Surfactant-Driven Marangoni Flow in a Milk Pool

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Get Wet - First Individual Image | ATLS 5151-001 | Flow Visualization: The Physics and Art of Fluid Flow

University of Colorado Boulder | Report date: 18 September 2026

1. Context and intent

This is my first individual image for a course in flow visualization, where each assignment asks us to make a fluid phenomenon visible and photograph it well enough that both the physics and the picture stand on their own. The physical phenomena I chose is Marangoni flow shown through a shallow pool of whole milk seeded with drops of food dye. Touching the surface with a cotton swab loaded with dish detergent collapses the surface tension at the point of contact, and the surrounding surface pulls outward from that point, dragging the dye with it into radial filaments.

2. Apparatus and flow

The apparatus is sketched in Figure 1. A semi-translucent ceramic dish 24 cm across was raised on risers and filled with whole milk (King Soopers, 3.25% fat) to a depth h ≈ [5] mm, then left to settle. Four drops of blue food dye were placed 4–6 cm from the center, and a cotton swab dipped in undiluted dish detergent was lowered until it just touched the surface at the centre and held there. The in-plane length scale is the radius of the cleared disc and is roughly 5 cm.

Detergent adsorbing at the interface drops the surface tension from about 52 mN/m for clean whole milk at 24 °C (evaluated using Bertsch's regression formula to describe surface tension relative to temperature, Bertsch, 1983), to roughly 25 mN/m, leading to a change of 27 mN/m. The clean surface pulls outward on the contaminated patch and the milk beneath the central patch gets dragged up to the surface. This slows down after the initial steep gradient until the final result is present and static. Balancing the pull of the surface tension difference against the drag of the milk's viscosity, we can solve for the Marangoni velocity. With assumptions of $\mu \approx 2.0 \times 10^{-3}$ Pa s and $\rho \approx 1029$ kg/m^3 so that $\nu \approx 1.94 \times 10^{-6}$ m^2/s (University of Guelph):

$$U_M = \frac{\Delta\sigma h}{\mu L} = \frac{(2.7\times10^{-2}\ \mathrm{N/m})(5\times10^{-3}\ \mathrm{m})}{(2.0\times10^{-3}\ \mathrm{Pa\cdot s})(5\times10^{-2}\ \mathrm{m})} = 1.4\ \mathrm{m/s}$$

That is the first instant when the gradient is steepest. This however decays quickly, a fixed mass of insoluble surfactant spreading radially advances as $t^{1/4}$ (Jensen and Grotberg, 1992). The disc opens to a radius of roughly 5 cm in about 0.3 s, giving a more understandable average velocity of $U \approx 0.17$ m/s. Using this value and the depth as the length scale for our Reynolds calculation we find:

$$Re_h = \frac{Uh}{\nu} = \frac{(0.17\ \mathrm{m/s})(5\times10^{-3}\ \mathrm{m})}{1.94\times10^{-6}\ \mathrm{m^2/s}} = 4.4\times10^2$$

For the normal Reynolds number. Similarly, the in-plane Reynolds number was found to be $Re_L \approx 4.4 \times 10^3$. Both values are well within the laminar region, matching the smooth well stretched filaments. This is also the reason as to why we do not notice any mixing/dissolving effects. The Marangoni number (Ma) checks whether the soap reaches the edge of the circle because the flow carries it there or because it spreads on its own and Péclet number asks the same question for the dye, with assumptions of $D_s \approx 1 \times 10^{-9}$ and $D_d \approx 5 \times 10^{-10}$ m^2/s:

$$Ma = \frac{\Delta\sigma L}{\mu D_s} = \frac{(2.7\times10^{-2}\ \mathrm{N/m})(5\times10^{-2}\ \mathrm{m})}{(2.0\times10^{-3}\ \mathrm{Pa\cdot s})(1\times10^{-9}\ \mathrm{m^2/s})} = 6.8\times10^{8}$$

$$Pe = \frac{UL}{D_d} = \frac{(0.17\ \mathrm{m/s})(5\times10^{-2}\ \mathrm{m})}{5\times10^{-10}\ \mathrm{m^2/s}} = 1.7\times10^{7}$$

Both numbers are large, which states that the transport is done almost entirely by the flow rather than by diffusion. The soap is carried outward by the motion it initiates, and the dye simply goes wherever the surface takes it, which is why the filaments stay sharp instead of blurring into the milk. The experiment is isothermal, so we can assume Gr = 0, and gravity only flattens the surface hence $Bo = \rho g L^2/\sigma \approx 4.8 \times 10^2$. Roché et al. (2014) show soluble surfactants like the dish soap drive Marangoni flows of finite radial extent set by a property called the critical micelle concentration and could be the reasoning as to why the cleared disc stops before the rim.

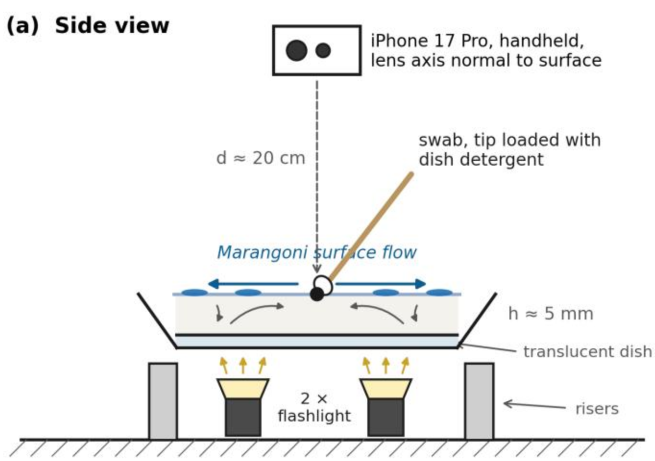

Figure 1. Apparatus. (a) Side view: a translucent dish of milk raised on risers, illuminated by two flashlights beneath, with the detergent-loaded swab at the center and the camera looking down the surface normal.

3. Visualization technique and lighting

Water-based blue liquid food dye was used, one drop at a time; it spreads on the interface rather than sinking, so it tags where the flow is. Whole milk at 24 °C is opaque, scatters strongly, and is about twice as viscous as water which slows the flow. The surfactant is liquid dish detergent on a standard cotton swab. Two flashlights were placed symmetrically beneath the dish and shone up through the milk with the room lights off. Lighting from below keeps out the flash hotspot that an overhead source would put in the middle of the surface.

4. Photographic technique

The image was taken handheld with an Apple iPhone 17 Pro, lens axis normal to the free surface, with no manual control over the exposure. The phone selected the shutter speedm ISO, focus and white balance automatically. The Ultra Wide camera (13mm, f/2.2) was used, which automatically crops to a 24 mm-equivalent field of view. At a distance of about 12 cm, since $w = 36 \text{ mm} \times d / f_{eq}$, the field of view is roughly 18 × 12 cm, framing the cleared disc and dye ring without the dish rim. The original capture is 3024 × 4032 px (12MP, HEIF) at 1/121 s and ISO 125, delivered as 1300 × 900 px after cropping and editing. The aperture is fixed, so shutter and ISO are the only exposure controls.

Processing was done in GIMP was started with an initial crop to remove the plate rim and lower right shadow. A local brightness lift was applied through a gradient mask to brighten the lower right corner that was caused by the uneven lighting from under. This was continued through the use of a white balance and the levels function in GIMP, it was also done to provide a better contrast and show the flow better. Finally the last addition to the image was padding in order to meet the image requirements (dark gray padding, export image as 1300x900 px).

5. What the image reveals

The filaments are streak-lines, so their radial alignment and outward thinning read the surface velocity straight off the print, and the sharp edge of the cleared disc is the surfactant front structure Jensen and Grotberg (1992) predict. The only issue I had with the photo was the uneven lighting that resulted from using two flashlights, the corner that was slightly darker because of how the image was taken created an unwanted gradient. I caught the final developed structure but not the first hundred milliseconds where the interaction happens. Reshooting a video at higher than 240 fps should be enough to capture the initial burst accurately. I would also vary detergent dilution and milk depth to check whether the cleared radius really is set by the critical micelle concentration, which a single experiment still image cannot distinguish from a front that simply decays.

References

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AI Assistance

Claude (Opus 5) was used to condense the text of this report, to check the scaling estimates in paragraph 2, provide LATEX formatted equations, and check for obvious grammatical errors. Image capture and all editing in GIMP were my own; AI was used only for explanations on how to use the editing tools to achieve the goals I wanted. All numerical values and cited sources were verified by the author.