is monitored with a digital voltmeter. For a certain value of particle numbers \( N_j \) (and also types of materials) there should be a nonlinear relation between \( \omega_i \) and \( V_{in} \), or in general

\[ \omega_i = \omega_i \left[ V_{in} \left( N_j \right) \right] . \quad (4) \]
Details of the experiment can be found in [11] and also the form of $V_\omega(N_j)$ implicitly in related thesis [12].

4. Results and discussion
There are about $22 \times 12$ observation points each for steel and plastic marbles in $h - \omega$ plane, where

$$h_j = h(N_j)$$

is particles bed height and $\omega_j$ is from (2). Each point in the plane can be identified simply with $(i, j)$ or $(\omega, h)$ coordinates. Figures 6 and 7 show the $h - \omega$ plane for steel and plastics marbles, respectively.

![Figure 6](image_url)

Figure 6. Characterization of motion modes in $h - \omega$ plane for steel granular materials.

Figure 6 shows modes of steel granular materials in rotating drum, which consists of five modes for rotational speed from 15 to 120 rpm. Those modes are slipping, slumping, rolling, cascading, and cataracting. Centrifuging mode does not occur. That happened because steel marbles has higher mass compared to the plastic ones. It requires higher rotational speed to reach centrifuging mode. Higher mass of steel also causes friction between steel marbles and drum wall not sufficient to hold the particles as the drum rotating, which it makes slipping mode easily occurred.

Plastic granular material has smaller mass than steel. It has also five modes of granular motion, but different than what steel marbles have. Those modes are slumping to partly centrifuging, while slipping mode is absence. Partly centrifuging happened when partly of bed has centrifuging mode and the other has cataracting mode. Observation result for plastic granular material is shown in figure 7. Since plastic marbles is lighter than the steel ones, with assumption that the friction of particles and the drum wall are the same for both materials, friction can hold the particles to move with the rotating drum and it prevents the occurring of slipping mode.

Figures 6 and 7 show the difference of the $h - \omega$ planes, which is slightly shifted to upper right corner for heavier particles. The order of modes (slipping, slumping, rolling, cascading, cataracting, and centrifuging) is the same for both materials. Transition lines between two adjacent modes can modelled simply as
Relation in (6) is a little bit different than proposed using point mass model [13]

\[ c_h \omega + c_\omega = 1. \quad (6) \]

which is independent of total particles \( m \) or particles bed height \( h \).

5. Conclusion
This study is able to characterize modes of pseudo-two dimension granular motion in rotary drum for two different types of granular materials. Granular motion mode is affected by types of granular materials, rotation speed, and amount of granular materials. Characterization of pseudo-two dimension granular motion modes in \( h - \omega \) plane will be shifted to positive \( h \) and positive \( \omega \) direction for heavier materials. This means that for the same rotation speed and the same amount of granular particles, granular motion mode for each material will be different.

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