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Towards a quantitative understanding of pyroclastic flows: Effects of expansion on the dynamics of laboratory fluidized granular flows

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ABSTRACT

We conducted laboratory dam-break experiments on initially fluidized granular flows using two different fine-grained powders (mean grain sizes 47 and 67 μm) down a smooth, horizontal channel with an impermeable base. The powders were first fluidized and expanded to a known degree in the flume reservoir, then released down the channel by opening a sliding gate. The mixture formed rapidly moving flows that defluidized and deposited progressively as they propagated. The experiments were similar to those carried out previously using volcanic ash by Girolami et al. (2008, 2010) but explored a much larger range of initial aspect ratios (height-to-length ratio, $a = 0.25$ to 4). They were designed to investigate the effects of initial expansion (up to 50 vol.% above loose packing) and aspect ratio on the dynamics of flow propagation and deposition, and to explore different scalings in order to determine the physical parameters governing these processes. The flows exhibit a similar behaviour to other types of transient granular flows, including three well defined propagation phases (acceleration, constant velocity, and stopping phases) and the progressive aggradation of a basal static layer during emplacement. The deposit aggradation velocity depends only on the initial powder expansion and is similar to that of a collapsing bed of the same powder, expanded by the same amount, under quasi-static, non-shearing conditions. At a given initial expansion, the maximum runout distance scales with the initial bed height h_0, the runout duration with $(h_0/g)^{1/2}$ and the maximum velocity with $(gh_0)^{1/2}$. However, runout distance and duration both increase with increasing initial expansion. This is attributed to the effect of hindered settling in delaying defluidization of the dense, but slightly expanded, suspension. The data enable us to identify an additive scaling law providing a smooth transition from non-expanded to expanded flows.

1. Introduction

Pyroclastic flows are a major hazard around volcanoes, and there is a need to develop quantitative models of their flow and sedimentation in order to make predictions of environmental and human impacts. Quantitative measurements of pyroclastic flows are commonly limited to frontal velocity (Levine and Kieffer, 1991; Loughlin et al., 2002) and acoustic or seismic signals (Calder et al., 2002; Ripepe et al., 2010); much of what we know about their physics is inferred qualitatively from deposits (e.g., Sparks, 1976; Branney and Kokelaar, 2002). Laboratory-scale experiments can play an important role in quantifying the physical processes operating during flow propagation, determining the dominant parameters governing the dynamics, and inferring scaling laws applicable to the natural systems.

In this paper, we focus on dense pyroclastic flows in which the particle concentration during transport is of the same order of magnitude as that in the final deposit. The broad spectrum of pyroclastic flow types range from short-lived, highly unsteady flows generated by lava dome collapse or by fallback of vulcanian eruption columns, to the quasi-steady ignimbrite-forming flows generated by sustained fountain collapses (Druitt, 1998; Branney and Kokelaar, 2002). The present paper concerns the dynamics of laboratory granular flows applicable to transient, unsteady pyroclastic flows of small volume (Girolami et al., 2008, 2010).

A large literature exists on the dynamics of transient 'dry' granular flows (i.e., those in which the effects of the interstitial fluid on the flow dynamics are negligible). Different experimental configurations (rectangular or axisymmetric) allow the slumping of a granular column and the abrupt release of grains across a horizontal surface (Balmforth and Kerswell, 2005; Lajeunesse et al., 2005; Lube et al., 2005; Mangeney-Castelnau et al., 2005; Lube et al., 2005). These different studies have resulted in a general understanding of such flows. Their behaviour is governed primarily by the initial aspect ratio of the column ($a = h_0/x_0$, where h_0 and x_0 are the reservoir height and length respectively) and not by the volume of material involved or the grain properties (size and shape). The flows exhibit three propagation phases: (1) a short initial acceleration phase, (2) a dominant constant-velocity phase, and (3) a brief stopping phase. They consist of a flowing layer above a

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basal static region that aggrades progressively with time until the flow is consumed and all motion ceases. Additional results, obtained from discrete element modelling simulations (Girolami et al., 2012; Wachs et al., 2010, 2012; Girolami et al., 2013), show that the dynamics of the three phases of transport is strongly dependant on the initial aspect ratio a. This parameter determines the ability of the column to convert potential energy to kinetic energy during the collapsing phase (Girolami et al., 2013). For a 2D channel geometry and initial aspect ratios less than about 2, only a superficial zone is involved in the flow (Girolami et al., 2013). The maximum runout distance scales mainly with the initial column height, so that $x_\infty - x_0 = K_x\, h_0$, where x_∞ is the runout and K_x is a constant. The initial geometry becomes important only at higher aspect ratios (Balmforth and Kerswell, 2005; Lajeunesse et al., 2005; Lube et al., 2005). Channel width and sidewall friction can also influence runout (Balmforth and Kerswell, 2005). The runout duration t_∞ scales with the gravitational free-fall time of the initial granular column: $t_\infty = K_t\,(h_0/g)^{1/2}$. The constants K_x and K_t depend on the material properties of the particles, such as the friction angle (Balmforth and Kerswell, 2005).

The ability of dense pyroclastic flows to travel long distances on slopes of only a few degrees has been attributed to friction reduction by non-equilibrium gas pore pressures and associated fluidization effects (Sparks, 1976; Wilson, 1980; Druitt et al., 2007; Girolami et al., 2008, 2010), so that studies of ‘dry’ granular flows are not strictly relevant. Fluidization is the process whereby a vertical gas flow passing through a granular bed generates an interstitial pore pressure that counteracts interparticle contact forces. This causes the granular material to take on liquid-like properties (Kunii and Lebenspiel, 1991; Rhodes, 1998). Roche and colleagues (2004, 2008) carried out dam-break experiments to investigate the effects of the interstitial gas on the dynamics of highly concentrated flows of fine (size <100 μm) glass beads. In their configuration the granular material was first fluidized under controlled conditions in a reservoir before release. The flows propagated down a horizontal channel with an impermeable base, allowing them to defluidize during emplacement. The gas-particle mixtures had a runout distance and runout time that scaled in the same way as for dry granular flows, and they exhibited the same three flow phases. In the predominant, constant-velocity, phase 2 the flow behaved as an inertial (i.e. inviscid) fluid with a frontal velocity $(gh_0)^{1/2}$ reflecting a balance between gravity and inertia (Roche et al., 2008). Further work showed that the flows defluidized through pore pressure diffusion and developed a basal static zone that accreted with time, so that deposition occurred progressively (Roche et al., 2010; Roche, 2012). In the experiments of Roche et al. (2004, 2008) the initial fluidized column of fine glass beads was expanded by no more than 8 vol.% above the loose packed state. However, experiments on poorly sorted, fine-grained volcanic ash (which forms the matrices of pyroclastic flows) have shown that this material can expand up to 45 vol.% when fluidized owing to the small particle size and low material permeability (Druitt et al., 2007).

Girolami et al. (2008) therefore carried out a similar series of dam-break experiments, but using initially fluidized volcanic ash capable of expanding up to 45 vol.% above the loose-packed state and, owing to its low permeability, of retaining gas pressure for longer than glass beads and hence causing longer flow runout at a given value of h_0. The ash was heated to 200 °C in order to reduce cohesive effects in the fine powder. The initially fluidized ash flows behave fundamentally like the glass-bead flows and thin progressively by deposition until they run out of volume. By using high-speed video imagery and a particle tracking algorithm, Girolami et al. (2010) showed that the upper surface of the deposit aggrades at a mean velocity identical to that inferred to take place at the base of a collapsing quasi-static bed of the same ash, expanded by the same initial amount, in the flume reservoir with the lock gate closed. Rapid shear apparently does not significantly influence the deposit aggradation rate beneath the flows of expanded ash under the conditions studied.

The present paper now extends the experiments of Girolami et al. (2008, 2010) on dense but expanded flows. The previous experiments on volcanic ash involved only a small range of initial column aspect ratios. In the present study we use two synthetic powders with different fluidization-expansion properties, as well as a larger range of aspect ratios. We compare their behaviour with that of the ash and explore explanations governing the propagation and sedimentation of dense, but slightly expanded, flows of fine-grained powders.

2. Fluidization concepts

A granular material is said to be fluidized when the drag force exerted by an upward interstitial flow of gas counterbalances the weight of the particles and generates interstitial pore fluid pressure, allowing the material to behave macroscopically in a manner analogous to a liquid (e.g., Kunii and Lebenspiel, 1991; Rhodes, 1998). Quasi-static (i.e., one-dimensional) beds of fine but cohesionless granular materials of mean grain size typically less than 100–200 μm (i.e. group A powders of Geldart's classification; Geldart, 1973) exhibit three regimes of fluidization according to the vertical superficial gas velocity imposed (V, gas volumetric flux divided by horizontal cross-section area): (1) an aerated regime in which V is less than the minimum fluidization velocity V_{mf} ($V < V_{mf}$); (2) a regime of uniform expansion in which $V_{mf} < V < V_{mb}$, where V_{mb} is the minimum bubbling velocity, and (3) a bubbling regime in which $V > V_{mb}$. If a fluidized group A powder is first uniformly expanded ($V_{mf} < V < V_{mb}$), then the gas supply is cut, pore pressure decreases through a diffusion process and the bed surface undergoes hindered settling at velocity V_{sett} which increases with the initial expansion, while a deposit aggrades from the base upwards at a velocity given by:

$$V_{agg} = V_{sett}/(E-1) \qquad (1)$$

where $E = h_0/h_{mf}$, h_0 is the initial (expanded) bed height, and h_{mf} is the height at loose packing (i.e., at minimum fluidization velocity V_{mf}; e.g., Geldart, 1973; Lettieri et al., 2000; Druitt et al., 2007). The fractional expansion (fraction of excess gas) is equal to E-1.

Druitt et al.'s (2007) experiments showed that hot fluidized, poorly sorted sub-2 mm volcanic ash taken from the matrices of block-and-ash flow deposits and ignimbrites expanded significantly (up to 45 vol.%) prior to the onset of bubbling. Uniform expansion was greatest for fine-grained pyroclastic flow materials but decreased as coarser grain sizes were added. Our present experiments were therefore designed to evaluate the effects of initial uniform expansion on the dynamics of dam-break experimental flows of fluidized powders.

3. Experimental methods

The two powders, FCC and EZ, are industrial cracking catalysts used in the oil industry. FCC has a larger mean grain size (67 μm) than EZ (47 μm), and is better sorted (Table 1). Both powders are coarser and better sorted than the volcanic ash used in Girolami et al. (2008, 2010; Fig. 1, Table 1). FCC is non-cohesive and readily fluidizable at room temperature, whereas EZ is slightly cohesive and requires heating to expel atmospheric moisture before it can be fluidized. The EZ particles are more angular than the FCC ones. The maximum expansion possible in the non-bubbling state is larger for EZ (up to 50 vol.%) than for FCC (up to 25 vol.%). In some experiments, tracer particles of 500-μm silicon carbide were added in proportions up to a few vol%.

The experiments were carried out in a linear flume consisting of a rectangular fluidization reservoir (length 0.3 m, height 0.5 m, width 0.15 m), separated by a lock gate from a horizontal channel (length 3 m, height 0.3 m, width 0.15 m) built of aluminium and pyrex (Fig. 2). A metal partition enabled the material to be limited to a part of the reservoir, therefore reducing the effective reservoir length from 0.3 to 0.2 or 0.10 m. The reservoir and underlying windbox were heated