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EXPERIMENTAL STUDY OF A GRANULAR MATERIAL FALLING THROUGH A VERTICAL PIPE

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Abstract. *Generally speaking, modern manufacturing methods of high-technology materials rely heavily on the utilization of granular materials. In many applications, the granular flow depends only on gravity. This paper reports experimental measurements of density waves of granular flows falling down in a vertical tube. In our experiments, the grains consisted of glass beads with diameter within* $106\,\mu m \leq d \leq 212\,\mu m$*, flowing down in a 3 mm diameter vertical glass pipe. Under these conditions, density waves appeared and were filmed with a high-speed camera. Density waves are characterized by alternating low and high compactness regions. The wavelength and the celerity of density waves were determined by digital image processing. Experimental results show that the mean wavelength is independent of the mass flow rate, and that the mean celerity has negative values and it has a linear dependence on the mass flow rate.*

Keywords: *granular flow, density waves, gravitational flow, pipe flow, digital image processing*

1. INTRODUCTION

The processing of granular media and aggregates consumes roughly 10% of all the energy produced on the Earth; this class of materials ranks second, only behind the water, on the scale of priorities of human activities (Duran, 1999). Several numerical and experimental studies have been conducted concerning granular flow in a vertical tube (Lee (1994); Raafat *et al.* (1996); Aider *et al.* (1999); Bertho *et al.* (2002); Bertho *et al.* (2003); Ellingsen *et al.* (2010); Franklin and Alvarez (2015)), any advance in understanding the physics of granular materials would have a major economic impact. The granular materials are involved in several industrial process, such as, pharmaceutical, cosmetic, manufacturing, construction, etc., however, its behavior is not yet well understood. In many industrial processes granular flows driven by gravity are commonly encountered, as in emptying silos or hoppers, modeling such flows is not an easy work, since they involve complex interactions of moving grains with the surrounding air, bounding walls, and other grains (Bertho *et al.*, 2003). One phenomenon that appears in the granular flows driven by the gravity inside a pipe, and which we are interested, is the appearance of density waves. Such flows may display undesired intermittency, and in some cases permanent blockage effects (Aider *et al.*, 1999). In addition, intermittent flows may induce very large, potentially destructive, pressure variations (Bertho *et al.*, 2003). These density waves can be reproduced, at the scale of the laboratory, with glass beads (as granular material) falling down in vertical glass pipes. Raafat *et al.* (1996) studied the characteristic geometry of the density waves, for their experiments they used a conical hopper attached to a vertical pipe of a length of 1.30 m and an internal diameter D of 2.9 mm. As granular material, they used small glass beads of mean diameter d of 0.2 mm, and glass splinters of mean size between 0.09 and 0.2 mm. 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.

The humidity H in the granular materials is other aspect that must be considered. Aider *et al.* (1999) using an experimental setup similar with that of Raafat *et al.* (1996) and with glass beads of average diameter d = 0.125 mm, observed that the humidity range must be between 35% and 70%. Values above of 70% produce clogging, due to capillary forces between particles, or between the particles and pipe wall. For the case when the humidity is lower than 35%, the electrostatic forces domain, and this also produces flow blockage. Aider *et al.* (1999) determined flow regime values associated to the density waves. When the grain mass flow rate W was 1.5-2.5 g/s were produced oscillating waves, and when W was 2.5-5 g/s propagative waves appeared. Therefore, it is possible to stated that 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 (Becco *et al.*, 2005). Moreover, it shall be mentioned the characteristics of experimental setup designed by Bertho *et al.* (2003). They used a vertical glass tube of a length of 1.25 m and internal diameter D of 3 mm, and spherical glass beads of diameter $d = 0.175 \pm 0.025$ mm. In both experiments Bertho *et al.* (2003) and Aider *et al.* (1999), a linear charge coupled device (CCD) camera was used for measuring the density variations; the frequency set by Aider *et al.* (1999) was up to 200 Hz, which is larger than the characteristic frequencies of the flow variations. The mass flow rate in the experiments was varied by an adjustable constriction located at the bottom of the tube. To determinate the wavelength and the velocity of granular density waves, Aider *et al.* (1999), Bertho *et al.* (2003) and Becco *et al.* (2005) used spatiotemporal diagrams, which are stored as numerical data arrays and visualized using any image processing program.

This paper is devoted to the density waves of granular flows falling down in a vertical tube using glass beads with diameter within $106\,\mu m \leq d \leq 212\,\mu m$. The wavelength and the celerity of granular density waves were determined by digital image processing using a numerical code developed in MATLAB environment. The descriptions of the experimental setup 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 SETUP

2.1 Experimental device and procedure

The experimental device is schematically presented in Fig. 1. It consists of 1.0-m-long vertical glass tube with an internal diameter D of 3 mm. It is attached to a conical hopper with an opening angle of 60 °, initially filled with glass beads. At the bottom of the tube a variable constraint (valve) is disposed, which can be moved across the pipe allowing one to adjust the outflow. The tube was vertically aligned (within $\pm 5°$) and both the hopper entrance and the exit of valve were at atmospheric pressure. The grains consisted of spherical glass beads with mean diameter d between 106 and 212 μm, and specific mass of ρ_s = 2,500 kg/m^3. Before performing the tests, the temperature and the humidity were measured within ± 0.5 $°C$ and ± 2.5$\%$ respectively. This is important because the flow regime is associated with the humidity value. The hopper was filled with clean grains, then the valve was partially opened to allow the grains to be driven by the gravity down the pipe, the mass flow rate was determined from the time variation of the measured mass, using a chronometer and a balance with ± 0.01 g of accuracy. The flow was visualized with a high speed camera with a spatial resolution of 1,280 px × 1,024 px mounted on a tripod to get an optimal control of field of view. The camera allowed to use high acquisition frequencies, up to 1,000 Hz, this makes possible capture the characteristics of grains flow that occurs very fast, besides the camera was fully controlled by a computer. In order to enhance the amount of the light the tube was illuminated by a grid of LED (Light Emitting Diode). This type of illumination is used because it avoid beating between the light source and the camera frequency.

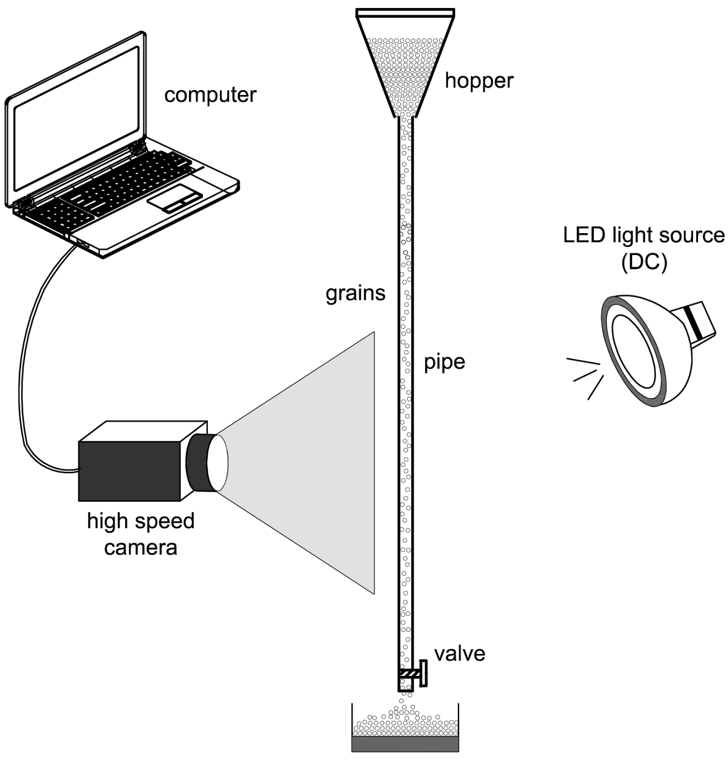


Figure 1: Experimental setup.

In the present studies the acquisition frequency was equal to 250 Hz. According to Aider *et al.* (1999) this value is larger than the characteristic frequency of the flow variations. The number of acquired images for each test was 1,500

(a) (b)

Figure 2: (a) Schematic view of free fall regime. (b) Schematic view of density wave regime. z is the vertical coordinate and λ is the wavelength of the granular plugs.

and were performed seven tests. Raafat *et al.* (1996) proposed that each individual density wave consists of two parts, the first being highly compact and dense, known as grains plug (sometimes known as clog), and the other being a bubble filled with air. Our observations were oriented to granular plugs. The density waves were experimentally obtained with a moderate constriction at the bottom of the tube. Figure 2 shows a schematic view of free fall regime, and Fig. 2b shows a schematic view of density wave regime. Table 1 summarizes some tests conditions. It presents, for each test run, the room temperature T, and the room relative humidity H.

Table 1: Tests conditions and mass flow rate.

Run	T	H
...	$^\circ C$	%
1	26	44
2	24	41
3	25	43
4	25	41
5	24	42
6	25	41
7	26	42

As it was previously mentioned, the number of tests was seven and the number of acquired images for each test was 1,500, giving a total of 10,500 images in RGB format to be analyzed. The numerical code developed uses the MATLAB functions for digital image processing. This numerical code provides measurements of wavelength and the celerity of the density waves. The next section presents the code.

2.2 Digital images processing

1. Entry:
   (a) Image
   (b) Frequency
   (c) Scale
   (d) Threshold
2. Loop (until the total numbers of images is achieved):
   (a) Reading an image

   (b) Selection of the area of the image that contains the grains flow
   (c) Converting RGB image to grayscale image
   (d) Converting grayscale image to binary image
   (e) Seeking areas greater than tube diameter
   (f) Showing images while they are computing
   (g) Storing granular plugs positions at different time instants

3. Post-processing:
   (a) Computation of the mean celerity of the granular plugs
   (b) Computation of the mean wavelength of the granular plugs

4. Graphs display:
   (a) Plotting the upper and bottom positions of the granular plugs as a function of time
   (b) Plotting mean wavelength λ of the granular plugs as a function of mass flow rate W
   (c) Plotting mean celerity v_p as a function of mass flow rate W

A brief explanation of some of the numerical code steps is given next.

- Image (1.a): each one of images acquired during the tests
- Frequency (1.b): it refers to the camera frequency used during the test. The time is calculated with this parameter.
- Scale (1.c): it allows to convert the image pixels to millimeters. It is calculated using a calibration image taken before the tests began.
- Threshold (1.d): as already stated, the density waves have two parts, the first highly compact, and the second filled with air. The selected threshold value must eliminate those zones that contains grains that belong to the second part, in other words, zones that are not part of plug.
- 2a: reading image and save as a matrix
- 2b: the code only seeks the image area that contains the grains flow, this area is limited by the tube walls. The next steps of the code only analyses the rows and columns involved.
- 2d: converts a grayscale image to binary image; therefore, functions as: regions props, and others associated with filters and threshold can be used.
- 2e: the code only searches the grains areas greater than tube diameter, this is by definition of granular plug.
- 2g: the upper and bottom positions of the plugs are saved in two row vectors
- 3a: The mean celerity is calculated using a linear adjust of the plugs trajectories.
- 3b. The mean wavelength is computed using the median calculated with the subtraction of the positions saved in the row vectors.

Figure 2a 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 format, next it is converted to binary format, and finally the code identify the plugs and the upper and bottom positions are marked. The Fig. 2b shows the presence of plugs with negative celerity, i.e., they propagated upward. The time between Fig. 2a and Fig. 2b is 0.16 s.

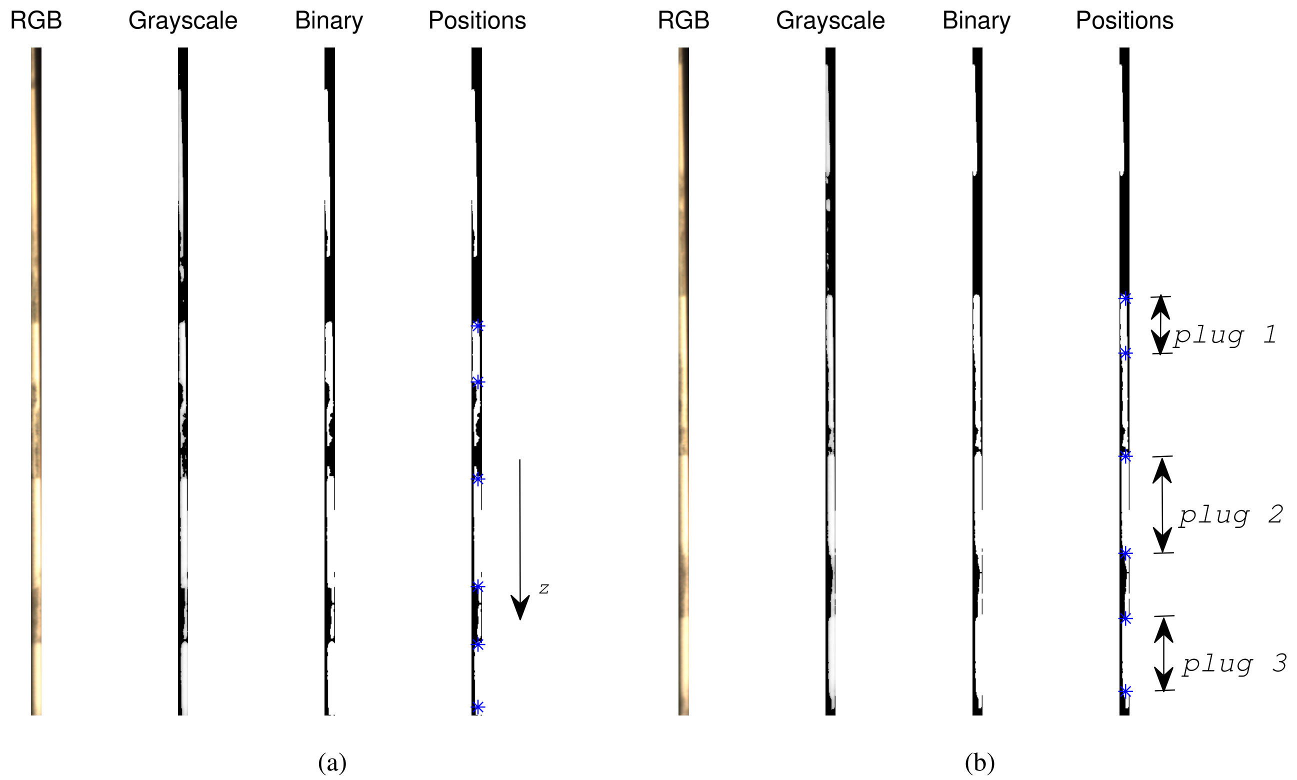


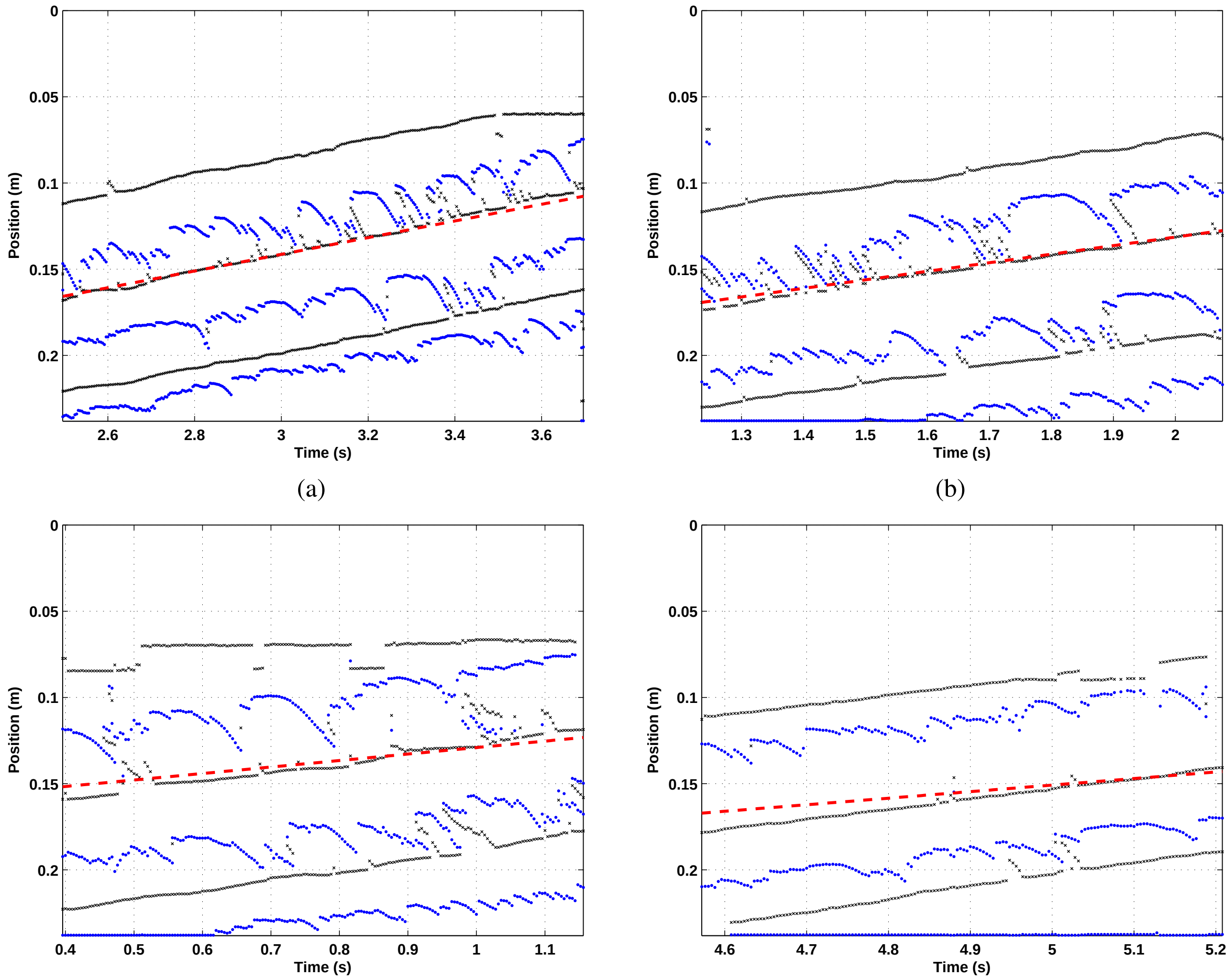
Figure 3: Density waves experimental observed. (a) The image while is being computed, the code has identified three granular plugs, (b) the plugs propagated upward. The elapsed time is 0.16 s.

3. RESULTS AND DISCUSSION

Figure 4 (a,b,c,d) presents the granular plugs positions as a function of the time at several mass flow rates, showing the behavior of the density waves obtained in the conditions summarized at Tab. 1. The vertical axis represents distances measured along the flow tube, the height of field of view is 237 mm. The field of view was taken in the tube section where the density waves appeared. The horizontal axis corresponds to time, increasing from the left to right. The variation as function of time for the upper positions of plugs is shown in black. For this zone a linear approximation allows determining corresponding slope. The variation for the bottom positions of the plugs is shown in blue, in some cases this zone has roughly zero celerity, and in others has negative mean celerity. The mean celerity of the plug, v_p, can be roughly determinate by the slope obtained for the upper zone. The slope shows that the plugs have negative mean celerity (according to our space reference). The plugs propagate upward. Qualitative observations confirm that fact. At Aider *et al.* (1999) is mentioned that v_p is also equal to the celerity of the moving plugs once a stationary propagation regime has been reached. Figure 4 also shows that v_p is approximately independent of height within the analyzed field. The calculated mean celerity, showed in dashed line, at Fig. 4a is -0.0434 m/s at mass flow rate W = 0.44 g/s. The other calculated values are summarized in the Tab. 2.

Table 2: Mean celerity calculated at several mass flow rate.

Run	W	v_p	λ
···	(g/s)	(m/s)	(m)
1	0.37	-0.0366	0.0306
2	0.40	-0.0389	0.0304
3	0.44	-0.0434	0.0305
4	0.52	-0.0491	0.0304
5	0.67	-0.0631	0.0304
6	0.55	-0.0538	0.0306
7	0.58	-0.0566	0.0301



(a) (b) (c) (d)

Figure 4: Plug positions as a function of the time at several mass flow rate. The plug upper and the bottom positions are shown in black and blue respectively. The mean celerity is shown in red dashed line, (a) v_p = -0.0434 m/s, (b) v_p = -0.0538 m/s, (c) v_p = -0.0366 m/s, and (d) v_p = -0.0566 m/s.

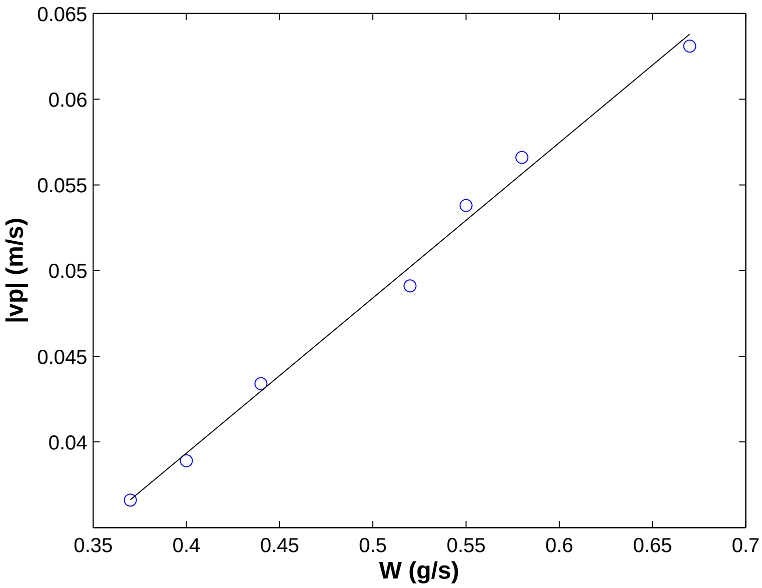


Figure 5: Variation of the mean celerity v_p of plugs as a function of the mass flow rate W. $\circ$ corresponds to measured v_p values and the continuous line is a linear fitting, showing the approximate linear dependence of v_p as a function of W.

It is important to point out that the mean celerity was negative for all tests. In our observations, the plugs always propagated upward, contrary to the flow direction. On the other hand, in previous works, Aider *et al.* (1999), Bertho *et al.* (2002) and Bertho *et al.* (2003); the plugs showed tendency to propagate downward, in same direction of the flow. That fact could be explained due to the environmental conditions and the flow rate used in our tests. In the cited studies the mass flow rates were ten times greater than our rates, however the environmental conditions were not significantly different. Raafat *et al.* (1996) used mass flow rates similar to our flow rates, they obtained values for v_p similar to the values calculated with the algorithm developed in the present study, besides, they showed that the plugs velocity is independent of measurement height and constant along the pipe. The velocity v_p plots in the Fig.4 shows a behavior similar to the observations done by Raafat *et al.* (1996). Aider *et al.* (1999) showed that the plugs mean celerity has a linear dependence on the mass flow rate; in this sense, we considered convenient to investigate if there would be linear dependence in our experiments. The variation of v_p (absolute values) as a function of W is displayed in Fig.5. The celerity of plugs increases linearly with W and ranges between -0.0366 and -0.0566 m/s. The results of linear dependence are similar to those provided by the literature.

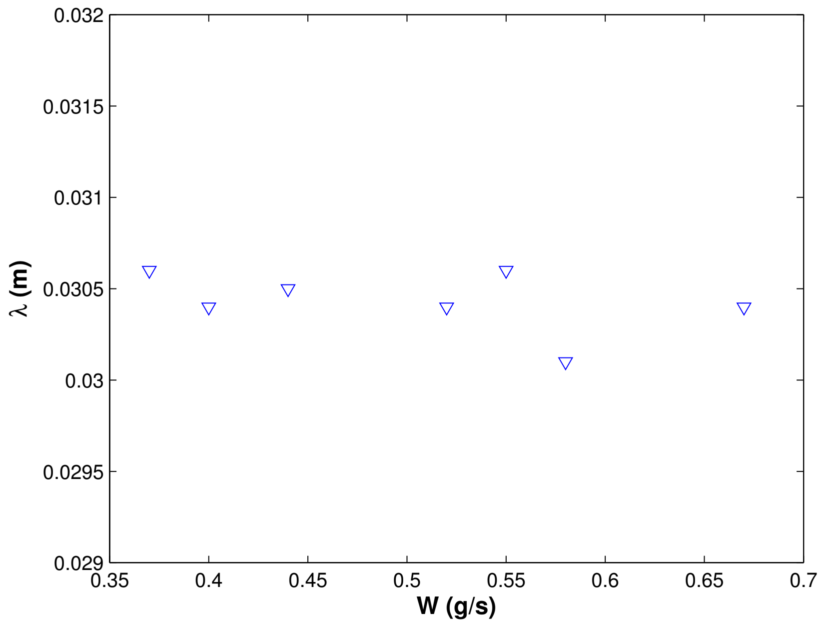


Figure 6: Characteristic wavelength of plugs as a function of the mass flow rate W.

In addition, the dependence of v_p on W could be calculated using a linear approximation, then extrapolating that variation one could observe that v_p would go to zero for a positive non-zero mass flow rate value; therefore, the mean velocity of the grains would be larger than v_p; individual grains could flow from upper to bottom position of plug (Aider *et al.*, 1999). In the present work the linear approximation was not done. The fact that the mean velocity of the grains would be larger than v_p explains because in our experiments had transient waves with stationary plugs. Finally, the Fig. 6 presents the mean wavelength of the plugs λ as a function of the mass flow rate W. As can be seen, λ is nearly independent of mass flow rate W, the latter is in good agreement with the results founded by Raafat *et al.* (1996) and Bertho *et al.* (2003).

4. CONCLUSIONS

This work presented experimental measurements of density waves of granular flows falling down in a vertical tube. The objective of the paper was to determinate the mean celerity and the mean wavelength of the high-compactness regions (plugs) of granular flow. Both the mean celerity and mean wavelength were calculated using a numerical code developed in MATLAB environment. A key observation concerns the direction of the mean celerity: in all tests the plugs propagated upward, contrary to flow direction; therefore, the celerity had negative values, and it corresponds to the celerity of the upper positions of the plugs. The bottom positions of the plugs had roughly zero celerity in some cases, and in others the plugs had negative mean celerity. In addition the mean celerity has 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 wavelength is independent of mass flow rate. Our results are in good agreement with the information of previous studies. An important issue for future works will be to 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.

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