Phase Diagram of Vertically Shaken Granular Matter

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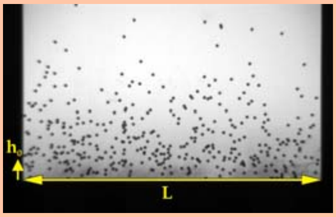
Goal

We want to construct a full experimental phase diagram for a vertically shaken shallow granular bed, and to find the dimensionless control parameters that govern the various phase transitions.

Experimental setup



- Quasi 2-D container: Length x Depth x Height (L x D xH) = 101 x 5 x 150 mm.
- Partially filled with glass beads of diameter d=1.0 mm.
- The frequency f is linearly increased (@75 Hz/min) for fixed amplitude a.
- The experiment is recorded with a high-speed camera.

Dimensionless control parameters

1. Shaking parameter: $\frac{a^2\omega^2}{g\ell}$ (ω=2πf and g=9.81 m/s²)

   i.e., the ratio of the kinetic energy inserted by the vibrating bottom and the potential energy associated with a typical displacement of the particles ℓ.

   - For *mild* fluidization the displacement of the particles is determined by the amplitude of shaking, since the bed closely follows the motion of the bottom;

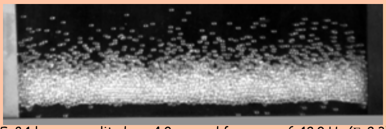
   $\ell \propto a \Rightarrow \Gamma = \frac{a\omega^2}{g}$ (dimensionless shaking acceleration)

   - For *strong* fluidization the particles move faster than the bottom. Therefore their motion is no longer determined by the amplitude and some intrinsic length scale needs to be taken, such as the particle diameter;

   $\ell \propto d \Rightarrow \frac{a^2\omega^2}{gd} \equiv S$ (dimensionless shaking strength)

2. Number of particle layers: F
3. Inelasticity parameter: $\varepsilon = \left(1-e^2\right)$ (taken to be constant)
4. Aspect ratio: $\frac{L}{h_0} >> 1$ (h_0 denotes the bed height at rest)

Bouncing bed



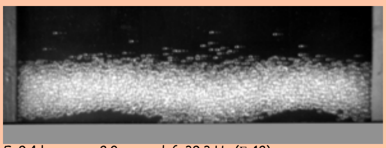
F=8.1 layers, amplitude a=4.0 mm and frequency f=12.0 Hz (Γ=2.3)

The granular bed bounces as a single body.

Gravitation *plus* the friction with the container walls has to be overcome.

This occurs for *mild* fluidization, so Γ is the relevant shaking parameter.

Undulations



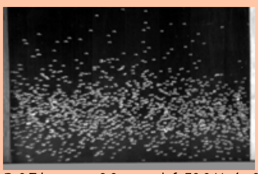
F=9.4 layers, a=2.0 mm and f=39.3 Hz (Γ=12)

The bed shows standing wave patterns oscillating at twice the period of shaking.

The particles along the bottom dilate horizontally and are forced into these arches.

It occurs for *mild* fluidization and the transition towards undulations is governed by Γ.

Gas



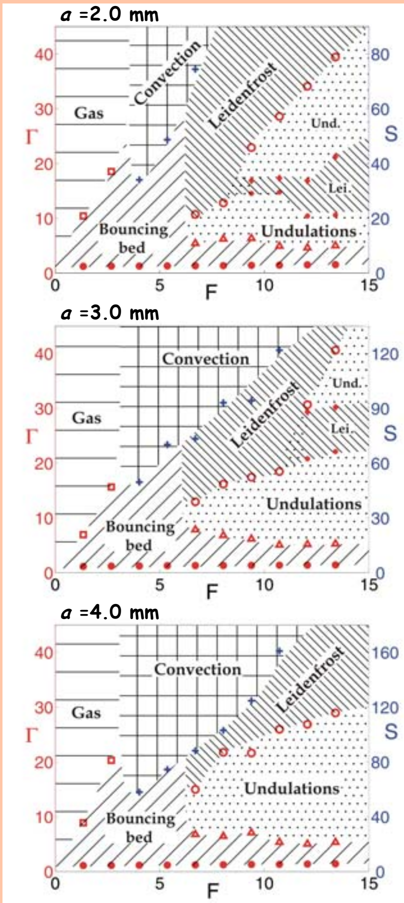
F=2.7 layers, a=3.0 mm and f=50.0 Hz (Γ=30)

A dilute cloud of particles moving randomly throughout the container.

This granular gas originates from a bouncing bed, which vaporizes above a certain shaking intensity.

Γ seems to control the transition, but too few data points are available to make this conclusive yet.

Phase diagram

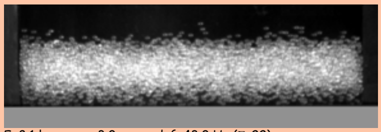


Both shaking parameters (Γ and S) are used in this diagram, each of them indicating the respective transitions they were found to govern.

Most phase transitions are hardly affected by the varied amplitude.

Exception: the transitions between the undulations and the Leidenfrost state for *intermediate* fluidization. Here is a competition of length scales: the amplitude a, the particle diameter d and additionally the wavelength of the undulations, which depends on the elastic properties of the particles. This becomes especially clear for a = 2.0 mm where the competition results in an alternation of states. By increasing a it becomes the dominant length scale and the alternation vanishes.

Granular Leidenfrost effect



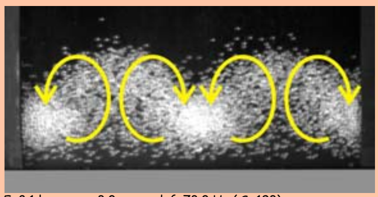
F=8.1 layers, a=3.0 mm and f=43.0 Hz (Γ=22)

A dense cluster of beads is elevated and supported by a dilute gaseous layer of fast beads underneath.

The bottom layer of the undulations evaporates and forms the gaseous region. This is analogous to the original Leidenfrost effect in which a water droplet hovers over a hot plate on its own vapor layer.

It occurs for *intermediate* fluidization, so both Γ and S are candidates to describe this transition: the best shaking parameter here turns out to be Γ.

Convection



F=8.1 layers, a=3.0 mm and f=73.0 Hz (S=193)

Counter-rotating convection rolls, reminiscent of Rayleigh-Bénard cells in an ordinary fluid heated from below. The beads move upwards in the dilute regions and are sprayed sideways to the dense clusters.

Convection is triggered when a set of particles in the cluster get more mobile than the surrounding area, in this way creating an opening in the bed.

This takes place for *strong* fluidization, so S is the relevant shaking parameter for this transition.

References

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