Gallery of Fluid Motion

Coat or collapse?

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Archimedes' principle states that the upward buoyant force on a submerged object is equal to the weight of the liquid it displaces. For large objects, this is often sufficient to predict whether they will float or sink: objects less dense than the liquid tend to float, while denser objects sink. However, this principle primarily applies to macroscopic bodies and does not fully capture the physics governing small, dense objects at liquid interfaces. Galilei [1] first noticed that Archimedes' principle overlooked the liquid displaced by the meniscus around the object, which provides an additional supporting force due to surface tension [2]. Research on the stability of dense objects at liquid interfaces is crucial for understanding natural phenomena and developing novel industrial applications [3], especially for many-particle systems. Here, we experimentally investigate the stability of an aggregate of dense particles by mechanically deforming it with a rod, which leads to either a uniform particle coating or collapse of the particle layer.

Particle aggregation at liquid interfaces is commonly observed in everyday situations, such as when breakfast cereals like Cheerios cluster at the surface of a bowl of milk. This phenomenon, coined the "Cheerios effect," arises due to capillary forces acting between floating objects [4]. The physics behind this effect involves the deformation around floating objects due to surface tension, which generates a curved meniscus around them. If two particles are close enough, the curvature of their menisci causes them to attract or repel. In the case of small floating objects like those in cereal, their menisci curve upward, creating attractive capillary forces that pull the particles together. This attractive force increases as the separation distance decreases, resulting in aggregation. When a large number of dense particles aggregate at an interface they form a monolayer commonly referred to as a "granular raft." The stability of granular rafts differs from that of single particles since the liquid displaced per particle by the meniscus decreases as the raft size increases [5]. The stability criterion for a granular raft formed at an oil-water interface is

$$\mathcal{D} = \frac{\rho_s}{\rho_w - \rho_o} \frac{2a}{\ell_c} < 3, \quad (1)$$

where $\mathcal{D}$ is a dimensionless parameter related to the effective density [6] and compares the density of the particles at the scale of the raft thickness $2a$ to buoyancy at the scale of the capillary length

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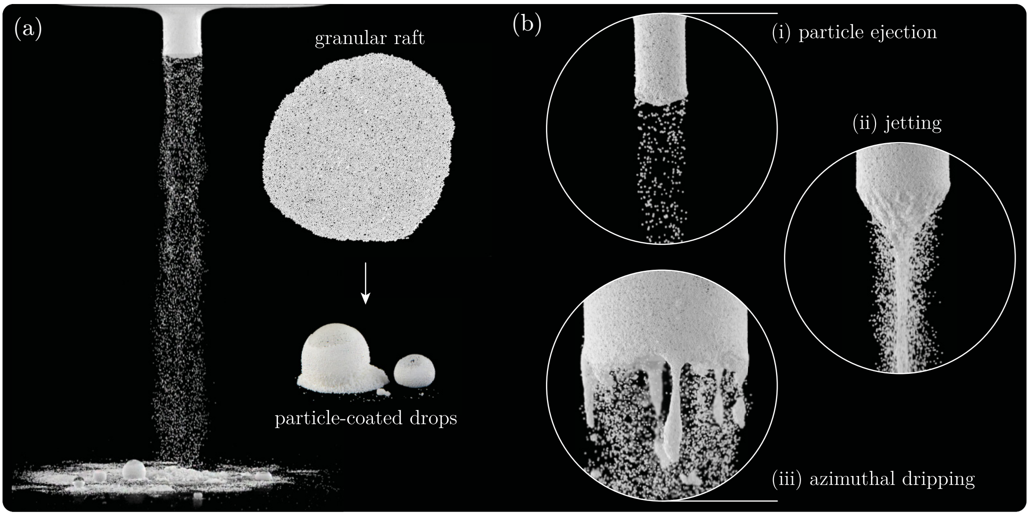

FIG. 1. (a) A granular raft at an oil-water interface destabilized by a cylindrical rod ejects particles and creates particle-coated drops. (b) Three types of raft destabilization are observed: (i) particle ejection, (ii) jetting, and (iii) azimuthal dripping.

ℓ_c. Here ρ_s, ρ_w, and ρ_o are the density of the particle, water, and oil, respectively; a is the particle radius; and $\ell_c = \sqrt{\sigma/(\rho_w - \rho_o)g}$ is the capillary length. In our experiments we target $\mathcal{D} < 3$ to explore the dynamic response of "infinite rafts" to external stress.

Granular rafts exhibit unique mechanical properties as they respond to stresses. For example, compression has revealed many features previously observed in floating elastic sheets, including wrinkling [7] and a wrinkle-to-fold transition [8], suggesting one consider the raft as an elastic continuum. However, the stress distribution within these composite interfaces exhibits features characteristic of a granular media, such as the Janssen effect [9]. In many cases, both the granular and elastic nature play a role in the stress response of granular rafts. This duality is highlighted in our experiments that probe the stability of granular rafts through dynamic deformation by a solid object. Our experiment is similar to that used by He *et al.* [10] who studied particle rearrangement in rafts formed at an oil-water interface due to indentation by a solid object. Large indentation depths can lead to destabilization as the raft slides down the rod resulting in the formation of particle-coated "armored" oil drops that sink to the bottom of the container [11]. Our experiments focus on the role of indenter geometry and velocity in determining the stability of granular rafts, revealing a number of unique modes of destabilization and a novel particle-coating process.

A typical experiment is shown in Fig. 1(a) in which an acrylic rod of radius r deforms a granular raft with velocity v. The granular raft sits at the interface separating mineral oil with density $\rho_o = 850\ \mathrm{kg/m^3}$ and viscosity $\mu_o = 17.3\ m\,\mathrm{Pa\,s}$, and distilled water with density $\rho_w = 997\ \mathrm{kg/m^3}$ and viscosity $\mu_w = 1\ m\,\mathrm{Pa\,s}$. The interface has an interfacial tension $\sigma = 44\ m\,\mathrm{N/m}$ and corresponding capillary length $\ell_c = 5.2\,\mathrm{mm}$. The oil layer thickness was $h_o \approx 10\,\mathrm{mm}$. The raft comprised fused zirconium oxide microspheres (Glen Mills, USA) with density $\rho = 3789\ \mathrm{kg/m^3}$ and radius $a = 132 \pm 13\ \mu\mathrm{m}$, providing a $\mathcal{D} = 1.3 < 3$ such that large stable rafts could be formed. The raft was imaged from the side using a Nikon D3500 DSLR camera and Micro-NIKKOR 105 mm lens. The background is made absolutely black by leaving a void space behind the tank, approximately 2 m across, and illuminating the particles with a Godox SL-200W III studio light. A typical image of a granular raft before and after destabilization is shown in Fig. 1(a).

Deforming the granular raft with a rod can destabilize it whenever the velocity exceeds a critical value $v > v_c$, which depends upon the rod geometry and $\mathcal{D}$. Three modes of destabilization are observed which largely depend upon the rod radius [cf. Fig. 1(b)]. Mode (i) shows single particle

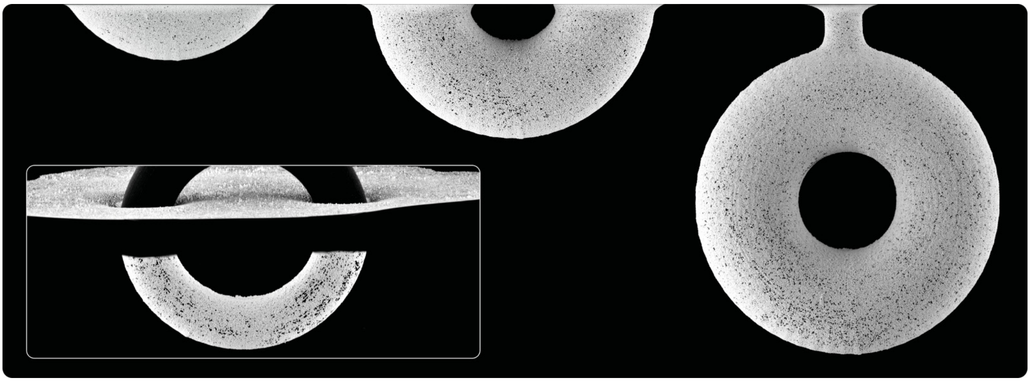

FIG. 2. A torus with major radius $r_{\mathrm{maj}} = 50$ mm and minor radius $r_{\mathrm{min}} = 36$ mm lowered through a granular raft at a velocity $v = 0.05$ mm/s is coated with a layer of particles. Inset image shows an angled perspective view of a torus during coating ($r_{\mathrm{maj}} = 50$ mm and $r_{\mathrm{min}} = 26$ mm).

ejection from the bottom of the smallest ($r = 3.2$ mm) rod. Mode (ii) shows jetting behavior for an intermediate-sized ($r = 6.4$ mm) rod, which produces small armored oil droplets that result from a Plateau-Rayleigh-like instability, similar to the experimental results of Abkarian *et al.* [11]. Here single particle ejection and azimuthal wrinkling of the granular raft occur at the base of the rod demonstrating both granular and elastic features. Mode (iii) shows azimuthal dripping for large ($r = 25.4$ mm) rods, whose size is larger than the capillary length. Here the simultaneous shedding of droplets around the circumference of the rod provides an efficient means of rapid production of armored droplets. In all cases, destabilization continues until most of the raft has sunk, leaving only a stable "cap" of particles at the bottom of the rod.

Below a critical velocity v_c, the rod does not destabilize the raft but rather is coated by the particles. This coating process extends to objects more complex than rods. Figure 2 shows the coating process for a torus with major radius $r_{\mathrm{maj}} = 50$ mm and minor radius $r_{\mathrm{min}} = 36$ mm deforming a granular raft with velocity $v = 0.05$ mm/s. This coating process "wraps" objects in a particle layer in a manner similar to what would occur for a floating sheet, but also extends to nontrivial topologies provided the holes have radius $r_h > \ell_c$. The process is reversible and the object may be raised through the oil layer without destabilizing the raft provided $v < v_c$, which removes most particles from the object and reforms the granular raft.

This poster demonstrates how indenting a granular raft reveals both elastic features of these composite interfaces, such as the formation of wrinkles, and granular features like particle ejection and rearrangement. Our results have application in coating technologies, where monolayer particle coatings are desired, and oil spill remediation [11], where the increased oil encapsulation rates seen with large rods may be desirable. Further investigation into the dynamic stability of granular rafts will provide deeper insights into their structural integrity and stress response.

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