

Dye in Milk Flows around Honey Droplets due to Surface Tension Differences

MCEN 5151: Flow Visualization

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Team First Assignment

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1 Introduction

The image of blue dye spreading through milk after a dish-soap-coated cotton swab is inserted into the liquid visualizes a surface-tension-driven flow known as the Marangoni effect. This photograph was taken in accordance with the Team First assignment, utilizing the visualization principles outlined in MCEN 5151: Flow Visualization. The local addition of detergent changes the interfacial properties of the milk, creating a surface-tension gradient that drives fluid motion along the milk-air interface. Three honey droplets, each approximately 1 cm in diameter, are also present in the field of view. The dye paths curve around these regions, providing a second flow feature in which the motion interacts with localized variations in viscosity and density. The purpose of this Team Second flow-visualization experiment was to capture the transient motion initiated by changing the surface tension of milk. This transient, time-dependent behavior is central to the image: rather than depicting a steady flow driven by a pump, the photograph captures a transient response to a localized surface-chemistry change. Artistically, the photograph creates an almost cosmic effect with the dark colors contrasting to the white and with the honey droplets bringing forth golden star-like speckles.

2 Flow Phenomena

To analyze the fluid dynamics within the image, identification of the main flow phenomena around the honey droplets is crucial.

A boundary layer can be identified along the perimeter of the honey droplet. As shown in Figure 1, the boundary layer represents the thin region of fluid surrounding the droplet where viscous effects create significant velocity gradients. Because honey is substantially more viscous than the surrounding milk, the flow within the honey droplet is expected to move much more slowly than the surrounding fluid. At the liquid-liquid interface, the velocity of the milk and honey must remain continuous, while a velocity gradient develops across the surrounding fluid and within the honey. This results in localized viscous shear as the milk flows around the droplet.

Another identifying feature of this flow is the curved shear region surrounding the honey droplet. As the incoming milk is redirected around the droplet, the fluid experiences changes in velocity and direction, creating regions of elevated velocity gradients along the droplet's perimeter. These shear regions are particularly important because they illustrate the interaction between the relatively low-viscosity milk and the much higher-viscosity honey. The resulting flow deflection is visible in the photograph as the blue dye streaks curve around the darker honey regions.

Finally, a wake region can develop downstream of the honey droplet as the surrounding flow recombines behind it. The wake is characterized by a region of reduced velocity and potentially increased flow unsteadiness resulting from the interaction between the incoming flow and the droplet. Due to the viscosity difference between the milk and honey, the flow may experience localized separation or recirculation depending on the droplet interface and surrounding flow conditions. These downstream flow characteristics, along with the boundary layer surrounding the honey droplet, provide insight into the influence of viscosity and inertia on the observed flow and will be discussed further in the following sections.

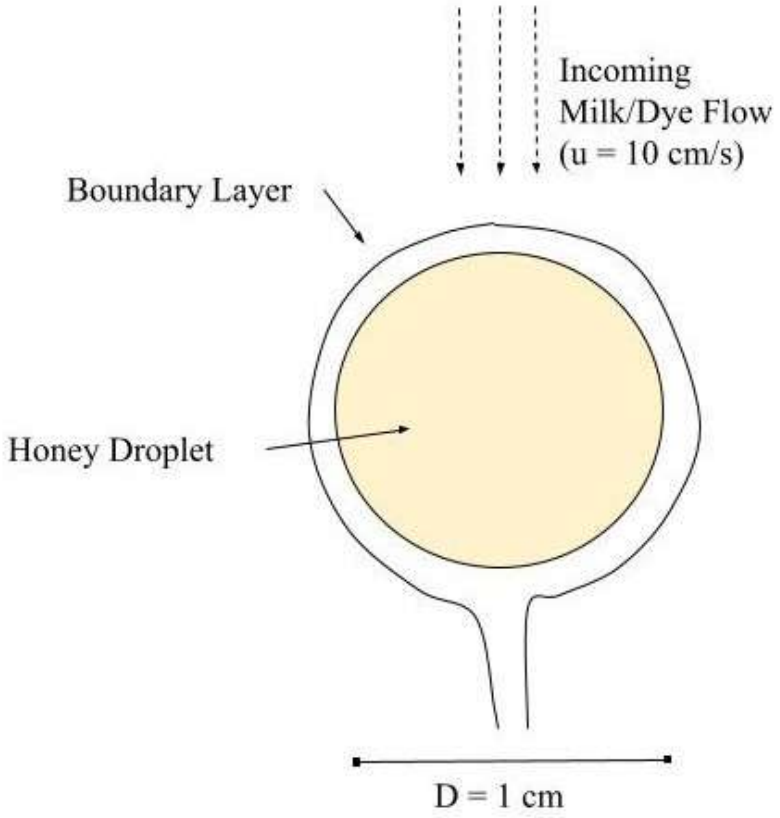


Figure 1: Flow Around Honey Droplet Analysis Diagram

To quantitatively characterize the flow around the honey droplets, representative fluid properties for whole milk at 20 °C are utilized. The density of the milk is approximately 1,030.5 kg/m^3, while its dynamic viscosity is estimated to be 2.03×10^{-3} Pa $\cdot$ s. The milk-air surface tension is approximately 0.0524 N/m. These values are based on published experimental measurements and correlations for whole milk [7, 6, 8].

The characteristic length is defined as the honey droplet diameter, which is approximately 0.010 m. The initial flow velocity is estimated to be 0.10 m/s based on the observed dye

movement. Using the density and dynamic viscosity values above, the kinematic viscosity is calculated to be approximately 1.97×10^{-6} m^2/s. Finally, gravitational acceleration is taken as 9.81 m/s^2.

These representative properties and experimental dimensions are used throughout the following nondimensional analysis. Since the actual milk temperature, fat content, and surface tension were not independently measured, the calculated values should be interpreted as reasonable estimates rather than exact experimental measurements.

2.1 Reynolds Number (Re_D)

The Reynolds number compares inertial forces with viscous forces in the milk. For the local flow around a honey droplet, the droplet diameter is used as the characteristic length:

$$Re_D = \frac{\rho U D}{\mu} = \frac{(1,030.5\,\mathrm{kg/m^3})(0.10\,\mathrm{m/s})(0.010\,\mathrm{m})}{2.03 \times 10^{-3}\,\mathrm{Pa \cdot s}} \approx 5.07 \times 10^2$$

The resulting Reynolds number is approximately 508. This indicates that inertia is important relative to viscosity at the initial reported speed, although the value alone does not establish that the flow is turbulent. The event is transient, surface-driven, and affected by the honey regions and by the depth of the milk layer. Local shear layers can remain laminar or become unsteady depending on the geometry and boundary conditions. As the velocity decreases, the instantaneous Reynolds number decreases in direct proportion to U; for example, a velocity reduced by one-half would also reduce Re_D by one-half.

2.2 Weber Number (We_D) and Capillary Number (Ca)

The Weber number compares inertia with surface tension, while the capillary number compares viscous stresses with surface tension. Both use the milk-air surface tension as the reference interfacial tension:

$$We_D = \frac{\rho U^2 D}{\sigma} = \frac{(1030.5)(0.10^2)(0.010)}{0.0524} \approx 1.97$$
$$Ca = \frac{\mu U}{\sigma} = \frac{(2.03 \times 10^{-3})(0.10)}{0.0524} \approx 3.88 \times 10^{-3}$$

The Weber number is approximately 2, meaning the inertia associated with the initial motion is of the same order as the capillary restoring forces when considered on the 1 cm scale. The capillary number is much smaller than one, indicating that viscous stresses are small relative to the milk-air surface-tension scale. These values are not contradictory: the Weber number reflects inertial deformation, while the capillary number reflects viscous deformation. In

addition, the soap changes the local surface tension, so the true local Weber and capillary numbers vary spatially as the surfactant spreads. The values above use the clean-milk reference surface tension and should be interpreted as baseline estimates.

2.3 Marangoni Stress Relative to Viscous Stress

The principal driving mechanism is the surface-tension gradient created by the soap. A useful stress comparison can be formed by estimating the Marangoni stress as $\tau_M \sim \Delta\sigma/D$ and the viscous stress as $\tau_v \sim \mu U/D$. Their ratio is:

$$M_\sigma = \frac{\tau_M}{\tau_v} \approx \frac{\Delta\sigma}{\mu U}$$

The actual surface-tension difference, $\Delta\sigma$, cannot be calculated because the soap formulation, concentration, amount transferred from the Q-tip, and local surface concentration were not measured. However, the denominator is $\mu U \approx 2.03 \times 10^{-4}\,\mathrm{N/m}$, or $0.203\,\mathrm{mN/m}$. Thus, a surface-tension difference greater than approximately $0.20\,\mathrm{mN/m}$ would make the Marangoni stress scale larger than the viscous stress scale under this estimate. This ratio is a stress-balance indicator, not a substitute for a conventional surfactant Marangoni number, which would require additional information such as surfactant diffusivity and adsorption/desorption kinetics. Manikantan and Squires emphasize that surfactant transport and relaxation processes determine how surface-tension gradients evolve over time.

2.4 Characteristic Time Scales and Unsteadiness

The characteristic convective time for fluid to move one droplet diameter at the initial velocity is:

$$t_c = \frac{D}{U} = \frac{0.010}{0.10} = 0.10\,\mathrm{s}$$

The viscous momentum-diffusion time over the same length is:

$$t_v = \frac{D^2}{\nu} = \frac{0.010^2}{1.97 \times 10^{-6}} \approx 50.8\,\mathrm{s}$$

The convective time is much shorter than the viscous diffusion time, consistent with the calculated Reynolds number being greater than one. The measured flow also decays rather than repeating periodically. Because no time-resolved sequence or oscillation frequency was recorded, a Strouhal number or vortex-shedding frequency cannot be assigned responsibly.

3 Visualization Technique

The execution of the flow visualization technique relied on a relatively simple setup consisting of a Petri dish, milk, food coloring, honey, and dish soap. To begin the experiment, the Petri dish was filled with milk until the bottom surface was just barely covered. Three honey droplets, each approximately 1 cm in diameter, were then placed into the milk using a Q-tip. Blue food coloring was subsequently added near the honey droplets, as well as at a separate location near the edge of the Petri dish, to provide visible tracers for the resulting flow. Once the setup was prepared, a Q-tip coated in dish soap was inserted into the food coloring near the edge of the dish, creating the localized surface-tension gradient that initiated the flow captured in the final photograph.

As shown in Figure 2, the camera was mounted on a tripod and positioned directly above the Petri dish to capture a top-down view of the experiment while remaining close enough to resolve the smaller details of the dye movement. A desk lamp, visible in the upper-left corner of Figure 2, provided approximately 600 lumens of illumination and was positioned 0.5 m from the Petri dish. The timing of the photograph was particularly important because the flow was transient and most pronounced immediately after the introduction of dish soap. To capture this initial movement, one hand was used to insert the soap-coated Q-tip into the milk while the other operated the camera, allowing the photograph to be taken near the peak of the flow response.



Figure 2: Milk, Dye, and Dish Soap in Petrie Dish Setup

4 Photographic Technique

This image was captured using A 2013 Canon eos Rebel T3i DSLR camera, resulting in an uncropped resolution of 5202×3464 pixels, which was cropped down to 1296×900 pixels. The image was taken using a 50 mm focal length, and operational exposure settings were set to ISO 800, an aperture of $f/5.6$, and a shutter speed of 1/160s.

The object-to-lens distance was approximately 1 ft (0.3048 m), yielding a physical field of view measuring roughly 8.75 in (0.2222 m) horizontally by 6.25 in (0.1588 m) vertically. The spatial framing was subsequently adjusted during post-processing in darktable. As shown in Figure 3, regions of flow above and below the affected zones were cropped out to minimize distractions and minimize glare. To bring out the blue tones and contrast to the white in the flow, the tone curve was adjusted to make the dark colors darker and the middle tones brighter. This allowed the blue dye zones to be highlighted without blowing highlights from the white milk in the image.

The spatial and temporal resolution of this image are also important considerations.

Temporally, the image is well resolved, as the flow features are captured without noticeable motion blur or loss of sharpness. This is particularly important given the relatively high initial flow velocity of approximately 10 cm/s. The smallest identifiable feature in the image is one of the blue dye streaks, measuring approximately 5 pixels in width. The original image is just over 5,000 pixels wide, while each honey droplet measures approximately 910 pixels in diameter. When considering the full image width relative to the smallest visible flow feature, the image captures approximately three orders of magnitude in spatial scale. When considering only the largest physical features (the honey droplets) and the smallest flow features, approximately 2.3 orders of magnitude in spatial scale are captured. This demonstrates that the image is sufficiently resolved to distinguish both the larger-scale flow structures around the honey droplets and the smaller-scale details within the dye streaks.

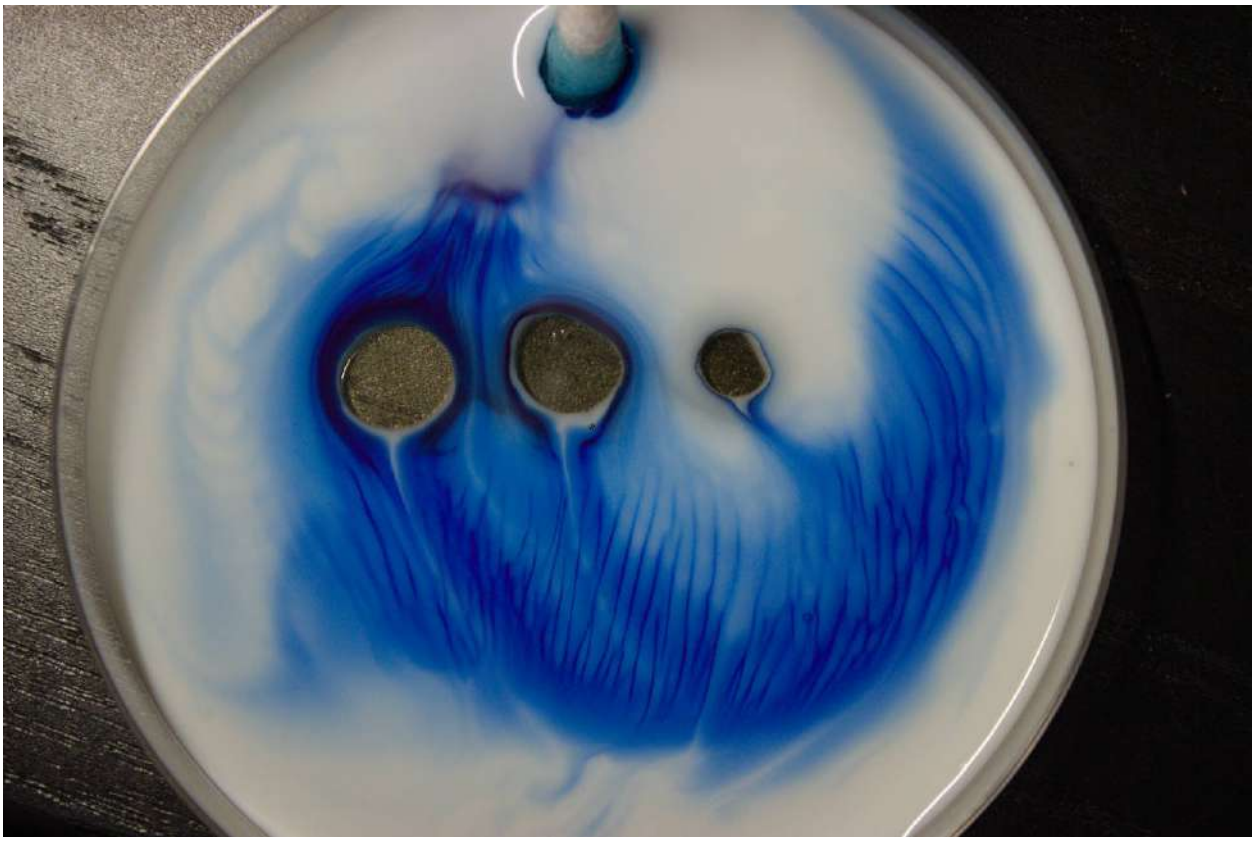


Figure 3: Original, Unedited Team Second Photo

5 Artists Statement

This image illustrates the beauty of a flow that, at first glance, appears to be a simple household experiment. While surface-tension-driven flow is commonly analyzed from an

empirical and theoretical perspective, this photograph highlights the visual complexity of the Marangoni effect through the way the blue dye spreads, streaks, and curves around the honey droplets. The contrast between the blue dye, white milk, and darker honey regions creates an interesting visual representation of the underlying fluid mechanics. At the same time, the photograph can be analyzed to better understand surface-tension gradients, viscous effects, and the interaction between fluids of significantly different properties without requiring extensive computational resources or complex experimental equipment.

Future work will incorporate improvements to post-processing and using different tools in darktable to bring out the lighter colors more without sacrificing the detail in the darker colors.

Further development of this study could explore a variety of different experimental configurations, including changes in honey droplet size, spacing, and quantity, as well as variations in the location and amount of dish soap introduced into the milk. These changes could provide insight into how different geometries and localized viscosity variations influence the surrounding flow. Additional experiments could also investigate different liquids to observe how changes in viscosity, density, and surface tension affect the resulting flow patterns.

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