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Inviscid behaviour of fines-rich pyroclastic flows inferred from experiments on gas–particle mixtures

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Abstract

Experiments were carried out on granular flows generated by instantaneous release of gas-fluidised, bidisperse mixtures and propagating into a horizontal channel. The mixture consists of fine (<100 μm) and coarse (>100 μm) particles of same density, with corresponding grain size ratios of ~2 to 9. Initial fluidisation of the mixture destroys the interparticle frictional contacts, and the flow behaviour then depends on the initial bed packing and on the timescale required to re-establish strong frictional contacts. At a fines mass fraction (α) below that of optimal packing (~40%), the initial mixtures consist of a continuous network of coarse particles with fines in interstitial voids. Strong frictional contacts between the coarse particles are probably rapidly re-established and the flows steadily decelerate. Some internal friction reduction appears to occur as α and the grain size ratio increases, possibly due to particle rolling and the lower roughness of internal shear surfaces. Segregation only occurs at large grain size ratio due to dynamical sieving with fines concentrated at the flow base. In contrast, at α above that for optimal packing, the initial mixtures consist of coarse particles embedded in a matrix of fines. Flow velocities and run-outs are similar to that of the monodisperse fine end-member, thus showing that the coarse particles are transported passively within the matrix whatever their amount and grain size are. These flows propagate at constant height and velocity as inviscid fluid gravity currents, thus suggesting negligible interparticle friction. We have determined a Froude number of 2.61 ± 0.08 consistent with the dam-break model for fluid flows, and with no significant variation as a function of α, the grain size ratio, and the initial bed expansion. Very little segregation occurs, which suggests low intensity particle interactions during flow propagation and that active fluidisation is not taking place. Strong frictional contacts are only re-established in the final stages of emplacement and stop the flow motion. We infer that fines-rich (i.e. matrix-supported) pyroclastic flows propagate as inviscid fluid gravity currents for most of their emplacement, and this is consistent with some field data.

Keywords: Volcanology; pyroclastic flows; analogue experiments; fluidisation; granular flows; fluid gravity currents

1. Introduction

Pyroclastic flows consist of mixtures of gas and particles generated by gravitational collapse of lava domes

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or fall-back of eruption columns during explosive eruptions [1–3]. They represent major natural hazards because the flows are highly mobile as they can propagate over distances of the order of 1–100 km. A key issue for hazard mitigation is the better understanding of the physics of pyroclastic flows in order to develop appropriate models that aim to predict flow path, velocity, and run-out distance. Pyroclastic flows are highly polydisperse as particle size ranges from micrometric ashes to decimetric–metric blocks [4,5]. Decoupling between a basal dense layer and an upper dilute layer of fine particles elutriated from the lower part is common during flow propagation. In some cases, the dilute upper cloud may sediment quickly to form a secondary, surge-derived pyroclastic flow [6].

The present study focuses on dense, or at least the denser part of, pyroclastic flows the density of which is smaller but comparable to that of the resulting deposit, and whose emplacement mechanisms remain a matter of debate [3,4,7]. The gaseous phase probably has a fundamental influence on pyroclastic flow dynamics. A gas source is the exsolving of volatiles from the magma during ascent in the conduit, and subsequent fragmentation generates a fluidal mixture of gas and particles. Air entrapment at the flow front and gas release from particle abrasion during transport may generate additional sources of gas [8,9]. The amount of fine (ash) particles in the flow may have a fundamental influence on its emplacement as fines are likely to be highly responsive to any interstitial gas flux. This issue of the amount of fine particles in pyroclastic flows forms the focus of this paper.

Most published theoretical and laboratory studies on granular flows are not strictly relevant to pyroclastic flows as these commonly involve steady state flows of relatively coarse particles ($\gtrsim 100$ μm) whose dynamics are governed by interparticle friction and collisions, and with a negligible role for the interstitial gaseous phase [10–12]. The particle interactions commonly generate segregation of particles of different grain sizes [13–15]. However, recent studies indicate that interparticle friction may have a negligible influence in fast moving, unsteady flows generated by instantaneous release as driving forces are higher than the friction force for most of the flow emplacement [12,16,17]. Friction can also be considerably reduced if there is a continuous gas flux from below during flow propagation, and this greatly enhances the mobility of the granular matter even on a horizontal slope [18–20]. Experiments more relevant to the emplacement of pyroclastic flows consist of analogue flows generated from instantaneous release of gas-fluidised volumes of relatively fine particles (~80 μm) [21]. However, these flows propagated on constant slopes without leaving any deposit.

A more relevant case for the study of pyroclastic flow emplacement is a gas–particle flow generated from an instantaneous release that forms a deposit. We carried out experiments under these conditions on monodisperse flows propagating on a horizontal slope, and the results are reported in two publications [22,23]. These experiments revealed that, provided the particles are initially fluidised and sufficiently small ($\lesssim 100$ μm), flows propagate as buoyancy-driven fluid gravity currents, and internal friction is only significant at late stages of emplacement just before the flow stops. In contrast, flows of coarse and/or initially non-fluidised particles appear to be controlled throughout their emplacement by internal friction. The present paper extends our previous studies on monodisperse flows and we present an experimental investigation on bidisperse mixtures that is a first step towards the complex natural system. As monodisperse flows revealed contrasting patterns of behaviour depending on particle grain size, we particularly studied the role of the amount of the fine component on flow dynamics and emplacement. We show that bidisperse flows behave like monodisperse flows of fine particles above a threshold for the proportion of fines in the mixture.

2. Gas fluidisation of granular beds

Fluidisation is the process by which a granular material acquires a fluid-like behaviour and this is achieved when a gas flux passes vertically through a bed of particles [24,25]. At increasing superficial gas flow velocity (U_g), defined as the ratio between the air flow rate and the reservoir cross-sectional area, the drag exerted on the particles increases. In consequence, the weight of the particles is increasingly supported and internal friction is reduced. At this stage, the static bed is termed aerated. Fluidisation is achieved when the entire weight of the bed is supported, and this occurs at U_{mf}, the minimum fluidisation velocity. This incipiently fluidised, non-expanded granular medium is characterised by very weak particle contacts and internal friction is very low. The fluid-like nature of the bed means that objects rise or sink within the bed as their density is smaller or larger, respectively, than the bulk density of the bed, waves can form and propagate on the surface of the bed, and a jet will form if a container has a perforation in the wall. Bed expansion occurs at $U_g > U_{mf}$, and the top of the bed