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Piero Bareschino* Antonio Marzocchella† Piero Salatino‡
Teresita Gravina** Lucio Lirer†† Paola Petrosino‡‡

*Universita' degli Studi di Napoli Federico II
†Universita' degli Studi di Napoli Federico II
‡Universita' degli Studi di Napoli Federico II, salatino@unina.it
**Universita' degli Studi di Napoli Federico II
††Universita' degli Studi di Napoli Federico II
‡‡Universita' degli Studi di Napoli Federico II

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SELF-FLUIDIZATION OF FASTLY-MOVING GRANULAR GRAVITY CURRENTS WITH IMPLICATION ON PYROCLASTIC FLOWS

Piero Bareschino, Antonio Marzocchella, Piero Salatino
Dipartimento di Ingegneria Chimica
Teresita Gravina, Lucio Lirer, Paola Petrosino
Dipartimento di Scienze della Terra
Università degli Studi di Napoli Federico II
Napoli, Italy
T: 390817682258; F: 390815936936; E: salatino@unina.it

ABSTRACT

The fast motion of gravity currents of group A granular solids is studied with a focus on the dynamical structure of the frontal zone. The frontal zone of the current is "immobilized" and observed in a fixed frame of reference by letting the current flow inside a rotary drum, big enough to make curvature effects negligible. The establishment of a variety of flow regimes, including intermittent avalanching, periodic "plunging breaking" and permanent fluidization of the granular solids in the frontal zone, can be related to flow conditions and to the nature of the granular solids.

INTRODUCTION

During the last decade we have witnessed significant progress toward mechanistic understanding of the establishment and flow of pyroclastic gravity currents. In particular, the recognition of the role played by fluidization in the emplacement of dense pyroclastic flows, hypothesized since the late sixties (1-4), has recently received additional support (5-11). Notwithstanding, quantitative assessment of fluidization in pyroclastic flows is still poor. Broad uncertainties still characterize fundamental aspects of pyroclastic flows, like: a) the prevailing nature and source of the fluidizing gas, either endogenous or associated with entrainment of the surrounding medium; b) the rheology of aerated/fluidized dense gas-solid systems under high-speed strongly turbulent conditions; c) the perturbation to the classical phenomenology of fluidization determined by shear; d) the influence of solids polydispersity on fluidization, segregation and particle rheology; e) the complexity of bifurcational/dynamical patterns of rapid unsteady granular flows on account of the strong nonlinearity of the governing equations. The current lack of fundamental understanding, despite the extensive published literature on rapid granular flows (12), is largely due to the fact that investigations in this field mostly addressed steady flows of granular materials down inclines at velocities far smaller than those typical of pyroclastic density currents. Due to this limitation, most studies miss the complex dynamics of the frontal zone, which is likely to play an important role in the onset of fluidization. Moreover, the relative extent of frictional, collisional, streaming, elastic-inertial and turbulent stresses, which dictates the rheology of the flow (12), does not even approach conditions relevant to pyroclastic flows.

Recent studies on the subject have highlighted some features of subaerial rapid granular flows that might be relevant to pyroclastic density currents. The phenomenology associated with the dynamics of the frontal zone of gravity currents can be extremely variable depending on the propagation speed (and related Froude number) and on the medium within which the current propagates. In particular, some features observed in the frontal zone of subaqueous gravity currents (13) might also be relevant to the fast propagation of subaerial currents. Among these features, we underline the “overhang” effect, hypothesized by Wilson (3-4). The establishment of an “overhung” frontal zone and the fall-out of solids are associated with the establishment of dynamical overpressures in the basal layer of gravity currents (9) which may significantly exceed those predicted on the basis of the classical von Karman argument (14). Such overpressures provide the driving force for entrainment and uprise of the surrounding medium (particle-laden air) across the current which, in turn, may be responsible for aeration and fluidization of the granular system. Once established, the aerated/fluidized state of the granular solids is preserved over a de-aeration time scale which depends on the behaviour of the granular system with respect to fluidization. The relevance of the establishment of transient fluidization to the motion of the current is related to the comparison of the de-aeration and particle segregation time scales with a characteristic time scale of the flow (5,6).

The establishment of a fluidized state of the granular system significantly affects flow rheology. Frictional stresses as well as stresses of elastic-inertial nature (12) within the particle phase become vanishingly small as the granular systems is homogeneously fluidized, enhancing the propagation of gravity currents even on small slopes. The establishment of fluidized versus purely granular flow of the gravity current may be responsible for multiplicity of steady states and complex dynamical behaviour (9). Particle polydispersity (8,11) and sheared flow (7,10) are two keys to the establishment of homogeneous fluidization of granular systems. Polydispersity, an inherent feature of pyroclastic solids, is further emphasized by extensive occurrence of particle attrition in the flow (8). Cohesion and channelling in fine particle systems are suppressed by sheared flow, which considerably improves the quality of fluidization (7). Also particles belonging to the group B of the Geldart classification of powders can be brought to exhibit homogeneous fluidization and delayed bubbling behaviour as they are sheared (10).

The present study addresses the fast motion of gravity currents of group A granular solids with a focus on the dynamical structure of the frontal zone of the current and its interaction with the surrounding medium (air). The study is carried out with the aid of a rotary drum. The rationale of the experiment is that operating with a big rotary drum makes it possible to “immobilize” the front in a fixed frame of reference, a feature that enables thorough characterization of the structure of the front. At the same time the effect of curvature has been minimized by the use of a drum with a large (1800mm) inner diameter.

EXPERIMENTAL

Apparatus

The experimental apparatus is a big rotary drum, 1800 mm inner diameter and 200 mm width. The cylinder is rotated around its horizontal axis by a controlled step motor at a constant angular velocity in the range 5-30 rpm. The walls of the drum are made of 12 mm thick Plexiglas, which enables optical measurements under either front- or back-illumination. The roughness of the cylinder inner surface has been purposely increased by lining it with sand paper. A high-speed, highly light-sensitive mega-pixel CMOS camera interfaced to a computer and controlled with an image processing software was employed to record the experiments. Space resolution was 1024x1024 pixels, frame sampling rate was 1000 Hz. Post processing of video recordings was accomplished to obtain the main quantitative parameters of the flow.

Materials

The granular material used in the experiments was a narrow cut of FCC, 40μm diameter, 1580kg/m^3 particle density, belonging to the A-group of the Geldart classification of powders. The measured incipient fluidization velocity of the granular material was 1.3 x 10^{-3} m/s. Solids inventory was set at 9 kg, corresponding to a filling degree (the portion of the cylinder cross-section occupied by the bed) of 0.013.

RESULTS

The general phenomenology of granular motion is reported in Figure 1 as a function of the angular velocity of the drum. The peripheral velocity and the "canonical Froude" number, defined as $Fr_c = \omega R/(hg)^{0.5}$, corresponding to angular velocities of the rotary drum tested are reported in Table 1.

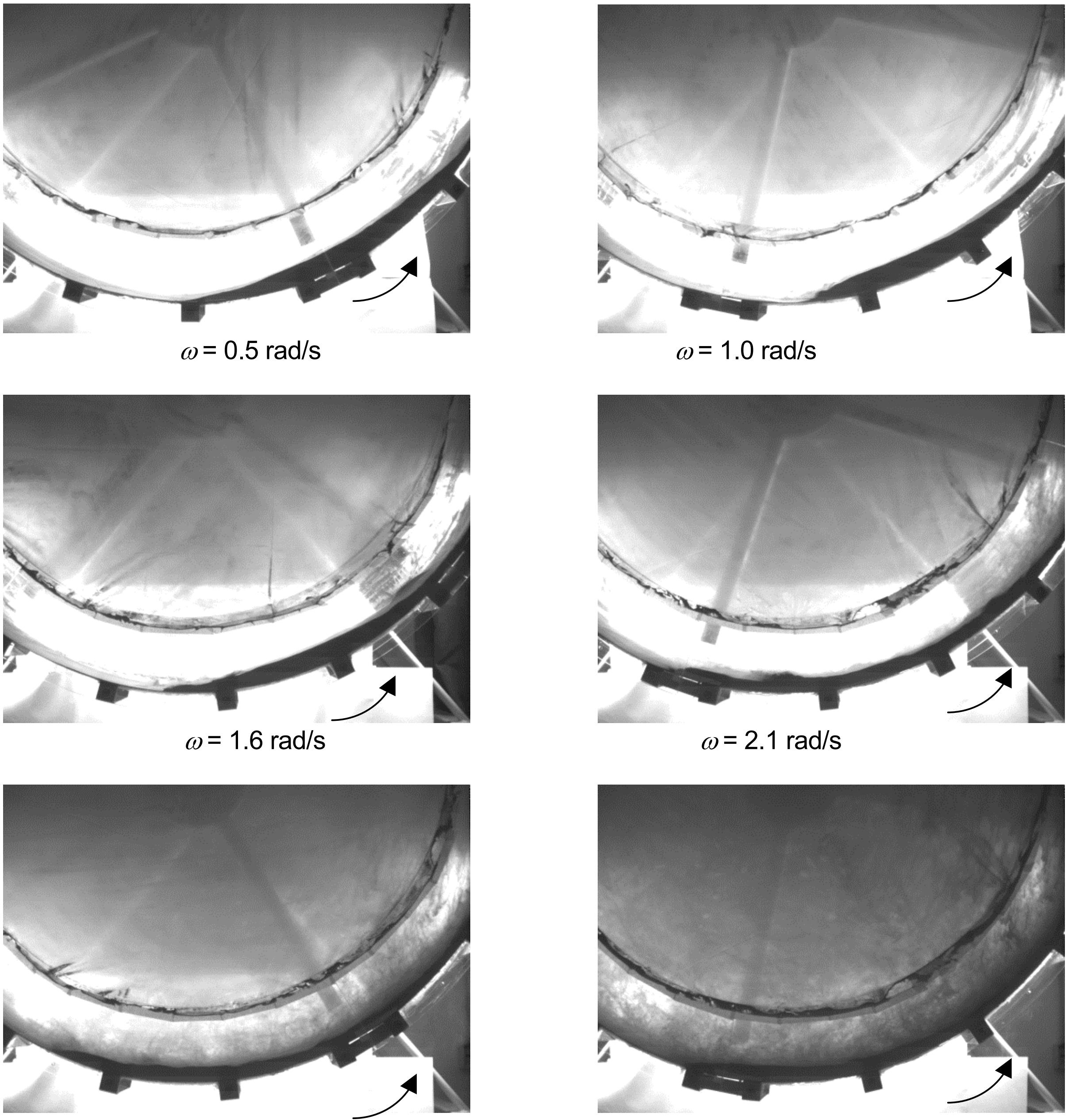
Single snapshots of continuous video recordings representative of the general behaviour observed throughout the tests are reported in this figure. With reference to the classification of flow behaviours in rotary drums proposed by Mellmann (15), the observed flow patterns conformed to:

a) *surging* (ω=0.5 and 1 rad/s): the flow is characterized by nearly rigid-body motion of the granular material with periodic switching of the nearly-planar free-surface of the bed between two limiting angles with respect to the horizontal, the upper of which being the static friction angle, the lower the dynamic one;

Table 1. Peripheral velocity and "canonical Froude" number for the experimental condition tested.

ω	**U**	**Fr_c**
rad/s	m/s	-
0.5	0.471	0.694
1	0.942	1.682
1.6	1.414	2.523
2.1	1.885	4.758
2.6	2.356	5.191
3.1	2.827	6.086

b) *slumping* (ω=1.6): the flow is characterized by quasi-periodic avalanching of bed solids occurring in a thin free upper layer of the bed. During each avalanche, the falling material entrains by shear the surrounding gas thus increasing its linear velocity as a consequence of its reduced apparent viscosity. As the falling material reaches the frontal region, it overhangs like a "plunging breaker", breaks down and deflates. Nearly rigid body motion characterizes the remainder of the bed. The upper-free-surface is still characterized by a nearly-planar shape;



ω = 0.5 rad/s

ω = 1.0 rad/s

ω = 1.6 rad/s

ω = 2.1 rad/s

ω = 2.6 rad/s

ω = 3.1 rad/s

Figure 1. Experimental profiles of the flow at different values of rotor angular velocity.

c) incipient *cascading* (ω=2.1): the free-surface of the granular bed becomes increasingly irregular and wavy and periodic avalanching onsets. The frequency of avalanches and the thickness of the upper layer involved in the avalanching process increase as the angular velocity of the drum increases. Occasionally, overhangs and "plunging breaker" behaviour occur along the upper free layer, as a consequence of avalanches overhanging each other. Entrainment of the surrounding air becomes extensive, both in the upper free shear layer and in the frontal region, driven by turbulence and vorticity. Due to the relatively long de-aeration time of the powder, the moving bed remains fluidized over the time interval between successive avalanches: a fluidized "tongue" of granular material paves the way to the main flow, occasionally moving uphill. Further increase in angular velocity leads to the fully developed cascading regime;

d) fully developed *cascading* (ω=2.6 and 3.1 rad/s): the avalanching process becomes continuous. The free-surface of the current, less well defined because of extensive elutriation/ejection of particles both in the frontal region and along the upper free shear layer, approaches the horizontal. The phenomenology of the motion resembles the behaviour of freely-moving inviscid liquids. The deflation time of the powder is far longer than the avalanching time: as a consequence, permanent fluidization of the whole granular bed is preserved.

The analysis of the regimes has been pursued further on a quantitative basis by frame-by frame measurement of: i) α, the central angle of the center-of-mass of the granular flow with respect to the vertical (see inset of Fig. 2); ii) σ^2, the variance of the time series

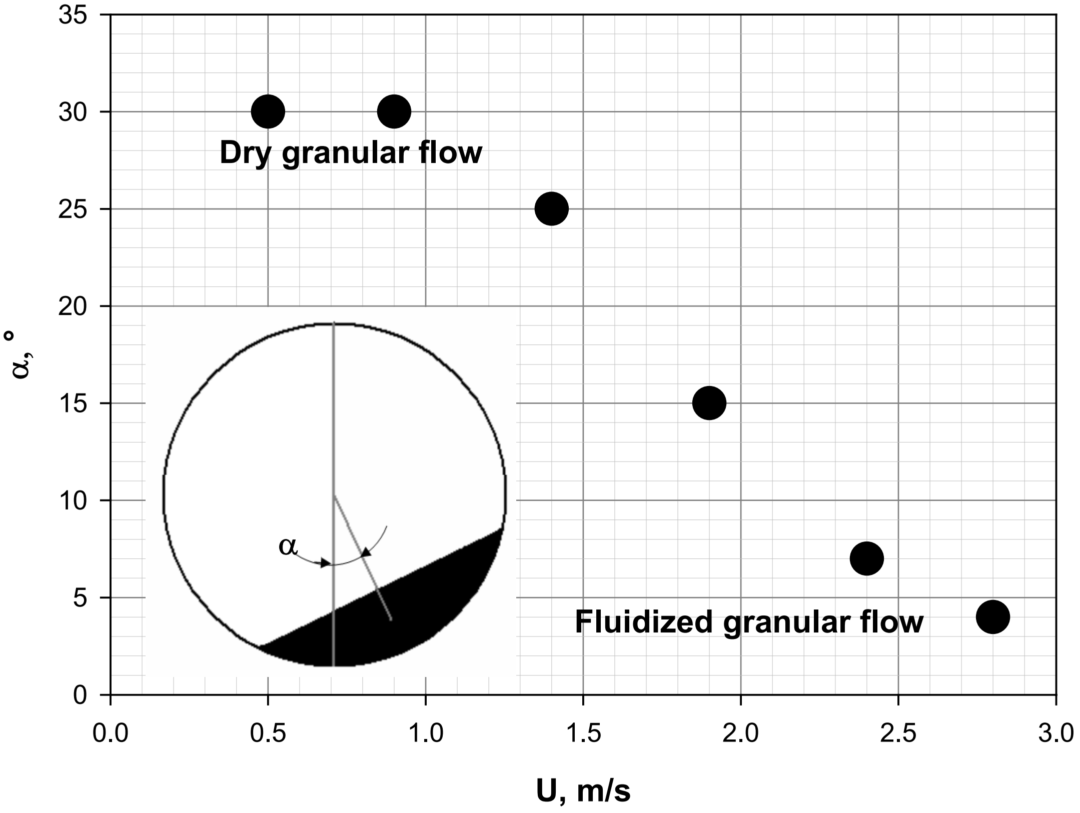


Figure 2. Mean central angle of the center-of-mass of the granular flow with respect to the vertical as a function of linear velocity.

of α; α and σ^2 are reported as a function of the linear velocity U in figures 2 and 3.

At low values of U (regime a, according to the previous description), the central angle α equals the dynamic angle of friction of the granular material. As the linear velocity increases in the range 1.5 – 2.0 m/s (regimes b and c), α decreases rather abruptly, reaching a very small value of about 5 degrees for U larger than 2.0 m/s (regime d). The pronounced decrease of α at linear velocities in excess of 1.5m/s (canonical Fr larger than about 2.5) should be related to the progressive change from a solid/plastic behaviour of the bed to a nearly inviscid one. The variance of α follows a non-monotonic trend: it is relatively small at low U, a maximum is found at around U = 1.5 m/s, σ^2 declines for U larger than 2m/s. The non monotonic trend of σ^2 reflects the conflicting effects of increasing amplitude of bed avalanching as the rotational speed is increased (U<1.5m/s) and of the dampening of periodic phenomena associated with the onset of the fluidized state (U>1.5m/s).

Altogether, the above observations suggest that: i) at small angular/linear velocity (and correspondingly small values of the shear rate) the granular flow shows a solid-plastic behaviour: the system undergoes plastic deformation to dissipate stresses; ii) as the angular velocity of the rotor increases, it can be speculated that the system undergoes an elastic-inertial regime as defined by Campbell (12), in which force chains characterized by rapid turnover withstand most of the stresses; iii) at even larger velocities, the inherent instability of the granular flow is responsible for the onset of avalanching, periodic at first, continuous at larger angular velocities. Under these conditions the phenomenology of the frontal region resembles that of "plunging breakers": projection of clusters of bed solids ahead of the front is driven by inertia, and is followed by collapse of the projected solids to the ground. Bed collapse forces the

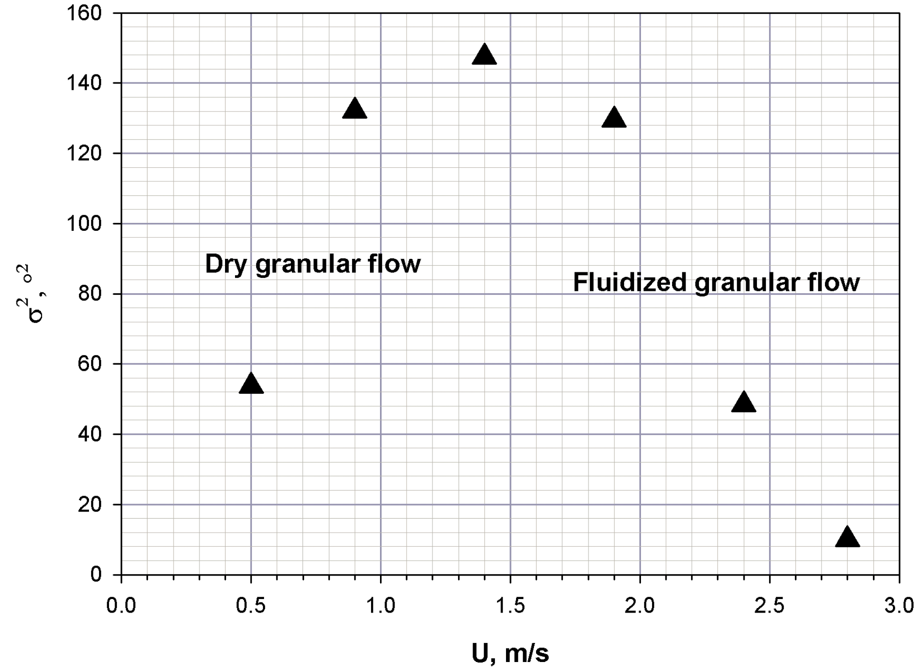


Figure 3. Time-variance of the angular position of the center-of-mass of the granular flow as a function of linear velocity

underlying air to percolate across the powder, promoting fluidization. This phenomenology broadly resembles the “overhang” effect of bed solids postulated by Wilson (3,4) and responsible for the motion-induced self-fluidization process of a granular current analyzed by Salatino (9). The main difference is that the projection/collapse of solids may occur as a quasi-periodic or periodic phenomenon rather than as a continuous on, depending on the velocity of the current. On the other hand, once fluidization is locally promoted by the collapse of bed solids, the extremely long de-aeration times of bed material ensures that the fluidized state is preserved over a time interval equal or larger than the flow time scale, and this smoothes out the effects of the intermittency of bed collapse. Altogether, the combination of air entrainment, fluidization promoted by avalanching and “plunging breaker” behaviour and inherently slow de-aeration of the bed powder is the key to the inviscid behaviour of the granular current observed at values of canonical Froude number larger than about 2.5.

CONCLUSIONS

The behaviour of group A granular currents moving over the ground has been simulated in experiments carried out with a big rotary drum. Experiments were focused on the structure and the dynamics of the frontal zone of the current, and on its interaction with the surrounding medium (air). Factors that promote air entrainment in the moving bed and the establishment of fluidization were assessed.

Experiments have been carried out in a range of angular velocities between 5 and 30rpm, corresponding to peripheral velocities in the range 0.47-2.9 m/s. A pronounced change of the phenomenology was observed across this range, with an almost abrupt change of the flow pattern from solid/plastic to free-flowing nearly inviscid at linear velocities between 1.5 and 2 (corresponding to “canonical“ Froude number of about 2.5).

The change of the flow regime is apparently related to the onset of avalanching, at rotational the inherent instability of the rapid granular flow. Avalanches eventually develop into “plunging breakers” whose collapse promotes extensive air entrainment and fluidization of the current. The scenario is completed by the extremely slow deaeration of the powder which ensures that the fluidized state, once established, is preserved over time intervals comparable with the flow time scale. The combination of avalanching and slow deaeration rate is the key of the self-fluidization process and of the nearly inviscid rheological behaviour of the current at large propagation velocity.

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