Pinned in Microgravity: How Colloidal Suspensions Inhibit Droplet Motion

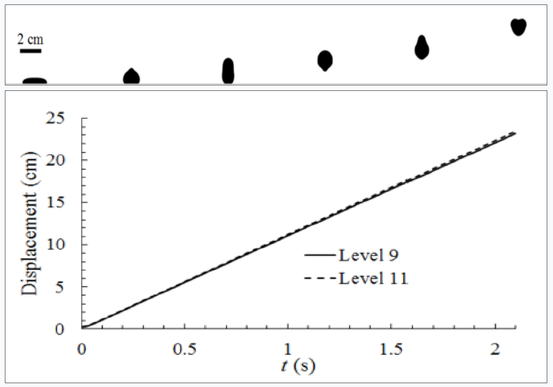
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Colloidal Dissipation & Puddle Jumping

Interfacial dynamics of colloidal soft matter in microgravity depend heavily on particle-induced changes to energy storage and dissipation. A primary manifestation of these dynamics is **"puddle jumping"**: the spontaneous detachment of a droplet from an engineered surface upon entering microgravity. Integrating colloids into the fluid matrix tunes bulk properties—specifically surface tension and contact line friction—allowing the puddle-jumping transition to serve as a diagnostic for complex fluid-surface interactions.

Mark Weislogel's work, shown below, illustrates the puddle jumping phenomena of a water droplet from a hydrophobic surface. The velocity is constant, and clear oscillations can be seen within the droplet.



Methods & Materials

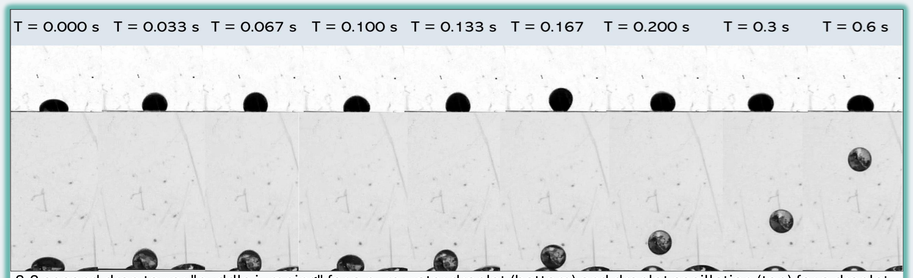
Substrate: Soot coated aluminum.
Colloids: 100 nm polystyrene at 0.1% by volume.
Fluid: DI Water.
Colloidal droplets were placed on a 2.2s drop tower rig by hand, and the resulting droplet dynamics were recorded by a camera (30 FPS), maximum Nyquist frequency of 15 Hz. This allows FFT of slow phenomena related to droplet dynamics.

Water droplets on soot coated aluminum plate. Contact Angle: 163°

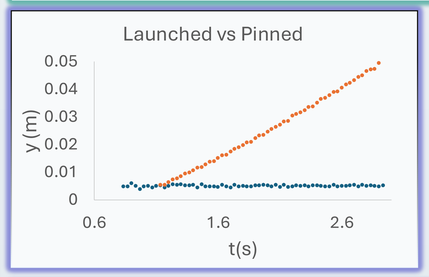


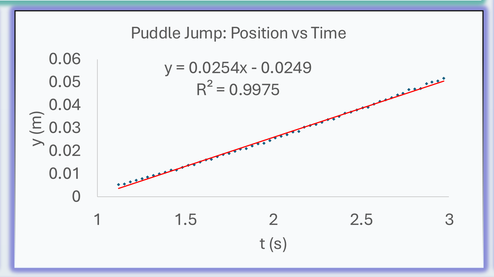


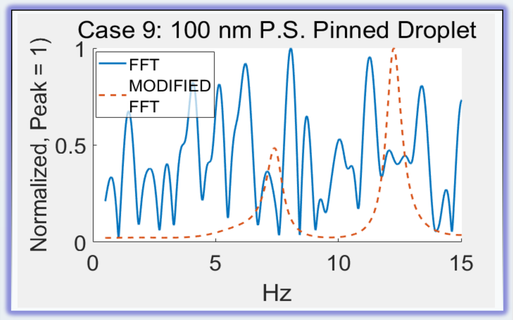
Hydrophobic Soot Covered Aluminum

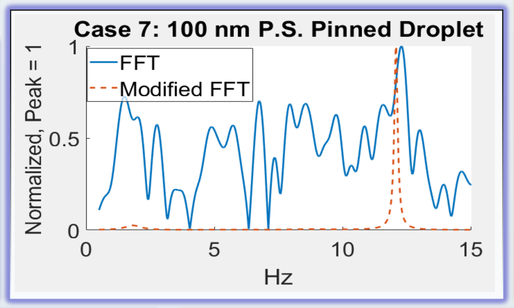


2.2 second drop tower "puddle jumping" for a pure water droplet (bottom) and droplet oscillation (top) for a droplet loaded with 0.1% by volume 100nm polystyrene spheres. Droplet volumes have been matched at 10μL. Maximum necking of the colloid laden droplet at **0.167** sec occurs approximately at the same time as the pure water droplet detaches.









- **Mechanism:** Adding 100–1000 nm colloids can prevent puddle jumping, but **not** through surface tension reduction. The suppression is primarily driven by internal dissipation and mechanical pinning.
- **Energetic Insignificance:** A 20 mN/m reduction in surface tension is insufficient to explain the failure to launch. The characteristic launch time (approximately 0.167) for colloid-loaded droplets is only **1.084** times that of pure water, confirming that surface energy changes are negligible.
- **Dissipation & Pinning:** Failure to detach likely stems from **extra viscous dissipation** disrupting internal flow and **contact line pinning**, where colloids anchor the droplet rim and weaken the inward momentum necessary for take-off.
- **Energy Diversion:** The persistent 12 Hz resonance suggests kinetic energy is being diverted into surface oscillations rather than translation. However, the exact cause of this surprising failure to detach remains an open question requiring further comparative frequency analysis.

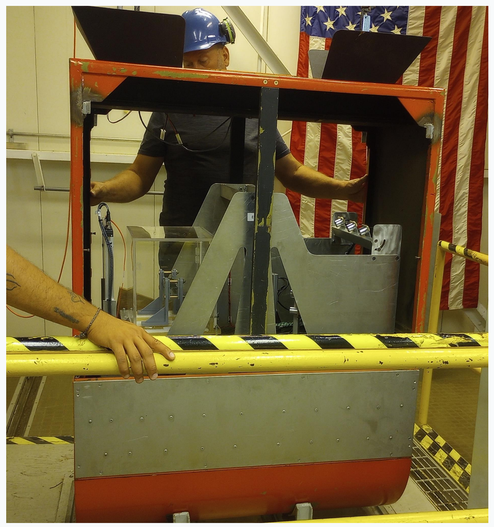
Analysis of Dissipative Mechanisms

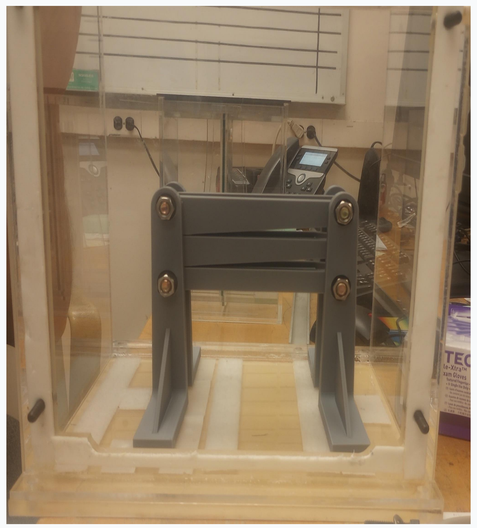
Droplet detachment in microgravity is governed by the conversion of surface potential energy into kinetic energy. The presence of colloids introduces non-conservative work terms that suppress this energy transition. The simplified energy balance will look like this: $\boldsymbol{KE = \Delta U_{surface} - (W_{pin} + W_{dissipation})}$

The analysis is complex due to the distinction between conservative surface energy and non-conservative losses. Surface energy, influenced by colloidal size and density [3], behaves as a potential energy (analogous to Hooke's Law) where work is conservative for small deformations.
In contrast, **pinning and dissipative forces** are non-conservative; they do not alter surface energy but reduce the kinetic energy available for droplet launch. We characterize surface tension through **static contact angles** and quantify **pinning work** by measuring advancing and receding angles during evaporation.

$$U = b\left(\frac{\sigma g}{\rho}\right)^{1/4}\left[1 - \cos\theta + 2\left(\frac{\pi H^3}{V}\right)^{1/2} - 6^{2/3}\left(\frac{\pi H^3}{V}\right)^{1/3}\right]^{1/2}$$

$$t_{jump} = \sqrt{2\sqrt{\frac{\rho}{\sigma g}}R_{drop}}$$

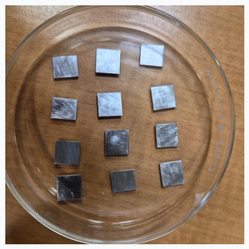




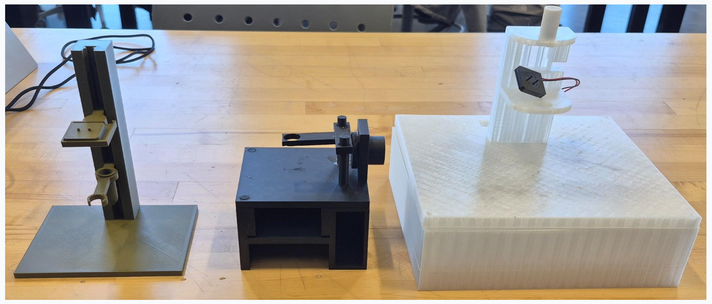
NASA GRC 2.2 s Drop Tower Rig (Left), 3D Printed Substrate Fixturing (Right)

Future Work

Future work focuses on establishing baseline jump/no-jump conditions through mechanized dispensing on a robust substrate. Immediate priorities include characterizing pinning and dissipative work via extensive contact angle dynamics and flow measurements for foundational publications. Long-term goals involve active colloid studies, integration into the 5.18s drop tower, and CubeSat experimental design.



Modified Superhydrophobic Zinc Substrate



Prototype development of highly accurate colloidal fluid dispenser (~8 μL)

This work builds on foundational studies in droplet dynamics and surface engineering. We acknowledge Dr. Mark Weislogel and co-authors for their numerical investigation of puddle jumping, which informed our experimental design and analysis [1]. We also acknowledge T. Okubo for seminal insights into how colloidal dispersions modify liquid–vapor surface tension and interfacial energetics [3]. Preparation of superhydrophobic substrates was inspired by the soot-based coating methodology reported by Esmeryan and Fedchenko [2].

References: [1] Avhad *et al.* 2020; [2] Esmeryan & Fedchenko 2023; [3] Okubo 1995.

Acknowledgments

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