

Liquid marble formation

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MCEN 5151: Flow Visualization

Assignment: Team First

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See the full video here: <https://youtu.be/Myv4o0lg5xw?si=UEHuYkmF-lzDUEjl>



Figure 1: Liquid marble formed by a droplet of water impacting a bed of sand

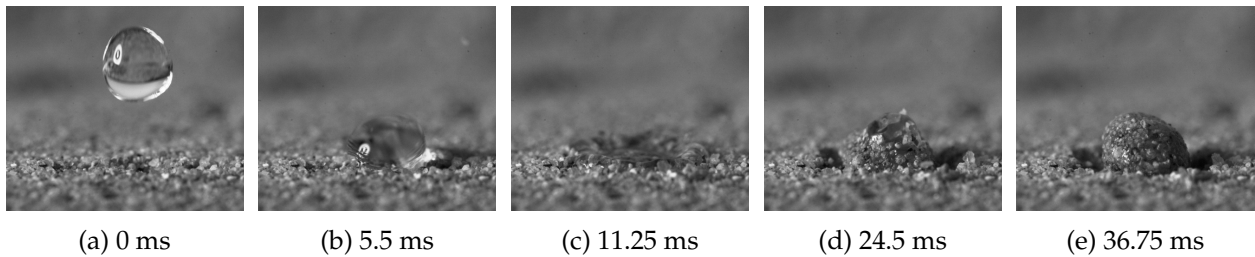


Figure 2: Time sequence: (a) falling, (b) impact, (c) spreading, (d) rebounding, (e) liquid marble

Context and Purpose

This video was made for the MCEN 5151 – Flow Visualization *Team First* assignment, with help from my teammates Alex and Will. My aim was to capture the formation of a liquid marble in slow-motion. Under certain conditions, when a water droplet impacts a bed of dry sand, instead of soaking in, it picks up sand grains and forms a shell. This is known as a “liquid marble,” a droplet of liquid coated in solid particles (Aussillous and Quéré, 2001).

I chose to capture this flow because it combines principles of fluid mechanics with granular physics, which my lab specializes in. The drop behaves like a liquid, constrained by surface tension as it spreads and rebounds, and the sand bed behaves as both a solid and a liquid. Other water drop impact studies focus on rain drops impacting soil and granulation processes used in industry, the most prevalent being pharmaceuticals (Trottet et al., 2025; Avrănescu et al., 2018).

I captured this video at 4,000 fps using a Phantom V2012 high-speed camera. Figure 2 shows a brief sequence of the process. While my deliverable is the video linked above, I also find the final image (Figure 1) of the liquid marble resting in the small crater it created visually appealing and satisfying.

Flow Apparatus and Physics

A drop of DI water ($D \approx 4.0$ mm) was released from a 5.8 mL transfer pipette onto a loose pile of dry sand ($d \sim 0.3 \pm 0.1$ mm). 30 drops of water from the pipette had a mass of 1.038 g, so the drop diameter was approximately

$$D = \left(\frac{6m}{\pi\rho} \right)^{1/3} = \left(\frac{6(3.46 \times 10^{-5} \text{ kg})}{\pi(1000 \text{ kg/m}^3)} \right)^{1/3} \approx 4.0 \text{ mm} \quad (1)$$

Figure 3 shows a schematic of the setup.

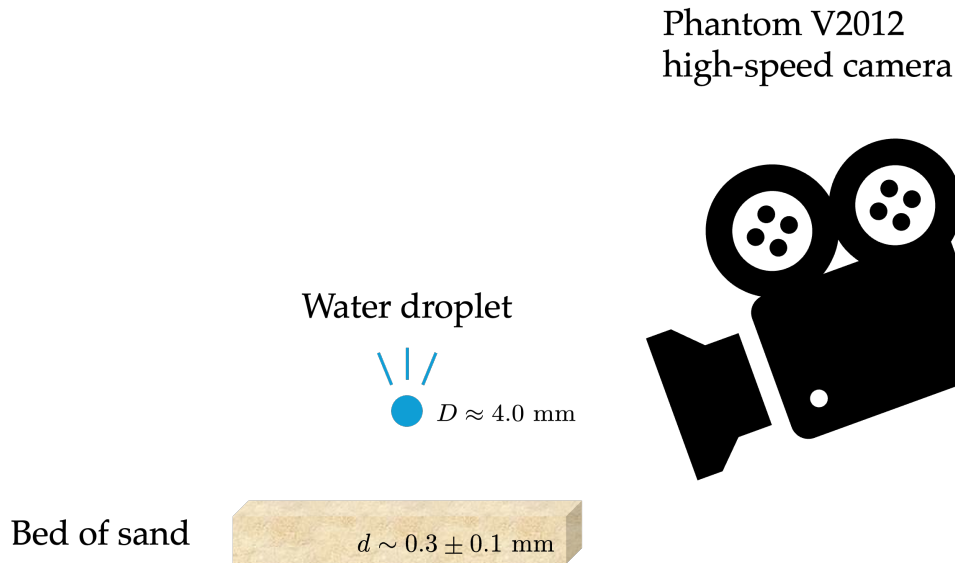


Figure 3: Schematic of the imaging setup

The process can be divided into 2 stages, each governed by different forces. The first stage is free-fall and impact, and the second is recoil where the drop captures grains and becomes a liquid marble.

Impact and spreading

Following Katsuragi (2011), we first estimate the velocity, U , of the droplet (dropped from 0.1 m) on impact:

$$U = \sqrt{2gh} = \sqrt{2(9.81 \text{ m/s}^2)(0.1 \text{ m})} \approx 1.4 \text{ m/s} \quad (2)$$

The Weber number is the ratio of the drop's inertia to its surface tension:

$$We = \frac{\rho U^2 D}{\sigma} = \frac{(1000 \text{ kg/m}^3)(1.4 \text{ m/s})^2(4.0 \times 10^{-3} \text{ m})}{0.072 \text{ N/m}} \approx 110 \quad (3)$$

where ρ is the density and σ is the surface tension of water. Since $We \gg 1$, inertia dominates at impact. We see this when the drop flattens after impact (Figure 2c), leaving behind a crater.

Clanet et al. (2004) showed that how far a drop spreads depends on whether surface tension or viscosity dominate. We can calculate the impact number, $P = We/Re^{4/5}$, where $Re = \rho U D / \eta$, to determine which regime our drop is in:

$$Re = \frac{(1000)(1.4)(4.0 \times 10^{-3})}{1.0 \times 10^{-3}} \approx 5600 \quad (4)$$

$$P = \frac{110}{5600^{4/5}} \approx 0.11 \quad (5)$$

$P < 1$, so the spreading is limited by surface tension. In the capillary regime, the maximum spreading diameter can be calculated (Clanet et al., 2004):

$$D_{max} \approx 0.9 D We^{1/4}, \quad (6)$$

For $We \approx 110$, this predicts $D_{max}/D \approx 2.9$. We measured $D_{max}/D \approx 2.25$ from the footage, about 25% smaller than predicted. This could be due to our sand bed deforming on impact. (Clanet et al., 2004) used a firm surface rather than a granular bed, so the droplet may have expended some energy to transport sand grains instead of spreading.

Rebound and grain capture

At maximum spread, the droplet's contact area with the granular bed is also at a maximum. As surface tension pulls the droplet back towards a sphere, hydrophilic sand grains stick to the drop's surface and are lifted off the bed to form a shell around the water droplet. Because the grains are small and lightweight, the capillary force is able to overcome gravity and hold the grains to the droplet. (Katsuragi, 2011) found that wettability governs how many grains are collected. Droplets impacting hydrophilic grains will generally pick up more grains than droplets impacting hydrophobic grains. The whole process took approximately 30 ms, which is why high-speed imaging was needed to capture this phenomenon.

Visualization Technique

The sand grains acted as tracers to visualize how the droplet boundary moved. The experiment was backlit by a custom LED panel and lit from a 45° by a Godox SL100D LED spotlight. The spotlight was angled to help maximize illumination of the sand bed and show the contours of the 3D droplet. Continuous LED lighting was needed to avoid flickering at 4,000 fps.

Photographic Technique

This footage was captured using a Phantom V2012 high-speed camera at 4,000 frames per second at a resolution of 1280 × 800 px. We used a 180 mm lens at $f/5.6$ roughly 0.5 m from the droplet. The field of view was approximately 33 × 20 mm. The exposure time was 240 μs and the Extreme Dynamic Range (EDR) was set to 30 μs . The video was uncropped and unedited. The only post-processing was adjusting playback speed in Final Cut Pro.

Discussion

The video shows a drop of water impacting a bed of sand, flattening into a pancake, and recoiling back into a spherical drop. As it rebounded, grains stuck to the surface of the water, forming a shell around the liquid droplet. These are known as liquid marbles. I am happy with the quality of the video, and I think that the black and white color palette works well to reduce distractions. Note that the camera only records in monochrome, so color footage wasn't an option. If we were to repeat this experiment, we would include a ruler or scale bar when recording to make measurements more accurate. We would also repeat the experiment with a finer, more uniform granular material to hopefully produce a better-quality marble. One of the biggest challenges we faced was ensuring the droplet was in focus. At such a close distance between the lens and the droplet, even though we stopped down the aperture as much as possible, the plane of focus was incredibly thin.

References

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