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Granular dynamics of cohesive powders in a rotating drum as revealed by speckle visibility spectroscopy and synchronous measurement of forces due to avalanching

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HIGHLIGHTS

- Granular dynamics of two cohesive lactose powders in rotating drums is studied.
- Surface slumping and intermittent collisional dynamics in the bulk are correlated.
- Powder avalanche dissipation is dominant for Geldart group A/B boundary powder.
- Collisional dissipation is more important for Geldart group C/A boundary powder.

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ABSTRACT

We have used speckle visibility spectroscopy (SVS) and synchronized force measurements to compare the granular dynamics of two cohesive lactose powders, with Sauter mean diameters of ~29 and ~151 μm, in a rotating drum. A load cell (LC) was used to measure forces on the drum mounting frame and enable monitoring of bulk powder motion; SVS is a dynamic light scattering technique particularly suited for studying dynamics in dense, non-ergodic granular systems. Our results reveal that surface slumping and intermittent collisional dynamics in the bulk of the bed are correlated, especially for the fine more cohesive particles (Geldart group C/A boundary), but not as much for the less cohesive larger particles (Geldart group A/B boundary). The specific dissipation energy of the particles in the drum is similar for both powders, and increases linearly with increasing drum speed. However, the dependencies of the load cell and SVS signals on rotation speed have opposing trends for these two powders, indicating different dissipation mechanisms for the different Geldart Groups; collisional dissipation is more important for the Geldart C/A powder, while for the Geldart A/B powder avalanche dissipation is dominant.

1. Introduction

Granular materials and powders in rotating drums are of wide interest not only because of their extensive use in the chemical, minerals, pharmacutical and food processing contexts, but also as model systems in the study of natural disasters, such as avalanches or landslides (Meier et al., 2007; Seiden and Thomas, 2011). Over the previous few decades, the overwhelming majority of the studies of such systems have focused on free-flowing or slightly cohesive materials (Castellanos et al., 1999, 2002; Fischer et al., 2008; Jiang et al., 2015; Metcalfe et al., 1995; MiDi, 2004; Orpe and Khakhar, 2007; Zhou and Sun, 2013). However, since many powder materials in nature and industry are substantially cohesive (i.e., interparticle forces are larger than the particle weight), additional work focusing on cohesive powder flow is highly desirable. Some recent work has examined cohesive granular systems (Chou et al.,

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2014; Liu et al., 2011; Pignatel et al., 2012; Tegzes et al., 2002, 2003), but these studies have typically used large spherical particles and moisture-induced cohesion.

For many powders, cohesive effects are influenced by other forces besides capillary, such as van der Waals forces, electrostatic or magnetic forces, mechanical interlocking between particles, and combinations of these (McGlinchey, 2005), which lead to flow dynamics different from those observed for moisture-induced cohesion (Alexander et al., 2006; Li et al., 2011; Lumay et al., 2012; Tomas, 2004). In the cohesionless case, it is well known that as the drum rotational speed increases, the granular flow takes on one of a number of regimes such as slumping, rolling, cascading, cataracting, and centrifuging. All of these regimes can be characterized by the angle of repose or flowing speed by imaging techniques (Fischer et al., 2008; MiDi, 2004; Orpe and Khakhar, 2007). In the case of cohesive powders, the behavior of the granular assembly is more complex. In particular, the angle of repose is difficult to measure because of the irregular surface of the flow and the continuous regime does not exist. Indeed, the cohesion induces intermittencies over the whole range of rotational speeds (Alexander et al., 2006; Lumay et al., 2012), and limits the effectiveness of popular imaging techniques.

Davies et al. (2002) introduced a load cell device for sensing the motion of particulate material in a rotating cylinder by tracking changes in the center of gravity of the particle bed, and subsequently demonstrated (Davies et al., 2004) that a load cell could be used to identify the initiation of an avalanche and to track its movement. Later, Alexander et al. (2006) used this method to compare the experimental flow behaviors of dry glass beads, wet glass beads, and "dry" cohesive powders with the DEM results. They found that dry cohesive powders exhibit history-dependent flow dynamics, significant dilation, and variable avalanche size. Davies and Webster (2010) used the method in experiments with powders from the four different Geldart Groups, and reported distinctive differences in the avalanching behavior of each group.

Studies of granular dynamics in the bulk region of a rotating drum are very scarce due to limitations of available experimental techniques. Because of strong multiple light scattering, video imaging based optical velocimetry techniques such as particle image velocimetry (PIV) (du Pont et al., 2005), and particle tracking velocimetry (PTV) (Jain et al., 2002; Warr et al., 1994), are restricted to dilute granular gasses or surface behavior. Even then, the spatial resolution is not fine enough for them to distiguish collisions between the grains. This limitation holds for other imaging techniques as well, like positron emission particle tracking (PEPT) (Lim et al., 2003; Parker et al., 1997), magnetic resonance imaging (MRI) (Nakagawa et al., 1993; Yamane et al., 1998), and X-ray microtomography (Seidler et al., 2000). Furthermore, none is fast enough to capture the high rates of the micro-collision of grains in the passive bed located in the lower part of the rotating tumbler. By contrast, diffusing-wave spectroscopy (DWS) (Pine et al., 1988), a dynamic light scattering (DLS) technique, can be applied to the study of dense granular media in very small volumes and can resolve the motion of grains over length and time scales of the order of several nanometers and several microseconds respectively (Kim and Pak, 2010; Zivkovic et al., 2009). It is, however, based on temporal correlation functions calculated as a time average, which cannot be used for time resolved measurements. And in our case, we are interested in the time dependence of collisions between particles.

In this paper, we report a study of the avalanche dynamics of two different lactose powders of different cohesion strengths in a rotating drum, by sychronized measurements with a load cell (LC) and speckle visibility spectroscopy (SVS). SVS is able to measure time resolved collisional motion of grains in dense systems with fine spatio-temporal resolution (Bandyopadhyay et al., 2005), which we have previously used to measure the intermittent avalanches on the surface of granular flow in a rotating drum (Yang et al., 2015). The experimental details of both techniques are introduced first, followed by a results section where both LC and SVS results are presented separately for two Geldart group powders followed by section with comparison of the results for these two powders.

2. Experimental details

2.1. Drum system

The results reported in this work are obtained in a drum with an inner diameter of 200 mm and length of 300 mm, as depicted schematically in Fig. 1. The drum, has a front face-plate of clear transparent perspex to permit optical access and cylindrical walls of semi-transparent perspex; it was half-filled with granular material and placed on a pair of rollers turned by a DC motor at rotation rates in the range 3–25 revolutions per minute (RPM). A white tape 12 mm wide and 100 mm long was stuck on the front face-plate as a reference flag for the jamming state of a powder in a SVS signal. The points A, B, and C on the profile of the granular material, as shown in Fig. 1, are the spot points used in this SVS study.

2.2. Granular material

The granular materials used in this study were two model milled lactose powders with size distribution parameters given in Table 1 (Saw et al., 2013a); also shown are surface–volume diameter, d_{32}, loose poured bulk density, ρ_B, and cohesion for the condition of zero preconsolidation stress, C_0, which was obtained from shear cell measurements (Saw et al., 2013b) following the approach outlined by Saw et al. (2013a) the particle density of lactose is 1540 kg m^{-3}. Note that the size distribution parameters were found using data obtained with a Malvern Mastersizer 2000, using bins equivalent to a full sieve analysis according to BS410 (British Standards Institution, 2000). The finer powder, termed powder CA, lies close to the C/A boundary in the Geldart

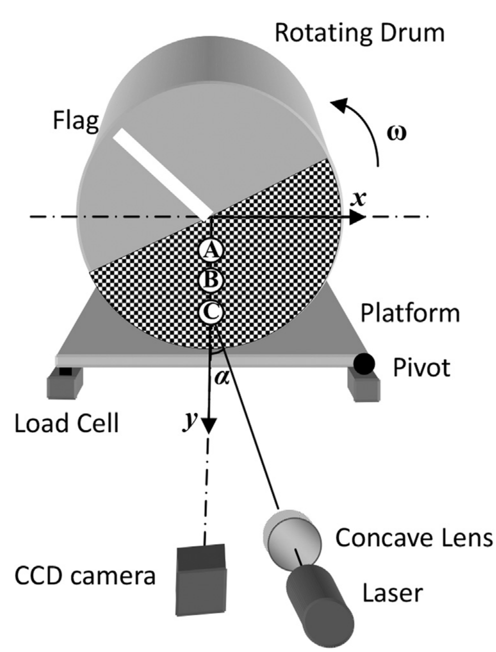

Fig. 1. Schematic diagram of the experimental set-up, showing the spot points, A (x=0 mm, y=15 mm), B (x=0 mm, y=25 mm), and C (x=0 mm, y=35 mm).