Density waves in the gravitational flow of grains in narrow pipes

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Introduction

Gravitational grain flows in pipes are common in industry. When the grains and the tube diameter are size-constrained, the granular flow may display large variations in the particle fraction along the pipe, that may evolve to density waves [1]. These waves, that consist of alternate regions of high and low grain concentration, may induce intermittency and/or blockage effects and, in some cases, high pressure transients [2, 3, 4].

This work is an experimental study on the regions of high grain concentration, known as granular plugs, and its main objective is to determine their lengths (λ) and celerities (v_p).

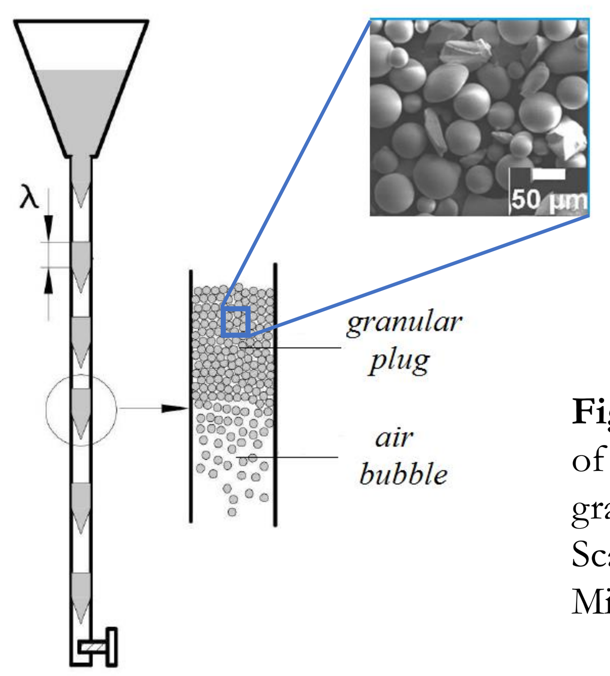

Figure 1. Schematic view of the density waves and grain image taken by Scanning Electron Microscopy.

Experimental procedure

A glass pipe of 3 mm ID and 1.0 m long was placed vertically, grains were introduced and flowed by gravity in the pipe, and the granular flow was filmed with a high-speed camera. The experiments were performed under controlled temperature and relative humidity. We employed spherical glass beads of ρ = 2500 kg/m³, divided in two populations: 106 µm < d < 212 µm, and between 212 µm < d < 300 µm. Moreover, we employed grains of both smooth and rough surface 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.

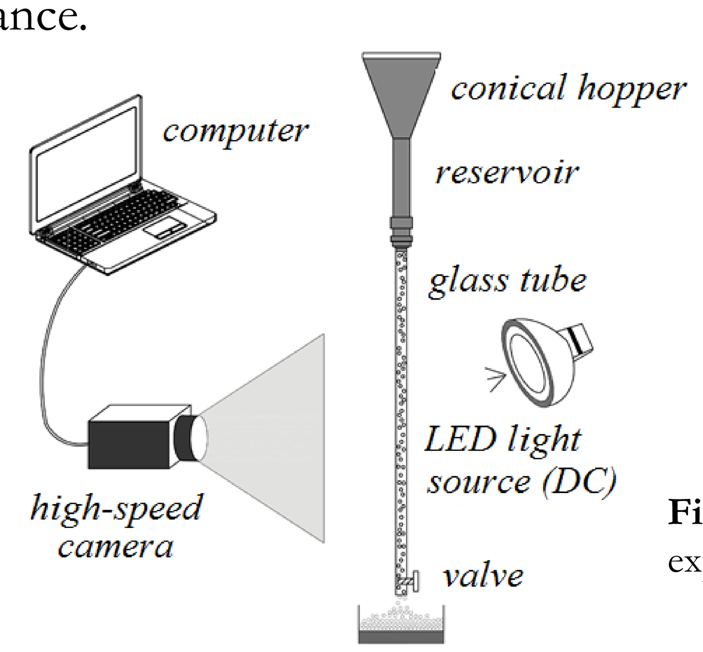

Figure 2. Layout of the experimental device.

Results and Discussion

An image processing code (developed in MatLab) was written to identify the granular plugs in the RGB images, to follow them along the images, and to compute their lengths and celerities (Fig. 3).

Two wave flow regimes were identified based on spatiotemporal diagrams. The first corresponding to density waves that propagated at a constant celerity (propagative wave regime), and the second corresponding to oscillating waves, with low and large amplitude oscillations.

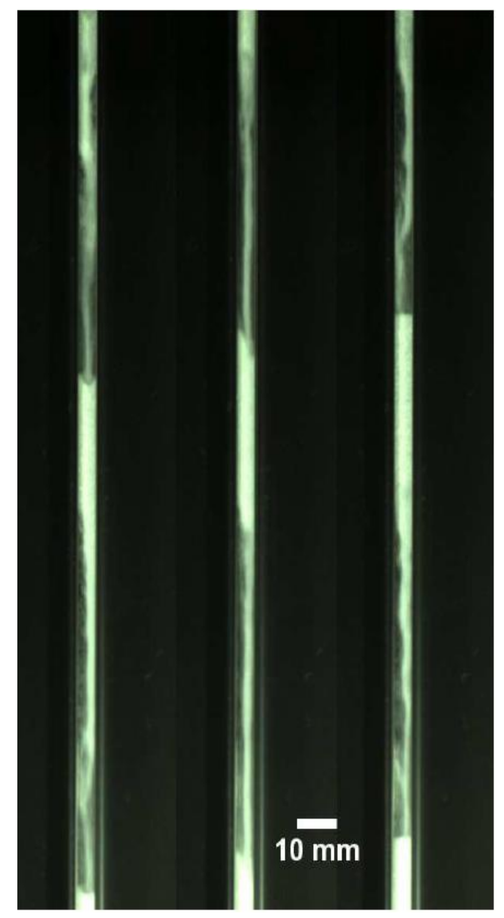

Figure 3. Images acquired during the tests showing density waves with negative celerity. The time between frames is 0.06 s.

Propagative wave regime

This regime appeared with smooth and rough surface grains, and diameters within 106 and 212 µm. In all tests within this diameter range, the density waves propagated upward, i.e., contrary to flow direction (negative celerity). The diagram in Fig. 4 is representative of all tests with grains in this diameter range.

In the spatiotemporal diagrams the upper and bottom plug positions are shown by black squares and blue circles, respectively. The mean celerity of plugs v_p is shown in the dashed line.

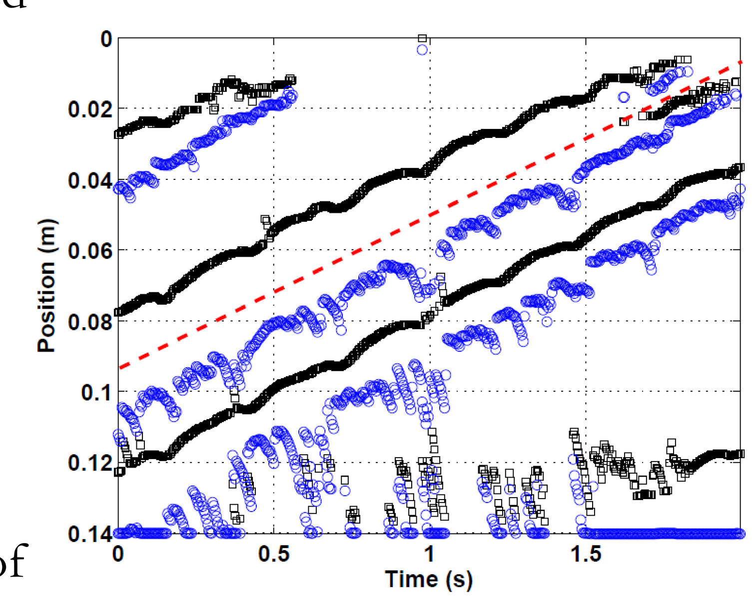

Figure 4. Spatiotemporal diagram of propagative wave regime for smooth surface grains. v_p = -0.0408 m/s, $\dot{m}$ = 0.40 g/s.

Oscillating wave regime

This regime appeared when the experiments were conducted using a batch of rough surface grains and diameters ranging between 212 and 300 µm. Density waves oscillated over a non-zero drift celerity (v_p). The plugs always propagated downward, in the same direction as the granular flow. Density waves oscillating at low amplitude appeared in some tests (Fig. 5). In other tests oscillating flows with amplitudes slightly larger than those observed in Fig. 5 were also detected (Fig. 6).

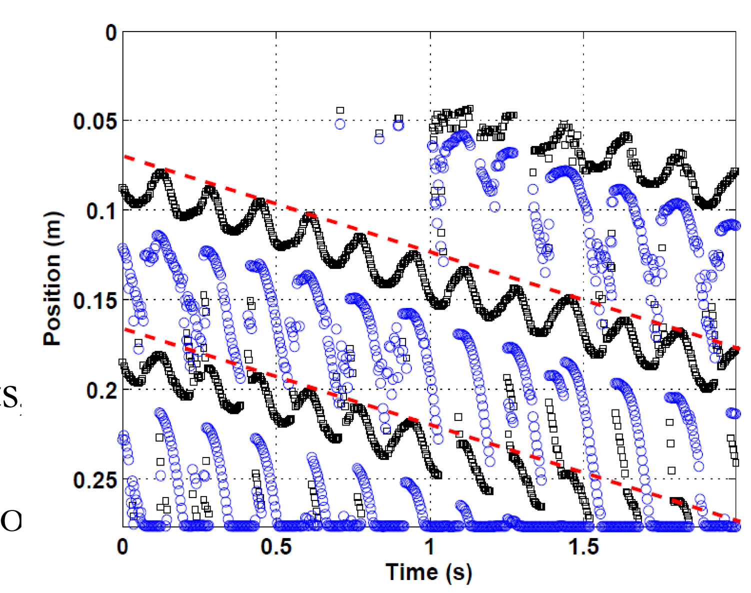

Figure 5. Spatiotemporal diagram of low amplitude oscillating waves. v_p = 0.0501 m/s, $\dot{m}$ = 0.37 g/s. The frequency of oscillations is in the order of 7 Hz.

Finally, the mean length of plugs λ was calculated using the spatiotemporal diagrams. The size of the plugs was approximately 30 mm (λ ≈ 10 ID), and it is independent of both the mass flow rate and the wave regime.

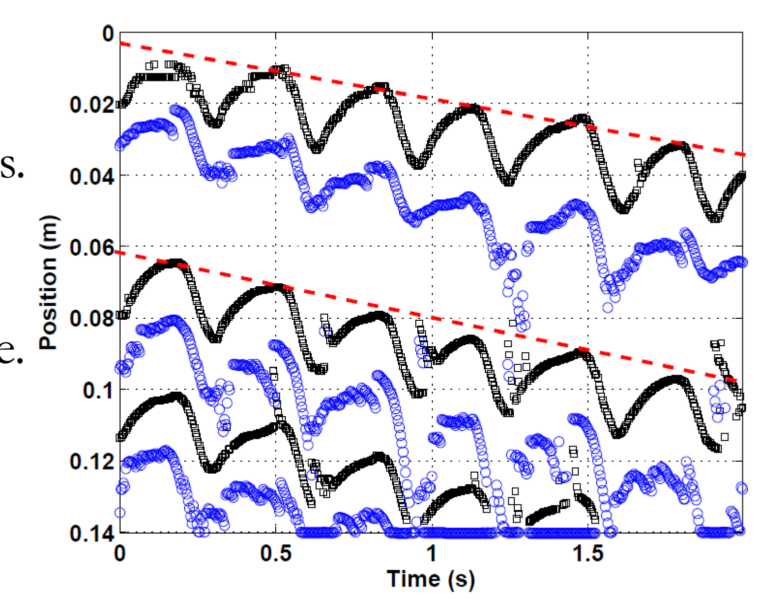

Figure 6. Spatiotemporal diagram of large amplitude oscillating waves. v_p = 0.0190 m/s, $\dot{m}$ = 0.25 g/s. The frequency of oscillations is in the order of 4 Hz.

Conclusions

When varying the mass flow rate $\dot{m}$ two wave regimes occurred: the density waves either propagated at a constant celerity or oscillated over a mean drift celerity. The density waves appeared with $\dot{m}$ between 0.1 and 0.95 g/s, ten times smaller than previously reported values. The relatively small mass flow rates may be due to two factors. The first is associated to the relative humidity (we observed density waves at relative humidity values smaller than those reported in previous works). The second is associated to the geometry and superficial roughness of the grains used. Images taken by Scanning Electron Microscopy allowed to observe that some grains were not perfect spheres, and that some grains contained little incrustations on their surface.

References

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For further information

For details of our work:

- E. M. Franklin, C. A. Zambrano: Length scale of density waves in the gravitational flow of fine grains in pipes, J. Braz. Soc. Mech. Sci. Eng. 37 (5) 1507-1513, 2015.

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