Team Second Report — Flow Visualization



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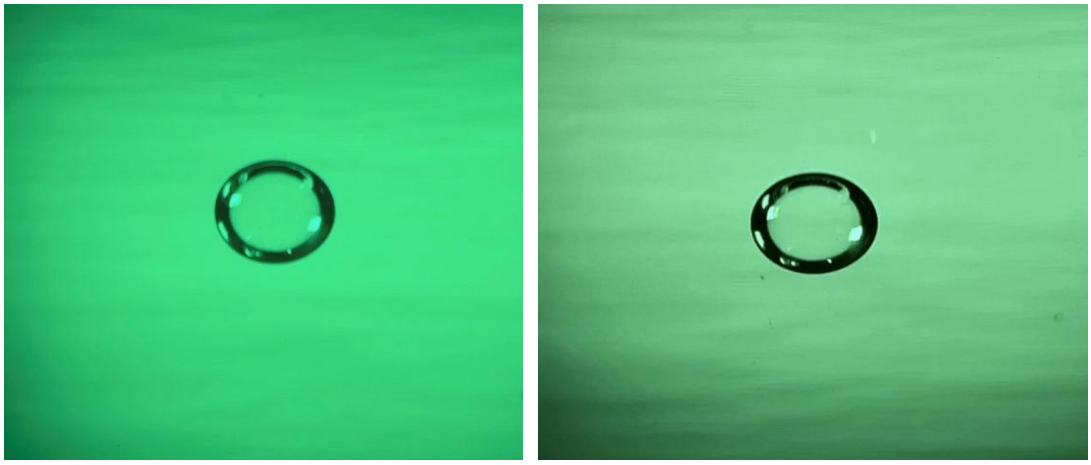
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Nomenclature

Bo = Bond number based on effective density difference
D = Antibubble diameter, m
D_j = Inner diameter of the straw (stream diameter), m
g = Gravitational acceleration, m/s^2
h = Drop height of the straw above the bath surface, m
R = Antibubble radius, m
r_j = Inner radius of the straw (stream radius), m
Re = Reynolds number
U_j = Velocity of the stream at the bath surface, m/s
We = Weber number of the stream
γ = Surface tension of the soapy solution, N/m
$\Delta\rho_{eff}$ = Effective density deficit of an antibubble, kg/m^3
ε = Thickness of the air shell, m
λ = Wavelength of the fastest-growing Rayleigh–Plateau mode, m
ν = Kinematic viscosity of the liquid, m^2/s
ρ = Density of the liquid, kg/m^3

I. Introduction

For the Team Second assignment, Tristan Brasov and I set out to create and photograph antibubbles and to draw a connection between what the camera sees to the forces that form them and hold them together. An antibubble is a thin shell of air enclosing an area of liquid and surrounded by that same liquid [2]. First reported by Hughes and Hughes in 1932 [1], antibubbles have mostly been treated as curiosity in the past; however, over the last two decades, the formation and collapse mechanisms of these bubbles have been studied with high-speed imaging [2,3]. A still shot from the original video and edited video is shown in Figure 1, captures antibubbles suspended in a solution of soapy water, where the air shell appears as a dark ring around a clear liquid core.



(a) *(b)*

Figure 1: (a) Origional Antibubbles in soapy water (b) Edited Version

II. Discussion

2.1 Experiment Apparatus

The apparatus can be seen, sketched in Figure 2. A clear container approximately 15 cm wide was filled with tap water mixed with a small amount of dishwashing soap, roughly 10 grams. A thin metal straw with a radius of 0.25 cm was used to drop the same solution onto the surface of the bath from a height (h) of 2.54 cm. The camera viewed the bath through the side wall against a black backdrop, and the field of view was about 6 cm across, centered just below the point where the stream entered. An LED light was positioned at the lower right side of the container facing up and across the volume of water at an angle of roughly 45°.

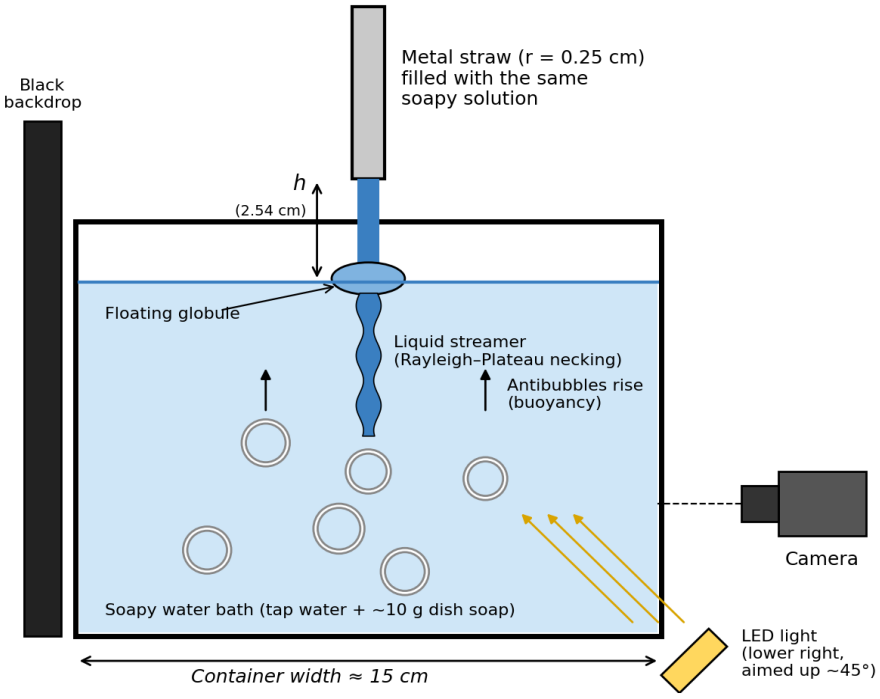


Figure 2: Sketch of the Antibubble Experiment (side view)

Without the soap acting as a surfactant, the solution released from the straw simply merges with the larger body of the solution; however, with our surfactant present, the solution released by the straw forms a globule that sits on the surface, separated from the larger body by a thin layer of air that the surfactant layers on both interfaces keep from draining instantly [2]. As more liquid is fed into the globule from the straw, the stream pushes it downward and drives a column of liquid, still wrapped in its thin air film, beneath the surface. Dorbolo and Vandewalle report that the area for antibubble production exists only a few centimeters below the surface [4]. After exiting this zone as individual antibubbles, each antibubble drifts slowly upward towards the surface.

2.2 Flow Physics

Several forces exist in this flow. Inertia is present as the liquid leaving the straw is what forces the air film below the surface in the first place. If the stream is too slow, the globule just floats and if it is too fast, then it breaks and only ordinary bubbles are produced instead. Surface tension then pinches the submerged column of liquid into separate spheres, forming the individual antibubbles. Once an antibubble has formed, the curvature of its two interfaces where air and water interact sets a Laplace pressure in the air shell that is higher than in the surrounding liquid [4].

Additionally, the effects of buoyancy acts on the small amount of air in the shell. Because the shell is extremely thin compared to the radius of the antibubble, the antibubble is only slightly lighter than the liquid around it and rises slowly, unlike an ordinary bubble of the same size. Gravity also drives the air within the shell toward the top of the antibubble, so the film thins at the bottom. Dorbolo et al. attributed the duration of an antibubble to its slow drainage rate of air, which continues until the film reaches a critical thickness where van der Waals attraction between the two interfaces causes the film to collapse [3]. High-

speed imaging shows that the bubble rupture begins at the bottom and that the air retracts into a tiny bubble that rises away [2].

2.3 Analysis

To characterize the flow, the properties of water at 20 °C were used for the liquid, ρ = 998 kg/m^3 and $\nu = 1.00 \times 10^{-6}$ m^2/s. The surface tension of dilute dish soap solution was assumed to be γ = 0.030 N/m. The velocity of the liquid at the liquid surface is computed using Equation 1.

$$U_j = \sqrt{2gh} = \sqrt{2(9.81\ m/s^2)(0.0254\ m)} = \ 0.71\ m/s \tag{1}$$

Using the inner diameter of the straw, D_j = 5 mm, as the length scale, the Reynolds number of the stream is given by Equation 2.

$$Re_j = \frac{U_j D_j}{\nu} = \frac{(0.71\ m/s)(0.005\ m)}{1.00\times10^{-6}\ m^2/s} \approx \ 3500 \tag{2}$$

A Reynolds number near 3500 means the stream is transitional, but because the liquid falls only 2.54 cm, there is little time for disturbances to grow and its surface stays smooth enough to form a clean globule. The more interesting physics comes from the Weber number, calculated using Equation 3, which compares the inertia of the stream with surface tension.

$$We_j = \frac{\rho U_j^2 D_j}{\gamma} = \frac{(998\ kg/m^3)(0.71\ m/s)^2(0.005\ m)}{0.030\ N/m} \approx \ 83 \tag{3}$$

With a Weber number of $We \approx 83$, inertia dominates surface tension, so the stream has enough momentum to push the air-wrapped globule below the surface rather than letting it rest on top. Taking an air shell thickness of $\varepsilon \approx 1$ μm, consistent with the micrometer-scale films described in [3], the effective density deficit of a 1 cm antibubble is only $\Delta\rho_{\text{eff}} \approx 3\rho\varepsilon/R \approx 0.6$ kg/m^3, less than 0.1% of the liquid density. The Bond number based on this density deficit, Equation 4, compares gravity with surface tension.

$$Bo = \frac{\Delta\rho_{eff} g R^2}{\gamma} = \frac{(0.6)(9.81)(0.005)^2}{0.030} \approx 5 \times 10^{-3} \tag{4}$$

Since $Bo \ll 1$, surface tension easily holds the antibubble in a spherical shape, and the slightly oval outline in Figure 1 is more likely a result of the viewing angle through the container wall. The same tiny density deficit means the antibubble is nearly neutrally buoyant, so it drifts upward only slowly rather than shooting to the surface like an ordinary air bubble.

For time resolution, the slowly rising antibubbles move only a small fraction of a millimeter between frames. With a 6 cm field of view across 1560 px, each pixel spans about 38 μm. The liquid leaving the straw enters at about 0.7 m/s and would need an exposure near 55 μs to freeze, so the stream near the surface shows motion blur while the antibubbles stay sharp.

2.4 Visualization Technique

No dye or seeding was needed, because the antibubbles visualize themselves through refraction and reflection at the air shell. The green LED light at the lower right of the container shines up and across the solution at about 45°, so light scattered through the water illuminates the field behind the antibubble and reaches the camera. Where this light strikes the edge of the air shell at a steep, grazing angle, it is reflected away from the camera, so the rim of the antibubble appears as a dark ring against the lit solution. Near the center, light crosses the thin shell almost perpendicularly and passes straight through, so the liquid

center stays clear. The solution was made with about 10 g of Dawn dish soap and approximately 3 cups of room-temperature tap water.

2.5 Photographic Technique

The video was recorded with an iPhone 16 Pro Max using its Ultra Wide camera, which has a 13 mm (35 mm equivalent) focal length and a fixed f/2.2 aperture. The phone was held about 2 cm from the front of the container, and the video was captured at 59.73 fps and played back at 30 fps. The shutter speed was 1/60 and the ISO was 1250, set automatically by the phone. Figure 1 is a single frame extracted from the video; the original frame was 1560×1260 px and was cropped to 788×1058 px. Additional contrast was added (approximately 40% more than the original) and black point was increased (approximately 50%) The Ultra Wide camera was chosen because it can focus very close to a subject, which allowed the 6 cm field of view needed to fill the frame with antibubbles. Its short focal length and small sensor also give a large depth of field even at f/2.2, keeping antibubbles at slightly different distances from the wall in focus. Recording at 59.73 fps limits each exposure to at most about 1/60 s, which is fast enough to capture the slowly rising antibubbles with little blur. Shooting through a flat side wall rather than from above avoided distortion from the curved free surface.

III. Conclusion

The image shows an antibubble, a liquid core wrapped in an air shell roughly a micrometer thick, formed when soapy water dropped from a straw drove an air-wrapped globule beneath the surface. The estimated Weber number of about 83 shows that inertia was strong enough to push the globule under the surface, and the predicted antibubble size of about 9.5 mm agrees with what the video shows. Once formed, the antibubble carries so little air that it is nearly neutrally buoyant and rises slowly, with the shell draining until van der Waals forces rupture it from the bottom [3].

The image fulfills its intent of showing that a stable antibubble can exist and what it looks like, and the dark ring against the lit bath makes the thin air shell easy to see. I like how the lighting turns the invisible air shell into a sharp, dark outline with bright highlights along its inner edge. I am less happy that a single frame cannot show the formation process at the streamer or the collapse of the shell, which are the most dynamic parts of the flow. I do wish I had included a slow motion visual of the bubble collapsing as well. One open question is how long these particular antibubbles lasted and whether their lifetime matched the drainage picture described in the literature.

In future work, I would like to record high-speed video of the release to watch the bubble form and pinch off, and to time the antibubbles from formation to collapse. Adding salt or sugar to the liquid in the straw would make the antibubbles neutrally buoyant or slightly heavy, so they could be held in view longer [4].

References

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[2] S. Dorbolo, H. Caps, and N. Vandewalle, "Fluid instabilities in the birth and death of antibubbles," *New J. Phys.* 5, 161 (2003).

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[4] S. Dorbolo and N. Vandewalle, "Antibubbles: evidences of a critical pressure," arXiv:cond-mat/0305126 (2003). https://arxiv.org/abs/cond-mat/0305126