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Particle dynamics in avalanche flow of irregular sand particles in the slumping regime of a rotating drum

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ABSTRACT

Slowly rotating drums are important due to their industrial application, but also as a simple model system for studying transient avalanche processes. A speckle visibility spectroscopy (SVS) alongside a simple imaging technique was used to measure the time-resolved avalanching of 1.3 mm diameter sand particles in a 35% full rotating drum operating in the slumping regime. The major difference from spherical particle dynamics is visual observation of granular compaction in the upper part of the drum at the beginning of the avalanching process which is not present in experiments with spherical particles. The SVS measurement of avalanching shows that the fluctuation velocity, so called granular temperature, increased sharply before plateauing then decreases sharply to zero during a typical avalanche event which is different to spherical particle behavior where these transitions are more gradual. Furthermore, the granular dynamics of avalanching flow is influenced by a visually observed flowing mound down the avalanching surface so there are more characteristic peaks in the plateau region of the signal for measurement point in the lower part of the bed. Overall, the observed plastic deformation is influencing the dynamics of the system in several ways indicating the importance of considering particle shape in the study of granular flow dynamics.

1. Introduction

Granular materials in rotating drums are of wide interest not only because of their extensive use in the chemical, mineral, ceramic, pharmaceutical and food processing contexts, but also as model systems in the study of natural disasters, such as avalanches or landslides [1,2]. The overwhelming majority of experimental and numerical studies have focused on spherical particles although granular systems in industry or nature frequently consist of non-spherical and/or irregular particles. The particle shape has a significant influence on granular dynamics [3–9] and one cannot simply extend theoretical and numerical models developed on assumption of spherical particles to these cases [10,11]. For example, this has driven a strong effort in the last couple of years in the development of non-spherical discrete element method (DEM) simulations and its application to systems of academic and/or industrial interest as reviewed by Lu et al. [12] and Zhong et al. [13]. Still, there is little knowledge about the granular dynamics of non-spherical particles and irregular particles inside rotating drum.

Experimental investigations of non-spherical and irregular particle behavior in rotating drums are scarce and rather limited in scope. The majority of studies were about mixing starting from the sixties [14,15] with several studies in the following decades [3–9]. These studies used various particles like rice [3,15], oat [15], sand [4,14], shale [7], limestone [4,5] and tablets [8,9] with some observations that mixing is probably promoted by sphericity [8,9,15]. Henein et al. [16] determined that transition to rolling regime for irregular particles is at higher rotating speeds and corresponding Froude number in comparison with spherical particles. Furthermore, the dynamic angle of repose was higher for irregular particles [16] which was confirmed as well in more recent experiments [8,9]. Studies on particle dynamics were even more infrequent and mostly limited to surface velocity profiles due to limitation of experimental techniques [16]. Boateng and Barr [17] determined noteworthy differences in near wall cross-section velocity profiles for irregular rice and limestone particles in comparison with spherical polyethylene particles. Longo and Lamberti [18] measured as well near wall cross-section velocity profiles using glass and sand particles but without specific discussion on the particle shape influence on the granular dynamics. Experiments with tablets [8,19] measured higher velocity of tablets in the avalanching free-surface layer of the drum in comparison with spherical counterparts. Dube et al. [9] used radioactive particle tracking technique with different tablets to find that particles with an aspect ratio greater than two have significant deviation in velocity profiles and residence time in comparison with spherical particle based

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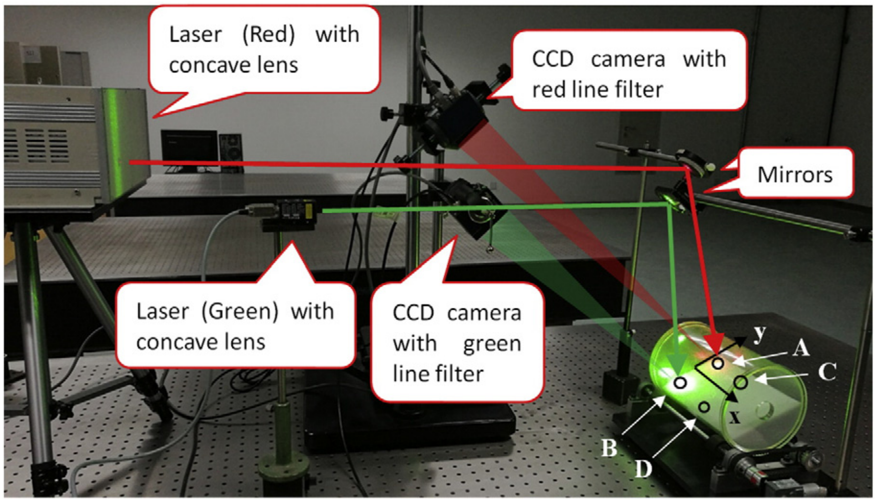

Fig. 1. The annotated photo of the experimental setup. Points A (x = 30 mm, y = 45 mm), B (x = 30 mm, y = −45 mm), C (x = 100 mm, y = 45 mm), and D (x = 100 mm, y = −45 mm) were the focus of the SVS analysis reported here.

models. Yamane et al. [20] used magnetic resonance imaging to examine the granular dynamics of irregular mustard seeds observing non-zero particulate diffusion in the bulk of the drum indicating that the so-called passive region is not completely static. There are only few experimental studies of temporal evolution of particle dynamics of transient flowing layer during discrete avalanches of slumping regime for spherical [21,22], but none, as yet, for non-spherical particles.

Although many experimental methods are available for the study of particle dynamics in rotating drums, including particle image velocimetry (PIV) [23–25], particle tracking velocimetry (PTV) [19,26], PEPT [27,28], laser Doppler velocimetry (LDV) [18] and magnetic resonance imaging [20,29], some of these are restricted to two components of motion (PIV and PTV) while the remainder can only resolve the granular dynamics to a fine scale with relatively poor temporal resolution or *vice versa*. In contrast, speckle visibility spectroscopy (SVS) [22,30–32] is able to resolve the average of the three components of motion of grains in dense systems with spatiotemporal resolutions that allow the probing of the microdynamics of avalanches. We have previously used it for study of granular dynamics of both active avalanching layer [22,33] and the passive parts in the bulk of the rotating drum [32,33] using glass spherical particles [22,33] and cohesive lactose powders [32].

In this paper, we report a study of the avalanching of sand particles in a rotating drum under the slumping regime by a synchronized measurement method with two SVS systems as well as an imaging technique for dynamic angle of repose measurement. After a section on the experimental setup and methods, we first report in the Results and discussion section the visual observation of the avalanching of the irregular particles by imaging technique. The main part of the Results and discussion section is derived from analysis of synchronized SVS measurements including presentation and discussion on various statistics such as the avalanche duration, rest time, and peak fluctuation velocity. The variation of avalanche statistics with the axial and longitudinal positions and drum speed is presented and analysed.

2. Experimental method

2.1. Drum system

The results reported here were obtained in a cylindrical drum, Fig. 1, whose inner diameter, D, and length, L, are 142 mm and 200 mm respectively. The rotating drum, which is made of clear Plexiglas to permit optical access, was filled with granular material to fill 35% of its volume. The drum was placed on a pair of rollers turned by a DC motor at 0.1–2.3 revolutions per minute (RPM). Four points of the granular bed were studied here at the surface of the bed where avalanche flow occurs, two at the top (A & C points) and two in the bottom part of the bed (B

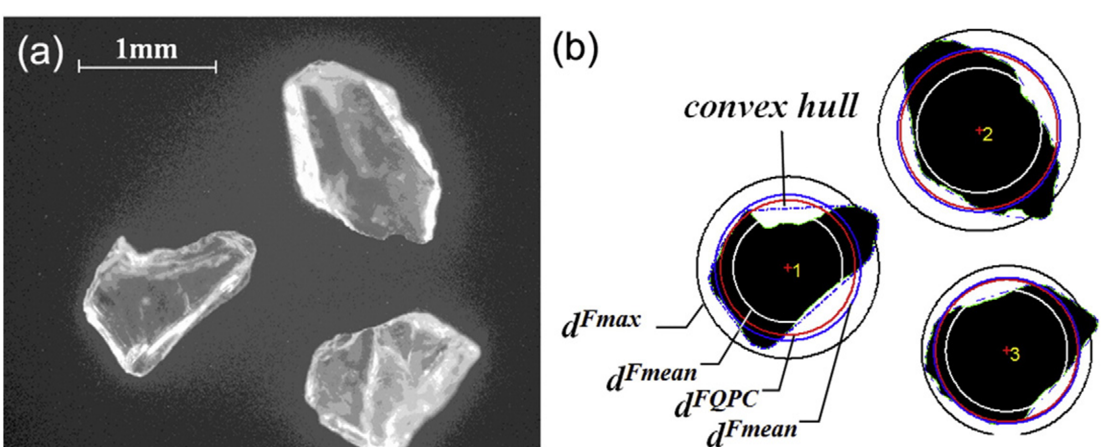

Fig. 2. (a) Example photo of glass sand particles under microscope with 1 mm scale bar and (b) corresponding binary image showing particle size and shape descriptors: equivalent projected area diameter (D^{EQPC}, red online), Feret diameters (D^{Fmean}, blue online) and convex hull.