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Intermittent gravity-driven flow of grains through narrow pipes

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HIGHLIGHTS

- Density waves of granular flows in vertical tubes are investigated experimentally.
- The celerity and length scale of waves were measured by digital image processing.
- In some experiments the waves propagated contrary to granular flow direction.
- A one-dimensional model consisting of dimensionless equations is proposed.
- A linear stability analysis was used to find the typical length of density waves.

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ABSTRACT

Grain flows through pipes are frequently found in various settings, such as in pharmaceutical, chemical, petroleum, mining and food industries. In the case of size-constrained gravitational flows, density waves consisting of alternating high- and low-compactness regions may appear. This study investigates experimentally the dynamics of density waves that appear in gravitational flows of fine grains through vertical and slightly inclined pipes. The experimental device consisted of a transparent glass pipe through which different populations of glass spheres flowed driven by gravity. Our experiments were performed under controlled ambient temperature and relative humidity, and the granular flow was filmed with a high-speed camera. Experimental results concerning the length scales and celerities of density waves are presented, together with a one-dimensional model and a linear stability analysis. The analysis exhibits the presence of a long-wavelength instability, with the most unstable mode and a cut-off wavenumber whose values are in agreement with the experimental results.

1. Introduction

Granular materials play an important role in our daily lives, for instance, arid regions occupy about 20% of Earth's surface, 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 [1]. As a result, gravitational flows of these materials are frequently observed in nature and industry. However, the behavior of granular flows is not well understood, as granular matter is a discrete medium whose rheology is unknown. Given the importance of granular flows, considerable work has been done to understand their dynamics and instabilities [2–6].

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.

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When the grains and the tube diameter are size-constrained, granular flow may give rise to instabilities. These instabilities consist of alternating high- and low-compactness regions (regions of high and low grain concentration, respectively), and are characterized by intermittency, oscillating patterns and even blockages [7–9]. Although this instability may appear under vacuum conditions [10,11], in the case of fine grains these patterns are recognized as the result of the interaction between small-size falling grains and trapped air.

Lee [12] investigated the density waves in granular flows through vertical tubes and hoppers using analytical techniques and numerical simulations. The author used mass and momentum equations to describe density and velocity fields. In the equations, the law of friction proposed by Bagnold [13] was employed and the effects of both air pressure and drag caused on grains were neglected. For the vertical tubes, the author found that kinetic waves exist and partially obtained a dispersion relation for the dynamic waves, which he did not solve. The numerical simulations were performed using molecular dynamics (MD), and the author found indications that the density waves are of kinetic nature. However, because air effects (pressure and drag) were absent in both the stability analysis and the numerical simulation, the results are not suitable in the case of fine grains in narrow pipes. In addition, in the case of density waves, the grains in high-density regions are in permanent contact; therefore, MD is not an adequate method since it assumes binary and instantaneous contacts.

Raafat et al. [9] 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 observed density waves for moderate grain flow rate and when the ratio between the pipe and the grain diameter is $6 \leq D/d \leq 30$. Furthermore, they proposed that the friction between the grains and the forces between the trapped air and the grains are responsible for the density waves.

Aider et al. [7] 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. [9] using glass beads with mean diameter of 125 μm. The density variations were measured using a linear CCD (charge coupled device) camera with frequencies of up to 2 kHz. Aider et al. [7] observed that the density waves consisted of high-compactness plugs ($c \approx 60\%$, where c is the compactness) 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 waves) or 2.5 g/s–5 g/s (propagative waves). The authors also noted that humidity H must be within 35% and 75%, otherwise the grains clogged the tube due to capillary forces ($H > 75\%$) or due to electrostatic forces ($H < 35\%$).

Bertho et al. [8] presented experiments on density waves using an experimental set-up similar to that of Raafat et al. [9] and Aider et al. [7]. The vertical tube ($D = 3$ mm, 1.25 m long) and the glass beads ($d = 125$ μm glass beads) were more or less the same as those of Aider et al. [7], 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.

Recently, Franklin and Alvarez [14] presented a linear stability analysis and experimental results for the vertical chute of grains in a narrow pipe. They found a dimensional dispersion relation to be solved numerically, and the analysis was limited to some small ranges of grains and pipes. The experiments were performed in a 1 m long glass tube of 3 mm internal diameter aligned vertically, and the grains consisted of glass beads of specific mass $\rho_s = 2500\ \mathrm{kg/m^3}$ divided in two different populations: grains with diameter within $212\ \mu\mathrm{m} \leq d \leq 300\ \mu\mathrm{m}$ and within $106\ \mu\mathrm{m} \leq d \leq 212\ \mu\mathrm{m}$. Franklin and Alvarez [14] reported the existence of granular plugs with length in the range $3 < \lambda/D < 11$, where λ is the plug length.

Numerical studies on intermittent granular flows in pipes have been carried out in recent years. Ellingsen et al. [15] studied the gravitational flow of grains through a narrow pipe under vacuum conditions. They performed numerical simulations based on a one-dimensional model for the granular flow where the collisions were modeled using two coefficients of restitution, one among grains and the other between the grains and the pipe walls. A narrow pipe was assumed and periodic boundary conditions were employed. The numerical results showed that granular waves could form in the absence of air if the dissipation caused by the collisions among the grains was smaller than that between the grains and the walls. However, the proposed model cannot predict the wavelength of the density waves in the presence of interstitial gas. Verbücheln et al. [16], using particle-based numerical simulations, found that density waves depend on the mass flow rate, particle distribution, and geometrical parameters of the pipe (pipe diameter and wall roughness). The authors reported plugs moving with constant velocity along the pipe. Moreover, they observed that the plugs do not break up with the impact of the smaller particle groups that fall onto it. In other words, the frictional forces that yield the arches leading to plug formation are strong enough to sustain the downward pressure on the granular column. The numerical simulations were conducted with different pipe diameters, but the granular plugs usually appeared when the diameter was 3 mm.

The density waves appearing in gravitational flows have similarities with the waves appearing in the vertical pneumatic conveying in dense regimes [17–20]. Konrad [17] presented a review on the pneumatic conveying of grains in horizontal and vertical tubes. For dense upward flows in vertical tubes, the author explained the formation of plugs as the interaction between the pressure differences between consecutive air bubbles (low compactness regions) and the weight of grains within the granular plug. The former is directed upwards, whereas the latter is subjected to the Janssen effect and results in a drag force directed downwards.

Borzone and Klinzing [18] studied the formation of plugs in a vertical pipe of 25.4 mm internal diameter. Coal particles with diameters in the range $16\ \mu\mathrm{m} \leq d \leq 63\ \mu\mathrm{m}$ were pneumatically conveyed, and the pressure drop and the plug length were measured. The authors reported granular plugs with lengths in the range $2 < \lambda/D < 15$.