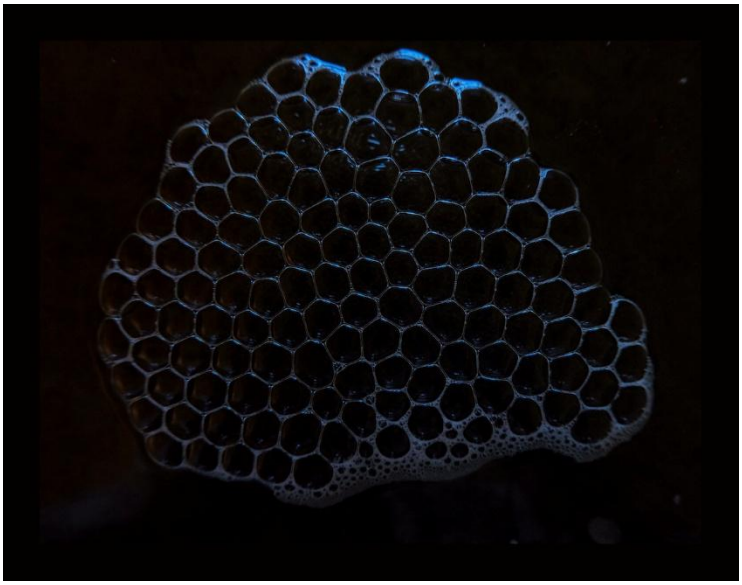
Team Second Report

Flow Visualization MCEN 5151-001

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Objective

The purpose of the image is to identify the physical phenomenon of bubble structure and formation when grouped together. The patterns that the bubbles make when interacting is due to a few different fluid phenomena explored in the report, including the Cheerio effect, buoyancy, surface tension, and energy minimization. This report is an exploration of the physical science principles involved in this pattern and its relationship to material microstructure.

Procedure

This was an experiment using common household items. In order to make semi-uniform bubbles, a tube and a small hole were needed. A mechanical pencil was used as the tube. Emptying it of the lead, eraser end, and internal mechanicals, resulting it a thin tube. Tape was used to plug the end, and a small hole was poked into the tape. The size of the hole are the steady air steam is very important in creating small uniform bubbles. Because of the limited access to material, a steady stream of air was provided by simply blowing through the tube. This resulted in a slightly non-uniform stream of air, which is why some of the bubbles in the photo are different sizes. A mixture of 1 part liquid soap to 10 parts water was poured into a large glass baking dish. The pencil was dipped halfway into the liquid before blowing to create the bubbles. This setup can be seen in Figure 1,

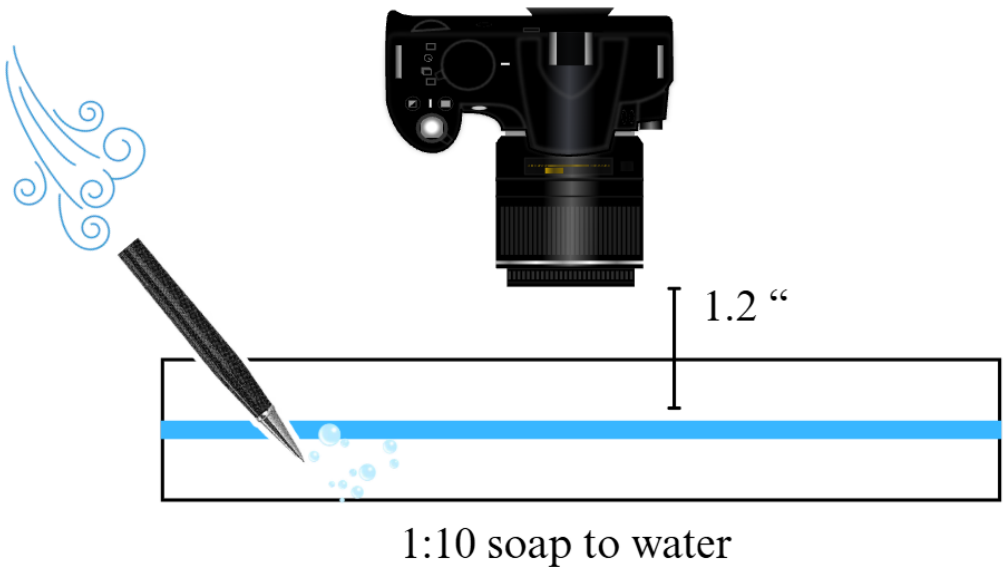


Figure 1: Diagram of setup.

Technical Analysis

The observed clustering of bubbles in a 1:10 soap-to-water mixture can be explained through several fluid phenomena, including buoyancy, the Cheerios effect, surface tension, and energy minimization. The bubbles have an average diameter (d) of approximately 3 mm, with some varying by ± 1 mm. The cluster of bubbles was observed to travel from the center of the dish to the sides. The velocity of this travel was calculated by timing how long the cluster traveled a certain distance. It was found that the velocity was 0.001 m/s. For the following calculations, the fluid is assumed to have the physical values shown in Table 1.

Density of water (ρ_{water})	$1000\ kg/m^3$
Dynamic viscosity (μ)	$0.001\ Pa\ s$
Surface tension (γ)	$0.030\ N/m$
Density of air (ρ_{air})	$1.2\ kg/m^3$
Fluid velocity (U)	$0.001 m/s$

Table 1: Fluid values used for calculations.

The Stokes number (St) describes the behavior of particles suspended in a fluid flow. It is defined as the ratio of a particle's response time to the characteristic fluid timescale [1].

$$St = \frac{\tau_p}{\tau_f} = \frac{\rho_{air} d^2 U}{18 \mu L} \quad (1)$$

Using a rigid sphere approximation, with the characteristic length (L) equal to the bubble diameter, the Stokes number is calculated as

$$St = \frac{(1.2)(0.003\ )^2(0.001)}{18(0.001)(0.003\ )} = 0.02$$

This small, estimated Stokes number suggests that the bubbles have relatively little inertia compared with the assumed fluid-motion timescale. Their motion would therefore be strongly influenced by surrounding fluid motion and interfacial forces rather than momentum alone [1]. However, this calculation uses the air density and the rigid-sphere Stokes relaxation model as approximations. Actual floating bubbles possess liquid films and deformable interfaces, so their effective inertia and drag differ from those of rigid particles. Consequently, the calculated value should be interpreted as an order-of-magnitude illustration rather than an experimentally determined Stokes number.

The observed attraction between bubbles and their tendency to accumulate along the container walls can be explained by the Cheerios effect, which occurs when floating objects deform the liquid surface and interact through capillary forces. These surface deformations create menisci that can attract neighboring bubbles and draw them toward the container walls, depending on the interface geometry. The capillary length is defined as

$$l_c = \sqrt{\frac{\gamma}{\rho_{water} g}} \tag{2}$$

Assuming a surface tension of 0.030 N/m, representative of some soap solutions, a liquid density of 1000 kg/m^3, and a gravitational acceleration of 9.81 m/s^2

$$l_c = \sqrt{\frac{0.030}{(1000)(9.81)}} = 0.00175m = 1.75\,mm$$

The bubble radius of approximately 1.5 mm is comparable to the capillary length. This suggests that both surface tension and gravity influence bubble interactions [2].

Buoyancy also contributes to the observed behavior by keeping the bubbles at the liquid surface. Using Archimedes' principle, an object immersed in a fluid experiences an upward force equal to the weight of displaced fluid, characterized by the equation below [1].

$$F_B = \rho_{water} g V \tag{3}$$

For a spherical bubble with a diameter of 3 mm, its volume is

$$V = \frac{\pi}{6} 0.003^3 = 1.14 \times 10^{-8}\, m^3$$

Thus, the buoyant force on a fully submerged bubble is approximately

$$F_B = (1000)(9.81)(1.4 \times 10^{-8}) = 1.39 \times 10^{-4} N$$

By comparison, the gravitational force on the air inside the bubble, assuming an air density of 1.2 kg/m^3, is approximately $1.66 \times 10^{-7}\, N$. Thus, the buoyant force is much greater than the weight of the bubble. This significant difference explains the tendency of bubbles to rise through the liquid. At the surface, however, the bubbles are only partially immersed, and the equilibrium position depends on buoyancy, surface tension, and the weight of the liquid film.

The honeycomb structure observed within the bubble clusters results from surface energy minimization and geometric packing. Surface energy is proportional to interfacial area, expressed as

$$E = \gamma A \tag{4}$$

meaning the system tends towards configurations that minimize the total interfacial energy. As bubbles accumulate, they deform against neighboring bubbles, creating shared interfaces and polygonal shapes. For similarly sized bubbles, hexagonal arrangements provide efficient two-dimensional packing geometry and can minimize the total film length. At equilibrium, three soap films typically meet at approximately 120 degrees, consistent with Plateau's laws [3]. Variations in bubble diameter can produce irregular cell geometries and deviation from perfect hexagonal

symmetry, which can be seen in the image. The captured bubble clustering therefore demonstrates how surface forces and energy minimization can produce organized structures.

Techniques

Visualization Techniques

Light and contrast were used to visualize the bubble formation. The light used was sunlight and an overhead ceiling light with a low ISO to achieve the dark look. The contrast was raised to highlight the boundary between the bubbles where the light was reflecting.

Photographic techniques

The camera used was a Fujifilm X-M1 with a Super EBC XC aspherical lens. The camera specs can be seen below in Table 2.

Focal Length	15-45 mm
ISO	1600
Aperture	f5.6
Shutter Speed	1/125
Original Dimensions	4896 x 3264
Edited Dimensions	1300 x 900
Distance from Camera	1.2 in
Spatial Resolution	0.04 mm/pixel
Temporal Resolution	0.008s

Table 2: Camera specifications and photographic techniques

The spatial resolution is calculated as the smallest object divided by the number of pixels covered. In this case the smallest visible object was around 0.2mm which covered about 5 pixels. Thus the spatial resolution is 0.04 mm/pixel.

The exposure time for a shutter speed of 1/125 is 0.008 s, and the distance the flow traveled in this time is the exposure time multiplied by the velocity of the flow, $0.008 \times 0.001 = 0.008\ mm$. Using the calculated spatial resolution, the pixel displacement per frame can be determine, 0.008/0.004=0.002. Thus, the fluid moved 0.002 pixels during the exposure time. This is small enough that motion blur is negligible.

In Dark Table, the photo's color contrast, local contrast, filmic RGB, and cropping were modified to bring a more ethereal feel to the image. Exact changes can be seen below in Table 3, as well as a side-by-side comparison of the original and edited images in Figure 2.

Name	**Value**	**Description**
Master Contrast	+6.70%	Make the white bubble boundaries more visible

Color Calibration	Input R - +1	Highlighted some of the red
Green-magenta contrast	1.96	Increased the red glow on the lower right side
Blue-yellow contrast	1.58	Increased the blue light from the upper right side
White relative exposure	4 EV	Increased brightness of the whites
Black relative exposure	-8 EV	Decreases the darks, making them a bit softer

Table 3: Photo editing done, the value, and the reasoning.

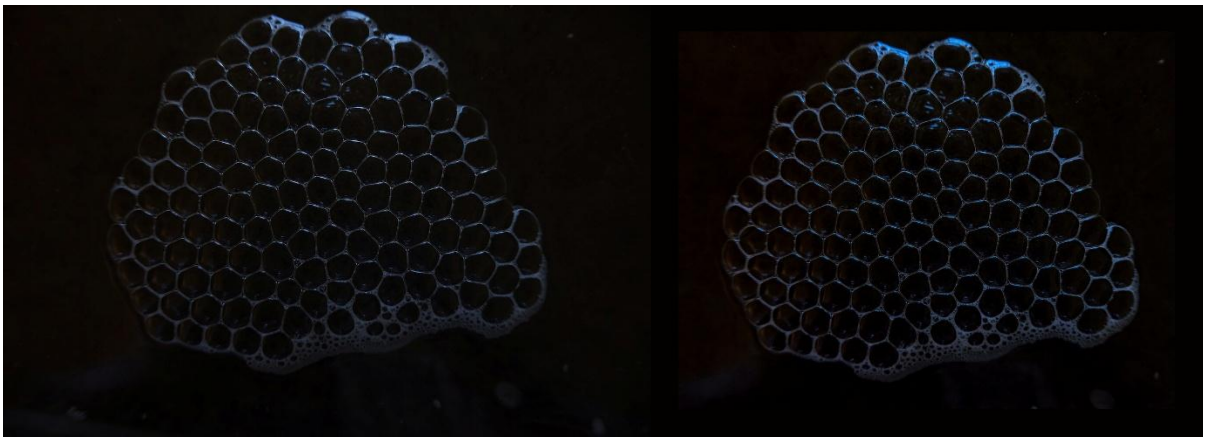


Figure 2: Before (left) and after (right) editing in Dark Table

Conclusion

The image reveals the artistic structure of a group of bubbles, representing the need for stability and closeness. The image is an example of energy minimization and surface tension and has a close resemblance to material lattice structures. I liked how ethereal the image turned out and how it's both otherworldly and familiar. I think it might have been interesting to represent the flow and movement of the bubbles as they are pulled away from each other, similar to dislocations in a material lattice structure. Due to equipment restrictions, this was not possible, but if I were to do this again, I would want to produce a video and capture the breaking and reforming of the hexagonal pattern.

References

[1] *Cameron Tropea; Alexander Yarin; John Foss, eds. (2007-10-09). Springer Handbook of Experimental Fluid Mechanics. Springer. ISBN 978-3-540-25141-5.*

[2] *Vella, D.; Mahadevan, L. (September 2005). "The Cheerios effect". American Journal of Physics. **73** (9): 817–825.*

[3] *Ball, Philip (2009). Shapes. Nature's Patterns: a tapestry in three parts. Oxford University Press. pp. 66–71, 97–98, 291–292. ISBN 978-0-19-960486-9.*