Powder Technology 214 (2011) 491–499

Contents lists available at SciVerse ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Experimental analysis of the dynamic properties of wet granular matter in a rotating drum

S.H. Chou, S.S. Hsiau *

Department of Mechanical Engineering, National Central University, Jhongli, 32001, Taiwan, ROC

ARTICLE INFO

Article history:
Received 14 June 2011
Received in revised form 30 August 2011
Accepted 8 September 2011
Available online 16 September 2011

Keywords:
Rotating drum
Liquid bridge force
Velocity
Granular temperature
Energy dissipation

ABSTRACT

We performed experiments to measure the dynamic properties of wet granular matter in a rotating drum device. Four different amounts of liquid and rotation speeds were used in the experiments. The purpose was to quantify the effect of the cohesive force in the granular system. The results show that when only very small amounts of liquid were added, no liquid bridges formed. This is because the liquid was first trapped on the surface of the particles due to the particle roughness. When the volume fraction of the fluid became larger, liquid bridges formed on almost every particle. The results showed that the addition of liquid contents, and changing the rotation speed, both had a significant effect on the dynamic properties of granular matter. This was due to the hysteretic formation and rupturing of liquid bridges and the introduction of inertial force to the device. After the liquid bridges formed between all particles the average energy dissipation due to the hysteretic formation and rupturing of the liquid bridges increased with an increase in the liquid content.

1. Introduction

The handling and processing of granular materials is important in a variety of different industries, such as pharmaceuticals, foodstuffs, ceramics, detergents, chemicals, plastics, etc. The ubiquity of granular materials in the processes involved makes how to handle them efficiently very important economically. Furthermore, their special properties (they can behave like solids, liquids or gasses without being any of them) have attracted the attention of the scientific community over the last two decades [1,2]. Granular solid material can be made to flow like a fluid, for example, in avalanches, hopper flows, and fluidized beds [3,4]. In such flows, the, granular kinetic energy may be transformed into thermal energy due to inelastic collisions between particles. Actually, the particles will stop moving if no extra energy is added to the system. The most common sources of input energy are from gravity, rotating the system, producing shear force at the boundary of the system, or vibrating the system. The rotating drum has become a commonly used experimental device used to investigate the physics of granular flow, partly because of its simple closed geometry. It is also in practical use in many industrial processes for the drying, segregation and mixing of granular materials [5–7].

When a horizontal circular drum partially filled with granular material is rotated about its axis, the material rotates as a solid body until it reaches its dynamic angle of repose. The angle of repose is an important parameter affecting the behavior of the granular flow in a rotating drum. Liu et al. [8] found that the upper and lower angles of repose could be influenced by the size of the drum, the fraction filled with particles, the speed of the rotation and the roughness of the particles. In the rolling regime, when the rotation speed is low enough, two distinct flow regions can be observed in the drum (see Fig. 1): a bulk solid-body rotation undergoing slow plastic deformation [9], and a thin flowing layer. The physical mechanisms mainly occur in the flowing layer.

There are a variety of industrial processes (wet granulation, granular condensation, drying, cake filtration, etc.) which involve wet granular matter [10–12]. However, in the past few decades, the behavior of wet granular matter has received less attention than that of dry granular systems. There are dramatic changes observed in the behavior of the granular flow when some amount of liquid is added to the material, due to the formation of liquid bridges between the particles which in turn cause an increase in interparticle cohesion [13–16]. Nase et al. [17] defined the Granular Bond Number Bo_g as the ratio between the maximum capillary force and the weight of the particle. Li and McCarthy [18] strove to extend this dimensionless group for nonuniform particle properties by rewriting the Granular Bond Number (Bo_g) for the binary-mixture system. They found that the cohesive effect was important when the Granular Bond Number is greater than 1. Kohonen et al. [19] showed that the number of liquid bridges increases as the liquid content increases, reaching a stable value when the liquid content becomes greater than a critical value. Samadani and Kudrolli [20] showed that segregation could be mitigated by adding a little liquid to a silo. They argued that in a wet

* Corresponding author. Tel.: +886 3 426 7341; fax: +886 3 425 4501.
E-mail address: sshsiau@cc.ncu.edu.tw (S.S. Hsiau).

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doi:10.1016/j.powtec.2011.09.010

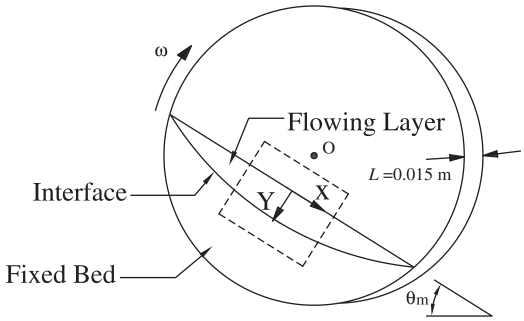

Fig. 1. Diagram of the tank rotated by the rotating drum showing the flow inside the drum which can be divided in two parts: a bulk solid-body rotation undergoing a slow plastic deformation; and a thin flowing layer.

granular system the number of liquid bridges influences the flow behavior. Yang and Hsiau [21,22] found that the self-diffusion coefficients and the fluctuation velocities were smaller in a wet sheared granular flow than in a dry sheared granular flow. Chou et al. [23] showed that the segregation condition could be predicted based on the angle of repose of the granular materials, regardless of the liquid content or viscosity, in the case of wet granular flows.

It is well known that the liquid bridge force has a significant influence on the static properties of wet granular matter. In this study, we employed a particle tracking method to measure the dynamic properties of wet granular matter. We studied the effect of the liquid bridge force on the dynamic properties of wet granular matter by adding silicone oils to obtain different liquid contents and utilizing different rotation speeds.

2. Experimental procedure

A schematic representation of the circular drum used in the quasi-two-dimensional experiments is shown in Fig. 1. The diameter of the drum is 0.3 m and the axial length L is 0.015 m. The back surface of the drum was constructed of a black anodized aluminum plate to minimize electrostatic effects on the particles and optical noise effects in the digital images. The front faceplate was made of clear acrylic to permit optical access. Before each experimental test, the glass faceplates were cleaned and coated with an inorganic film (water repellent silicone) to prevent the formation of liquid bridges between the particles and the walls. Mellmann [24] indicated that the rolling regime exists when $10^{-4}<Fr<10^{-2}$. In this study, we investigated the dynamic properties of wet granular matter in the rolling regime. A stepper motor and micro series driver combination were used to rotate the drum at speeds of 1 rpm, 2 rpm, 3 rpm, and 4 rpm, corresponding to the Froude number of $F_r=R\omega^2/g$ of 1.67×10^{-4}, 6.71×10^{-4}, 1.51×10^{-3}, and 2.68×10^{-3}, where ω is the angular velocity of the drum ($=2\pi/T$, $T=$rotation period); R is the radius of the drum; and g is the acceleration of gravity. The dimensionless axial thickness of the drum, defined as the ratio between the drum's axial length and the particle diameter, was set to 3.75 in this study. Mono-sized glass beads were used as the granular material in all experiments. These glass beads were 4 mm in diameter with a standard deviation of 0.09 mm and their density was 2.476 g/cm^3. Details of the experimental conditions are provided in Table 1.

In this study, the filling degree is defined as the ratio of volume occupied by the granular material to the total drum volume. The experiment is defined as a quasi-two-dimensional experiment. The filling degree is defined as the ratio of the area occupied by the granular material to the total drum area, formulated as

$$f=\frac{A_{\text{particles}}}{A_{\text{drum}}}=\frac{\alpha}{2\pi}-\frac{\sin\alpha}{2}, \quad (1)$$

Table 1
Experimental parameters: the particles are glass beads ($\rho_b=2476$ kg/m^3) with diameters of $d=4$ mm.

Filling degree (f):0.4	
Operating parameters	Drum speed (ω):0.1047 rad/s, 0.2093 rad/s, 0.3140 rad/s 0.4187 rad/s Liquid content (V^*):0, 1.996×10^{-3}, 9.9×10^{-3}, 14.778×10^{-3} 19.6×10^{-3}

where α is the segmental angle formed between the area occupied by the particles and the center of a circle.

The surface tension and density of the silicone oil added to the granular materials in this study were 19.7 mN/m and 0.953 g/cm^3, respectively. Prior to the experiments, specific amounts of silicone oil and glass beads were placed into a sealed jar, which was then shaken sufficiently to mix the silicon oil with the beads. The wet glass beads were then poured carefully into the drum. The weight of the sealed jar with the residual silicone oil was measured to regulate the error. The dimensionless liquid volume V^* can be given by $V^*=V_l/(V_l+V_s)$, where V_l is the volume of liquid; and V_s is the total volume of particles [22,23].

3. Image processing

The granular flow in the test section is assumed to be quasi-two-dimensional, in the streamwise direction along the x-axis and in the transverse direction along the y-axis. A high-speed CMOS camera (IDT X-3 plus, monochrome, capable of shooting 500–2000 frames per second (fps), with a resolution 1280×1024 pixels), was used to record the sequential motion of the granular flow during the experiments. The flow was illuminated by four halogen lamps: DEDO DLH650 650W 3200K.

Fig. 2(a) shows a portion of a raw grayscale image captured during the experiments. The raw images were first filtered with a Gaussian filter to diminish any high-frequency noise that might arise due to variations in light intensity. A Laplacian filter was then applied to enhance the image contrast which transformed the bright pixels into separate white patches as seen in Fig. 2(b). The light source caused bright spots to appear on the slightly reflective surfaces of the glass beads, which were employed to locate the individual spheres. The particle centers were identified by using a maximum brightness filter as can be seen in Fig. 2(c). The velocity field of the granular materials in the selected region is shown in Fig. 2(d). The velocity vectors between two image pairs were calculated with the autocorrelation technique. It is found that the velocity is higher at the free surface of the flowing layer than between the flowing layer and the fixed bed.

The autocorrelation technique was employed to process the stored images and to determine the shift of each tracer particle between two consecutive images [25,26]. A set of consecutive motion images is shown in Fig. 3. The small window ($n_{1x}\times n_{1y}$ pixels) in the first image outlines an identified tracer. The larger window ($n_{2x}\times n_{2y}$ pixels) in the second image outlines the area of possible locations of the tracer particle. In the first window we can see a shift in both directions (streamwise and transverse) by δs_i and δs_j pixels each time. This, multiplied by the corresponding pixel values for the second window, can be used to obtain the autocorrelation value $c(\delta s_i, \delta s_j)$

$$c\left(\delta s_i,\delta s_j\right)=\sum_{i=1}^{n_{1x}}\sum_{j=1}^{n_{1y}}P_1(i,j)P_2\left(i+\delta s_i,j+\delta s_j\right), \quad (2)$$

where i and j indicate the pixel coordinates in the images; and P_1 and P_2 are the pixel values in the two image windows. Natarajan et al. [26] and Hsiau and Jamg [25] used shifts of δs_i and δs_j when the maximum autocorrelation value c occurred for the movement of the