The granular Leidenfrost effect

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FOM

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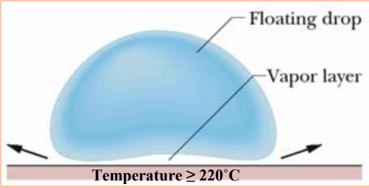
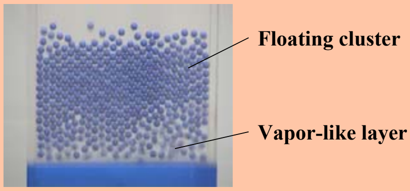
Johann Gottlob Leidenfrost (1756)



A drop of water hovering over a hot plate on its own vapor layer.

Granular Leidenfrost effect



Vertically vibrated glass beads: Above a critical shaking strength, a crystalline cluster (analogous to the Leidenfrost drop) floats on a vapor-like layer of much faster beads.

How to distinguish the cluster from the vapor-like region?

We employ the concept of pair correlations between the particles (N) in a horizontal strip (y, $y+dy$):

$$g_y(x) = \frac{1}{N} \sum_{i,j \; in\,(y,y+dy)} \sum_{i \neq j} \delta\left(x - \left(x_i - x_j\right)\right)$$

- Strip near bottom: particle positions show hardly any correlation, i.e., typically gas-like.
- Strip inside floating cluster: strong periodic, crystalline correlation in the x direction.

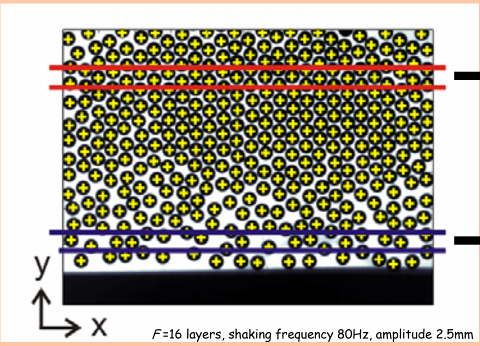
This clear distinction between periodic and non-periodic behavior in $g_y(x)$ is used in the order parameter O:

$$O(y) = \int \left| g_y(x) - g_{y,fit}(x) \right| dx$$

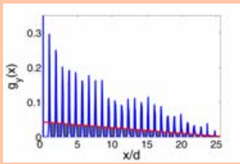
(the shaded area in the pair correlation plots)

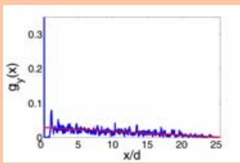
The transition from gas to crystal (the so-called inversion height h_{inv}) is located at the point where the slope of the fit through $O(y)$ is maximal.

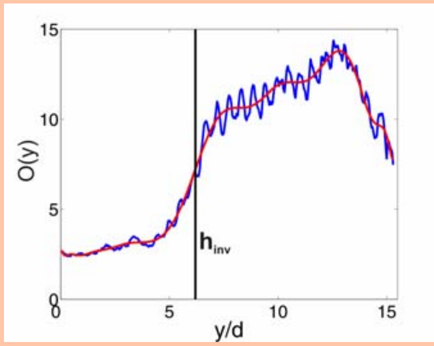
A non-zero inversion height is our key indicator for the Leidenfrost effect.



F=16 layers, shaking frequency 80Hz, amplitude 2.5mm







Hydrodynamic model

The effect is quantitatively described by three hydrodynamic equations:

Equation of state $\quad p = nT\dfrac{n_c + n}{n_c - n}$

Force balance $\quad \dfrac{dp}{dy} = -mgn$

Energy balance $\quad \dfrac{d}{dy}\left(\kappa \dfrac{dT}{dy}\right) = \dfrac{\mu}{\gamma l}\varepsilon n T^{3/2}$

(heat flux) (dissipation)

- p – pressure
- n – number density (n_c=2/√3d²)
- T – granular temperature
- m – mass of a single particle
- κ – thermal conductivity
- l – mean free path
- μ, γ - constants

Non-dimensionalizing these equations (and the associated boundary conditions) we find that the problem is governed by **three dimensionless control parameters**:

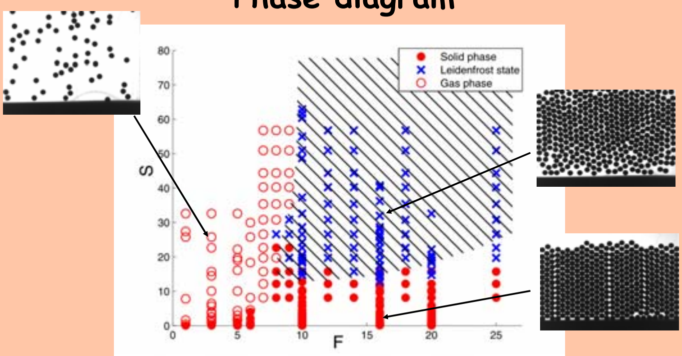
[1] The energy input $\quad S = 4\pi^2 \dfrac{m(af)^2}{mgd} = \dfrac{\text{typical kinetic energy a bead gets from bottom}}{\text{energy needed for a bead to jump to height } d}$

[2] The inelasticity $\quad \varepsilon = \left(1 - e^2\right)$

[3] Number of particle layers $\quad F$

- d – particle diameter
- e – coefficient of restitution

Phase diagram



- Excellent agreement between experiment (dots, crosses) and theory (shaded area).
- The Leidenfrost state shows up between the solid and gas phase, for sufficiently large shaking strength ($S \geq 16$) and number of layers ($F \geq 8$).

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