IMAGING PROCESSING APPLIED TO GRAVITY-DRIVEN GRANULAR FLOWS THROUGH A VERTICAL PIPE

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Abstract: *Gravity-driven flows of granular particles through a vertical pipe was studied experimentally using spatiotemporal diagrams obtained by digital imaging processing. The image processing was accomplished by employing a numerical code developed in MatLab in the course of this work. When the ratio of the tube diameter D to the grain diameter d is within certain limits,* $6 \leq D/d \leq 30$*, granular flows may give rise to density waves. These waves consist of regions of high and low grain concentration, denominated granular plugs and air bubbles, respectively. Our experiments were focused in the high concentration regions. The granular flow was filmed by a high-speed camera, while the particles fell down through a transparent glass pipe. An oscillating wave regime was observed which depended on the mass flow rate and the degree of humidity. In this paper, we report measurements of the celerity and mean length of granular plugs. The plugs propagated downward, in the same direction as the granular flow, with constant celerity along the tube, and its size was independent of the mass flow rate.*
Keywords: *fine grains, density waves, image processing, granular flow*

1. INTRODUCTION

The global annual production of grains and aggregates is approximately ten billion metric tons, and the processing of granular media consumes roughly 10% of all the energy produced worldwide. These materials ranks second, only behind the water, on the scale of priorities of human activities (Duran, 1999). Gravitational grain flows in pipes are common in industry. Some examples are the transport of grains in the food industry, the transport of sand in civil constructions, and the transport of powders in the chemical and pharmaceutical industries. Modeling these granular flows is not an easy work, since they involve complex interactions of moving grains with the surrounding air, bounding walls, and the other grains (Bertho *et al.*, 2003).

When the grains and the tube diameter are size-constrained, granular flow may give rise to instabilities. These instabilities are known as density waves and consist of alternating high- and low-compactness regions (regions of high and low grain concentration, respectively). When grains flow through a vertical pipe, typically three different situations may occur as a function of the mass flow: the granular flow can be in a free-fall regime, in a density wave regime, or in a compact regime (Raafat *et al.*, 1996).

Raafat *et al.* (1996) studied the formation of density waves in pipes experimentally. The experiments were performed in a $1.3\,m$ long tube with an internal diameter D of $2.9\,mm$ using glass splinters and glass beads with mean grain diameter d of $0.09\,mm$ to $0.2\,mm$ and $0.2\,mm$, respectively. They reported that to obtain the density waves it is necessary to keep the ratio D/d within certain limits, $6 \leq D/d \leq 30$: for experimental configurations using a ratio > 30 free fall regime was obtained, on the other hand, for a ratio < 6 only the compact regime was observed.

Aider *et al.* (1999) presented an experimental study of the granular flow patterns in vertical pipes. The experiments were performed in a tube similar to that of Raafat *et al.* (1996) using glass beads with mean diameter of $125\,\mu m$. The density variations were measured using a linear CCD (charge coupled device) camera with frequencies of up to $2\,kHz$. Aider *et al.* (1999) observed that the density waves consisted of high-compactness plugs separated by low-density regions; furthermore, the density waves appeared when the grain flow rate $\dot{m}$ was $1.5\,g/s\,-\,2.5\,g/s$ (oscillating wave regime) or $2.5\,g/s\,-\,5\,g/s$ (propagative wave regime). Additionally, they observed that the relative humidity must be between 35% and 70%. Values above of 70% produce clogging, due to capillary forces. For the case when the humidity is lower than 35%, the electrostatic forces domain, and also produces flow blockage.

Bertho *et al.* (2002) presented experiments on density waves using an experimental set-up similar to that of Raafat *et al.* (1996) and Aider *et al.* (1999). The vertical tube ($D = 3\,mm$, $1.25\,m$ long) and the glass beads ($d\,=\,125\,\mu m$ glass beads) were more or less the same as those of Aider *et al.* (1999), and a linear CCD camera was used. In addition, capacitance sensors were used to measure the compactness of grains at two different locations, and the pressure distribution was also measured. The experimental data showed that the characteristic length of the high-compactness regions of the density wave regime is in the order of $10\,mm$. In those experiments the mass flow rate was varied by an adjustable constriction located at the bottom of the tube.

In order to calculate the wavelength and the celerity of granular density waves, the literature reports that spatiotemporal diagrams are used, these diagrams are stored as numerical arrays and visualized using any image processing program. However, in the literature there is not enough information concerning how to build up these diagrams. This paper is devoted to the density waves of granular flows falling through a vertical tube using glass beads of diameter ranging between 212 and 300 μm. The length and the celerity of high grain concentration regions, known as granular plugs, are determined by digital image processing using a code developed in MatLab environment. The descriptions of the experimental set-up and procedure are presented in the next section. The results and the discussions are presented in the following section. The conclusion section follows.

2. EXPERIMENTAL PROCEDURE

2.1 Experimental set-up

Our experimental flow channel was a 1.0 m long vertical glass pipe with an internal diameter D = 3 mm. It was attached to a reservoir and conical hopper with an opening angle of 60^o, initially filled with grains (Fig. 1). Both the reservoir entrance and the exit valve were at atmospheric pressure.

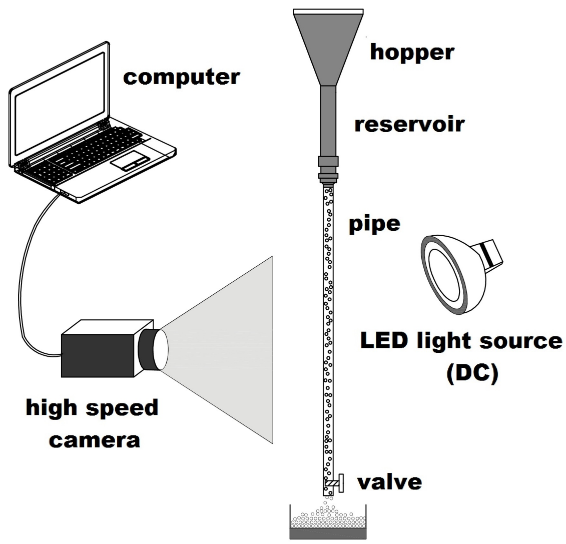


Figure 1: Experimental set-up

The granular material consisted of spherical glass beads with specific mass ρ_s = 2500 kg/m^3, and with diameter ranging between 212 and 300 μm. The mass flow rate $\dot{m}$ was varied by a valve located at the bottom end of the tube and measured using a chronometer and a balance with $\pm$ 0.01 g accuracy. The grain flow falling through the transparent pipe was filmed using a 1280 px $\times$ 1024 px high-speed camera mounted on a tripod. The camera was fully controlled by a computer and its acquisition frequency was 250 Hz. In order to provide the necessary light for low exposure times while avoiding beat between the light source and the camera frequency, LED (Low Emission Diode) lamps were connected to a continuous current source. The temperature and the humidity were measured within $\pm$ 0.5 ^{o}C and $\pm$ 2.5$\%$, respectively. These two parameters were controlled throughout every test. In the present study, we employed rough surface grains (beads that passed more than one hundred times through the pipe).

The density waves were experimentally obtained with a moderate constriction at the bottom of the tube. Figure 2 illustrates a schematic view of these waves, the two regions of high and low grain concentration are designated as plug and air bubble, respectively, besides λ is the mean length of plugs, i.e., the size of the granular plugs.

2.2 Image processing

A image processing code was developed to determine the length and celerity of the granular plugs from the RGB (red, green and blue) images. The code is based on the identification of the upper and bottom plug position along the images, and it has two main parts: an image treatment part and a position computation part. The following is a brief explanation of the image treatment.

Each image is acquired in RGB format during the tests and it is saved as a matrix. The first steps of the code are to open sequentially each one of these matrices, and to load scaling (in order to convert pixels to mm, a calibration image was acquired before each test) and to load threshold information (related to the image and light calibrations). Next, in each image the code detects the regions that contain the granular flow, and that is limited by the tube walls; therefore, the code only considers information belonging to this region. In the following, each image is converted to grayscale, and then to binary scale. Next, with the smallest granular plug assumed to scale with the tube diameter, the code searches the grain regions with lengths greater than 3 mm, and these are considered as the granular plugs. Once the plugs have been identified, the code saves their upper and bottom positions in a matrix.

The position computation part comprises several steps; plots the upper and bottom plug positions as a function of time (spatiotemporal diagram), determines the mean celerity of plugs by calculating the slope for the upper plug regions, and computes the mean length of plugs by calculating the difference between upper and bottom plug positions.

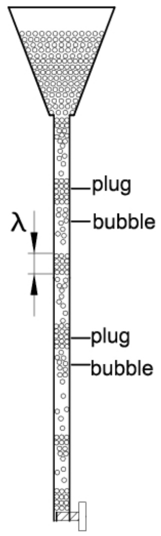


Figure 2: Schematic view of the density waves, λ is the wavelength of the granular plug.

Figure 3 presents an image of density waves experimentally observed. The frames sequence illustrates an image while it is being computed. At the left side, the image is in RGB format, then the image is converted to grayscale scale, next it is converted to binary scale, and finally the code identifies the upper and bottom plug positions (marked with asterisks). Fig. 3b illustrates the presence of plugs with negative celerity, i.e., they propagated upward. The time between Fig. 3a and Fig. 3b is 0.16 s.

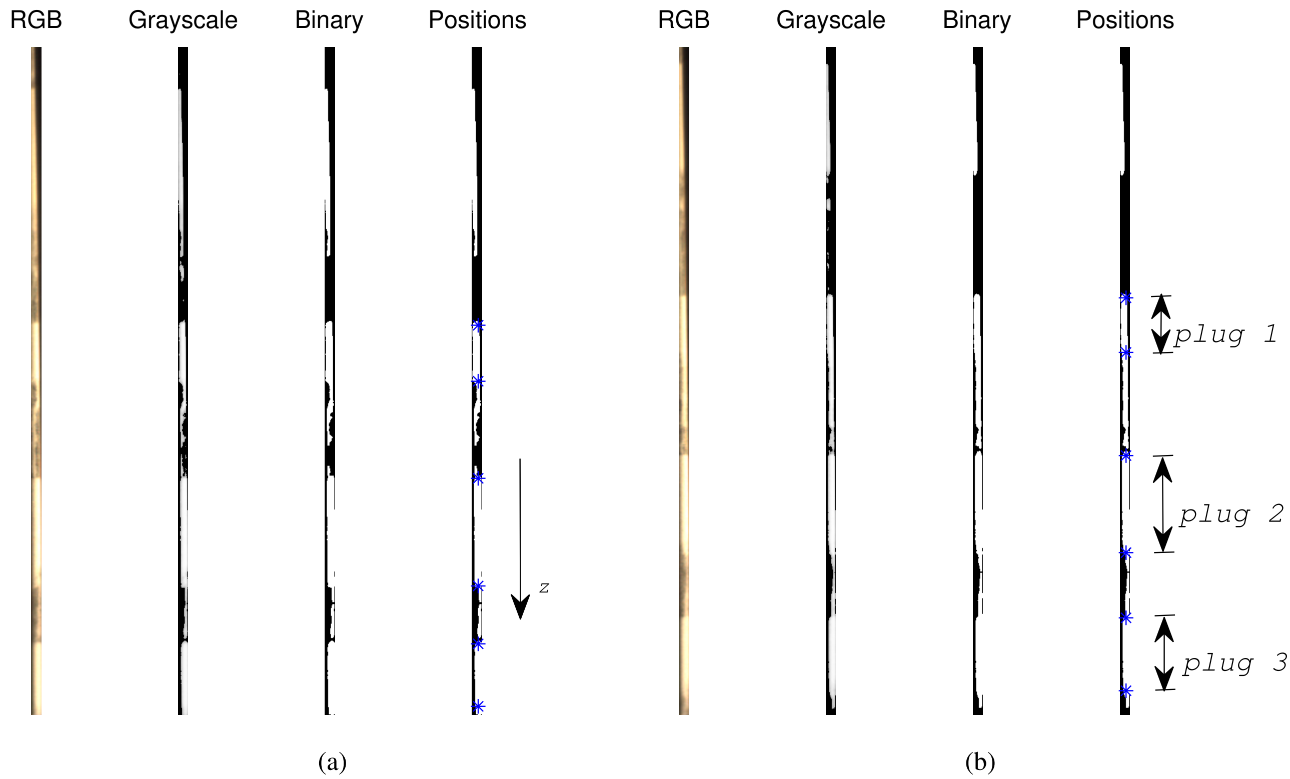
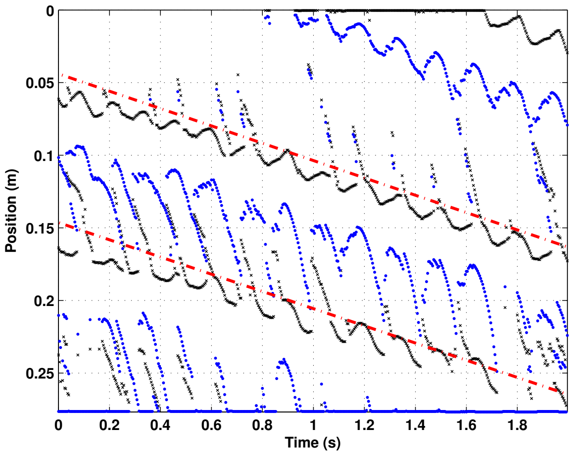


Figure 3: Example of plugs identification by the code. From left to right: image in RGB format, image converted to grayscale, image converted to binary format, and identified upper and bottom plug positions, marked with asterisks. (a) The code identified three granular plugs. (b) The position of three granular plugs identified in (a) after 0.16 s. z is the vertical coordinate

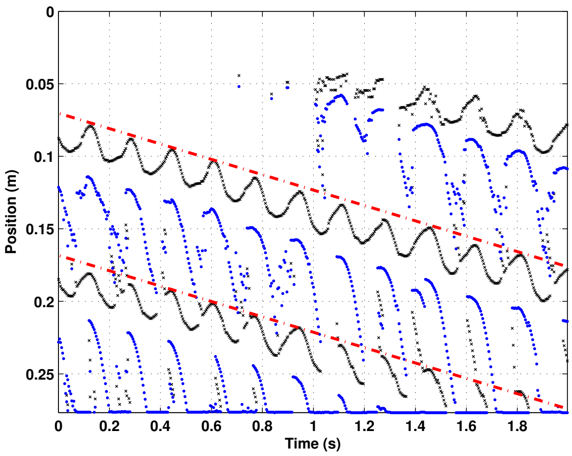
3. RESULTS AND DISCUSSION

Density waves were observed as soon as the granular flow began. The density waves may have positive or negative mean celerity, and they sometimes may present an oscillatory component. Aider *et al.* (1999) proposed that different celerity behaviors are due to different granular flow rates and humidity. In this study, we reported the results about oscillating density waves.

Previous works (Aider *et al.*, 1999; Bertho *et al.*, 2002) have reported that oscillating waves appeared when the mass flow rate $\dot{m}$ was within 1.5 $-$ 2.5 g/s, separated by internal air bubbles, in which the grain dynamics can be modeled locally as a free fall motion. In the present work, we observed density waves for the $\dot{m}$ values ten times smaller than those previously reported, and slightly smaller relative humidity values than those previously reported. The small values of $\dot{m}$ could be caused by two aspects. The first could be associated with the measured relative humidity values. We observed density waves at humidity values smaller than those reported in previous works, besides in our experiments the humidity was continuously controlled throughout each test, and it kept constant. The second aspect could be caused by the geometry and superficial quality of the grains. Images taken by Scanning Electron Microscopy allowed to observe that some grains are not exactly spheres, they had irregular shapes, and other grains contained little incrustations on their surface.



(a)



(b)

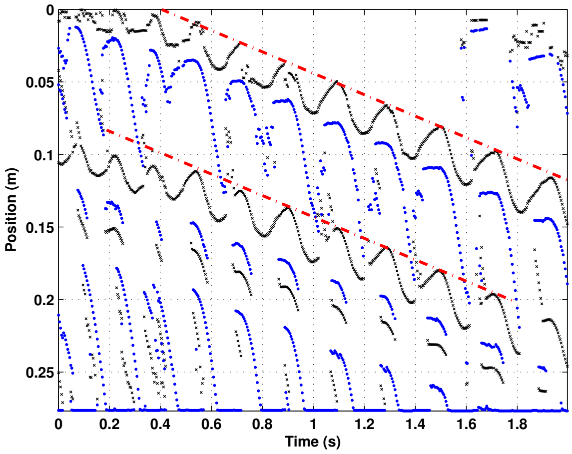
Figure 4: Spatiotemporal diagram of oscillating waves. The upper and bottom plug positions are shown in black and blue colors, respectively. The dashed line corresponds to the mean drift celerity v_p. (a) v_p = 0.0401 m/s, $\dot{m}$ = 0.35 g/s. (b) v_p = 0.0501 m/s, $\dot{m}$ = 0.37 g/s. The frequency of oscillations is in the order of 7 Hz.

Figures 4 and 5 correspond to typical spatiotemporal diagrams obtained from our tests. The frequency of the density waves, calculated using the these diagrams, is equivalent to 7 Hz. The mass flow rate $\dot{m}$ was ranging between 0.25 and 0.40 g/s, these values are approximately ten times smaller than previously published results. In oscillating wave regime, it was observed that the density waves oscillated over a non-zero drift celerity, which can be considered as the mean celerity of plugs v_p. The plugs always propagated downward, in the same direction as the granular flow, and v_p was constant along the tube.

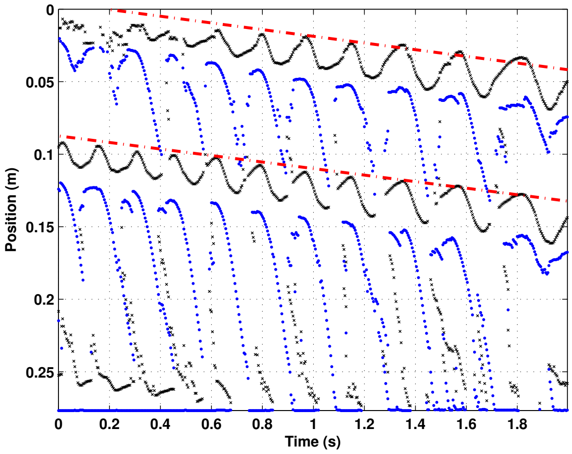
Figures 5a and 5b correspond to diagrams obtained with values very close to the superior and inferior limits of $\dot{m}$ determined for this wave regime. These figures show that the oscillating frequency is independent of the mass flow rate

Spatiotemportal diagrams show that the mean celerity v_p is independent of measurement height and is constant along the pipe. The variation of v_p as a function of $\dot{m}$ is displayed in Fig.6. The celerity of plugs increases linearly with $\dot{m}$ and ranges between 0.0200 and 0.0652 m/s. The results of linear dependence are similar to those provided by the literature.

Finally, Fig. 7 presents the mean wavelength of plugs λ as a function of the mass flow rate $\dot{m}$. As can be seen, λ is approximately independent of mass flow rate $\dot{m}$, the latter is in good agreement with previously reported results. Moreover, the mean size of plugs is approximately 30 mm.



(a)



(b)

Figure 5: Spatiotemporal diagram of oscillating waves. The upper and bottom plug positions are shown in black and blue colors, respectively. The dashed line corresponds to the mean drift celerity v_p. (a) v_p = 0.0652 m/s, $\dot{m}$ = 0.41 g/s. (b) v_p = 0.0250 m/s, $\dot{m}$ = 0.26 g/s. The frequency of oscillations is in the order of 7 Hz.

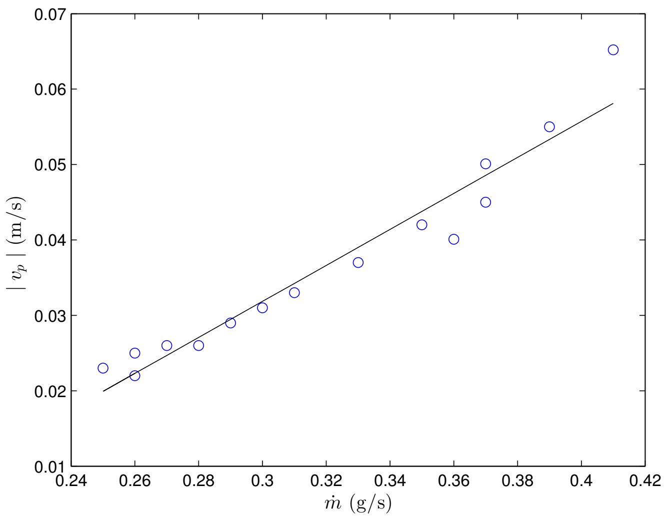


Figure 6: Variation of the mean celerity of plugs v_p as a function of the mass flow rate $\dot{m}$. ◯ correspond to values of celerity measured in several tests, the continuous line is a linear fitting showing the approximate linear dependence of v_p on $\dot{m}$.

4. CONCLUSIONS

This work presented experimental measurements of density waves in oscillating wave regime of granular flows falling through a vertical pipe. The objective of the paper was to determinate the mean celerity and the mean length of regions

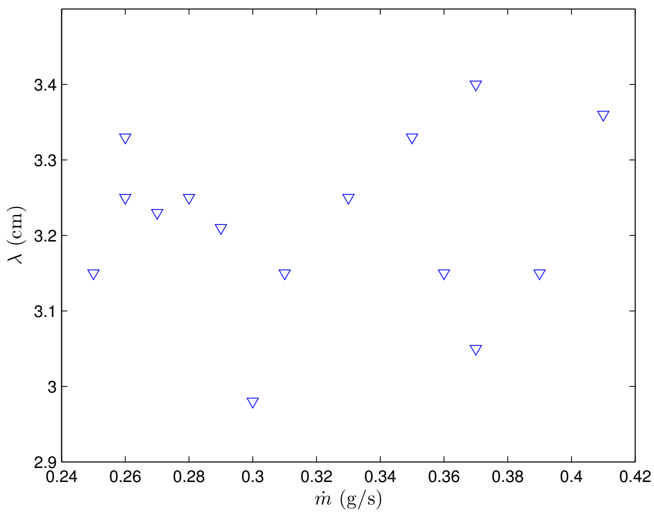


Figure 7: Characteristic mean length of plugs as a function of the mass flow rate $\dot{m}$. $\lambda \approx 30\ mm$

of high grain concentration, known as granular plugs. Both the mean celerity and mean wavelength were calculated using spatiotemporal diagrams. These diagrams were obtained from an image processing code developed in MatLab environment. The code permits to treat a large number of images automatically. Moreover, using the spatiotemporal diagrams we measured a characteristic oscillating frequency equivalent to 7 Hz, which is independent of the mass flow rate. In our experiments, we observed density waves when the mass low rate ranging between 0.25 and 0.40 g/s, these values are approximately ten times smaller than previously published results. These differences were recognized as result of both relative humidity conditions and surface state of the grains.

The mean celerity of plugs presents a linear dependence on the mass flow rate, and it is roughly constant along the pipe at least in the field of view analyzed. The mean length of plugs is independent of mass flow rate. Our results are in good agreement with the information of previous studies. An important issue to future works will be calculate the mean celerity and wavelength of the low compactness regions (bubbles), and to study the relation of these values with the mass flow rate. Other important task is to test tubes with other diameters and different mass flow rates.

5. ACKOWLEDGMENTS

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