GAS-INDUCED FLUIDIZATION IN WATER-SATURATED SANDS

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Summary The morphology and dynamics of gas crossing a liquid-saturated granular bed has a drastic importance in natural and industrial processes. Due to the repetitive rise of gas through the bed, a fluidized zone is formed, which exhibits a parabolic shape at long times for a single injection point. This work investigates the fluidization of a liquid-saturated sand submitted to an ascending gas flow, in confined geometry. First, we focus on the fluidization dynamics from the initial state of a loose-packing, homogeneous bed. The stabilization time of the central air channel which is always formed in the stationary state is quantified, and its scaling inferred from an energy balance. Second, we investigate the global characteristics of the gas trapped in the system, in the stationary state. In particular, we show that the gas volume fraction in the fluidized zone is independent of the injection flow-rate and the grain diameter.

INTRODUCTION

Gas-induced fluidization of liquid-saturated sands is a process widely encountered, from geophysical to industrial processes. For instance, air sparging for soil remediation [1, 2], CO_2 sequestration [3] or catalytic processes [4] are among the numerous applications of these three-phase flows, which are still an active research topic. Indeed, due to the strong coupling between the gas, fluid and solid phase, the full understanding of the dynamics of such processes is still difficult to capture – in particular, the morphology and dynamics of the fluidized zone where the strong mixing between the three phases occurs. Many experiments have been developed in the laboratory to investigate the invasion dynamics of a fluid (liquid or gas) inside a liquid-saturated sand. In buoyancy-driven systems, where gas is injected from a single point at the base of a vertical cell, it has been shown that the gas rising through the grains forms a central fluidized zone at long times. Its stationary shape is parabolic, and a slow, global grain motion has been reported, with convective rolls following an upward motion close to the central air rise, and plunging downward close to the fluidized zone boundaries [5, 6]. In this work, we focus first, on the growth dynamics of the central fluidized zone, up to its stationary shape. Then, we investigate the dynamics of gas bubbles trapped in this central zone, and entrained by the granular convection rolls.

EXPERIMENTAL SETUP & DATA ANALYSIS

The experimental setup consists of a vertical Hele-Shaw cell (40×30 cm, gap 2 mm), filled with polydisperse, spherical glass beads immersed in water. In all the experiments, the height of the granular bed is $h_g = 20$ cm, and the liquid is filled up to a height $h_w = 2$ cm above the grains free surface. The grain diameter can be varied according to the following batches: $d = 218 \pm 17$ μm, $d = 318 \pm 44$ μm, $d = 631 \pm 37$ μm and $d = 802 \pm 68$ μm. At time $t = 0$ s, air is injected at the bottom of the granular bed from a central nozzle of inner diameter 1 mm, at constant flow-rate, Q. Direct visualization is achieved by means of a strong, homogeneous backlight (LED panel) and a camera (PixeLINK, 1280×800 px^2) acquiring at 0.1 Hz. Typically, the evolution of the system is followed up to 20 hrs.

The air invasion is analysed by stacking the successive image differences $(\mathrm{I}_{k+1} - \mathrm{I}_k)$, according to the method detailled in [6]. We introduce first, the *flow density*, defined as $\rho_n(x,z) = \sum_{k=1}^{n-1} |\mathrm{I}_{k+1} - \mathrm{I}_k|$, and it normalized value $\bar{\rho}_n = \rho_n / \max(\rho_n)$. To quantify the grain motion, we then define the horizontal and vertical cumulation, as $n_x(x,t) = \sum_x \rho_n(x,z)$ and $n_z(z,t) = \sum_x \rho_n(x,z)$, respectively, and their normalized value $\bar{n}_x$ and $\bar{n}_z$ over a given time series.

RESULTS

Growth dynamics of the fluidized zone

Figure 1a displays the flow density map in the system at different times. The fluidized zone starts forming from the grains free surface, then propagates downwards until reaching its stationary, parabolic shape (white dashed lines, Fig. 1a). The analysis of $\bar{n}_x$ and $\bar{n}_z$ makes it possible to quantify the stabilization time τ_s of the central air channel (white dashed line, Fig. 1b). The stabilization time is a decreasing function of the flow-rate (Fig. 1c), and this trend does not depend significantly on the grain size. A theoretical argument accounting for the grain motion, based on the balance between the energy injected in the system and the energy necessary to move grains over the system height h_g, gives $\tau_s \propto Q^{-2}$, in good agreement with the experimental observations (Fig. 1c). This result enhances the importance of the coupling between the grains, fluid and gas motion. Indeed, for a rigid porous network, a simple geometrical argument gives $\tau_s \propto Q^{-1}$, which does not fit the experimental trend (Fig. 1c).

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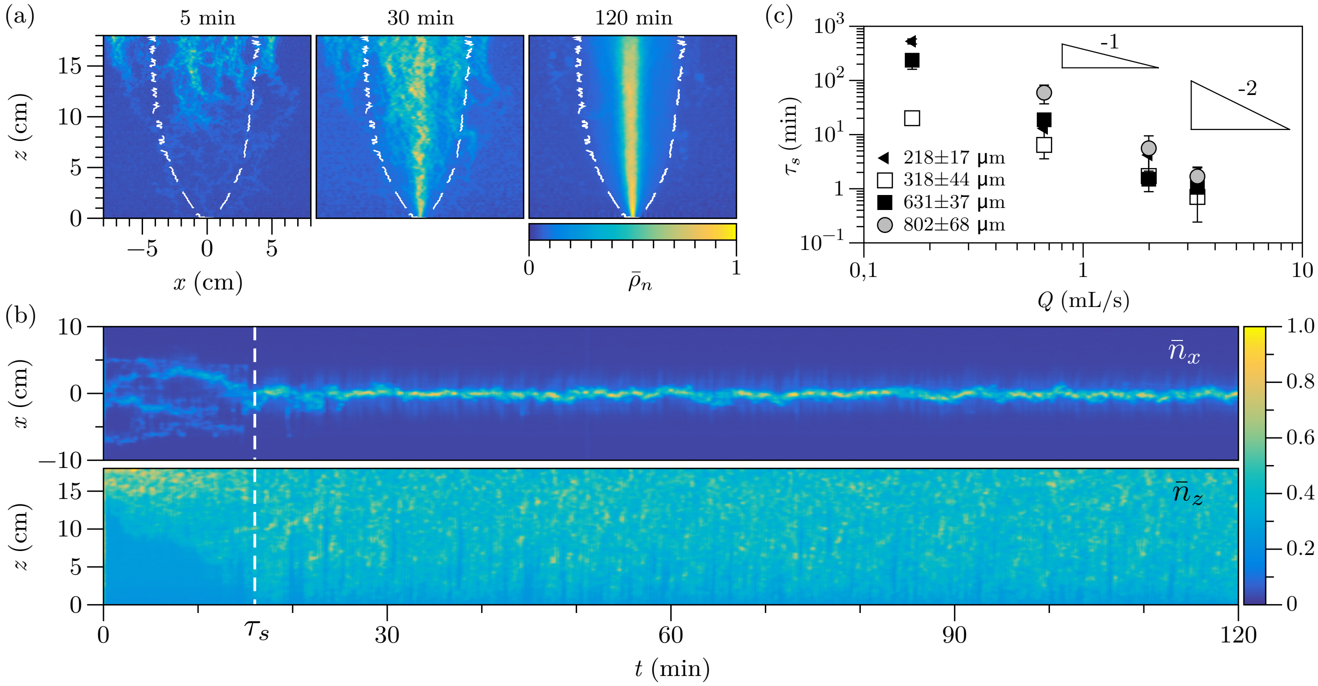

Figure 1: (a) Growth of the fluidized zone. The colors represent the normalized flow density $\bar{\rho}_n$, representative of the motion in the system. At short times, the motion concentrates close to the surface, then the fluidized zone develops downward. After about 20 min, the air rise focuses on the center of the fluidized zone. The white dashed lines represent the border of the fluidized zone in the stationary regime, at long times [$Q = 0.66$ mL/s, $d = 318 \pm 44$ μm]. (b) Spatiotemporal diagram of the horizontal ($\bar{n}_x$) and vertical ($\bar{n}_z$) cumulation [same parameters than (a)]. The stabilization time, $\tau_s \sim 18$ min, is indicated by the white dashed line. (c) Characteristic time of the air channel stabilization, τ_s, as a function of the flow-rate Q, for different grain size. The triangles indicate $\tau_s \propto Q^{-1}$ et $\tau_s \propto Q^{-2}$ (see text) [$h_g = 20$ cm, $h_w = 2$ cm].

Gas volume fraction in the fluidized zone

In a second part, we focus on the stationary regime, and investigate the air volume fraction, ϕ_a, trapped in the central fluidized zone. Without any asumption on the final shape of the fluidized zone, we quantify its volume and show that it increases as $Q^{1/2}$. Interestingly, the air volume fraction ϕ_a in the fluidized zone is roughly constant when varying the air injection flow-rate, and does not depend significantly on the grain size.

CONCLUSIONS

This work summarizes experimental results on gas-induced fluidization in water-saturated sands. Interestingly, for a single injection point, the final parabolic shape of the fluidized zone is similar to the gas invasion pattern in a rigid porous medium [6]. We propose that the granular bed region initially explored by gas percolation becomes more fragile, and finally leads to the central fluidized zone. After quantifying the growth dynamics of the fluidized region, we have shown that the gas volume fraction trapped in the fluidized zone is constant and of about 2%. This last result is of importance in applications such as air sparging or catalytic reactors, as it demonstrates that increasing the injection flow-rate does not necessarily increases the fraction of gas in the region where the three phases mix.

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