BUBBLE IN A BOTTLE (VIDEO)

TEAM FIRST, FALL 2023

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MCEN 5151 – Flow Visualization

27 September 2023

ACKNOWLEDGEMENTS
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Music Credits

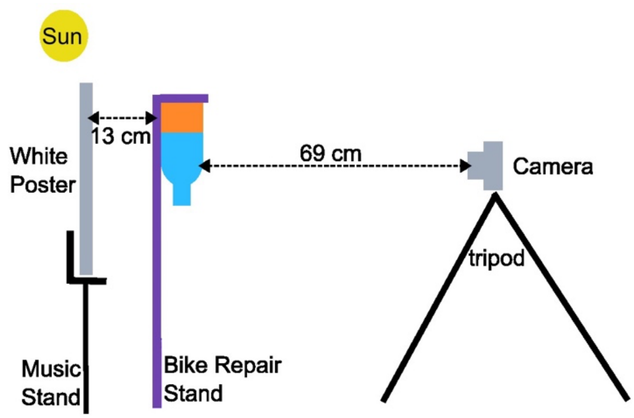
No. 10 A New Beginning by Esther Abrami

(YouTube Audio Library)

INTRODUCTION

I created a video of an inverted bottle discharging fluid as a part of the Team First assignment for the Fall 2023 iteration of MCEN 5151 – Flow Visualization at the University of Colorado Boulder. My *artistic objective* was to capture the beauty and chaos of the mixing of air, water, and mineral oil as a fluid pours out of the bottle. Through this video, I also aim to capture the multifaceted physics that occurs as the bottle empties. We see bubbles rise through the layers of fluid in the bottle, jets extend from the interface between the liquid and the gas, mixing of the various fluids, and “glugging” or “slugging” as the bottle empties. After much experimentation with various fluids (e.g., orange soda, sparkling water, glitter-seeded water, agave syrup, mineral oil and water, plain water, mouthwash, soapy water, and various combinations of the above liquids), I settled on a fluid mixture of mineral oil and water that I feel best emphasizes the mixing effects seen during the bottle emissions. The award-winning video of glugging created by Mayer et al. 2022 – which shows water, and glycerin discharging from a clear bottle – inspired me to experiment with bottle discharge.

SETUP



I captured this video around 10:41 am MDT on Saturday, September 23, 2023 near Niwot, Colorado facing due East next to a shed that shaded the area around my photographic setup*. In this video, you may see flecks of green light and a green reflection on the right side of the bottle. While that was not intentional, a tree about 5 meters to the right of the bottle reflected light onto the bottle. I filmed a few takes of this fluid experiment in which the tree reflection is not visible. However, I felt the tree’s reflection increased the color spectrum visible in the video and added a unique element that augmented the intrigue of the subject and the visibility of the motion.

In the video, I filled a clear bottle with 2 parts water and 1 part mineral oil by volume. I left space for about 3 parts air in the bottle so that the air/liquid interface throughout the video. In other words, 50% of the bottle was filled with air (6 fl. Oz), ~16.7% of the bottle was filled with mineral oil (2 fl. Oz), and ~33.3% of the bottle was filled with water (4 fl. Oz). I then capped the bottle with a synthetic cork. To hold the bottle in a fixed inverted position, I used a Park Tool bike stand designed to elevate a bike off the floor during repairs. In this video, I rotated the fixture to hold the bottle in an inverted position with the bottle’s neck directed downward.

* This information dictates the sun position. Since I relied on natural light, I felt this information was important to include.

During this inversion process, I tried my best not to mix the fluids too much; the differences in density between the mineral oil and water caused the liquids to reseparate and that rotational motion to dissipate before I started recording my video. In this video, the camera lies on a tripod about 69 cm from the spout of the bottle. For a neutral background, I placed a white backdrop about 13 cm behind this bottle. The backdrop (a white posterboard) was elevated and held in position with an adjustable music stand. To open the bottle, I - or an assistant (Jill Murphey) - quickly flicked the cork out of the bottle spout. I then filmed the fluid discharge from the bottle.

I have attached an Equipment list with links to the exact models I used at the end of this document in the Appendix.

PHYSICS

Upon opening an inverted bottle, the fluid contained within the bottle will begin to flow out rapidly. During this emission, the pressure of the air in the bottle lowers, creating a vacuum. The ambient air outside of the bottle is then "sucked in" in the form of a bubble (sometimes called a "Taylor bubble") (Davies & Taylor, 1997). This bubble then traverses the bottle moving to the lower pressure area of air. However, as the bubble travels through the bubble, the bubble interferes with the fluid flow. When the bubble spans the neck of the bottle, the bubble slows the expulsion of fluid from the bottle; but when the bubble is in the body of the bottle, the fluid can escape from the bottle more easily. Bubbles intermittently enter the neck of the bottle and interfere with the fluid discharge, generating a "glugging" effect. Depending on the velocity of the bubble, the rising bubbles can produce jets (i.e., "Worthington Jets") that protrude from the fluid/air interface. The impact of the jets with the surface of the fluid and the disintegration of bubbles within the fluid before reaching the surface can cause mixing of the fluid. In the experiment captured in this video, since we have two distinct fluids of distinct densities, this mixing is clearly marked by the different indices of refraction between the fluids.

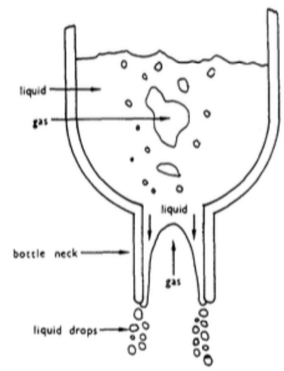


Figure 4. Flow pattern around the neck of a bottle during emptying.

Figure 1: *A sketch of the discharge of fluid from a bottle* (Whalley, 1987).

DISCHARGE

One of the quantities we care about most during bottle discharge is the time it takes for the bottle to completely empty (Clanet & Searby, 2004). We can calculate the Wallis flooding constant C – derived by Wallis et al. and modified by Whalley et al., 1987 – to account for slugging phenomena. C describes the difference between dimensionless superficial velocities of the liquid and the gas in a tube:

$$C = \frac{{\rho_G}^{1/4} + {\rho_L}^{1/4}}{[(\rho_L - \rho_G)gD]^{1/4}}\left(\frac{4V}{\pi D^2 t}\right)^{1/2}$$

$$= \frac{(1.225\ kg/m\text{^}3)^{1/4} + (933.33\ kg/m^3)^{1/4}}{[((933.33\ kg/m\text{^}3)^{1/4} - (1.225\ kg/m\text{^}3))(9.8\ m/s\text{^}2)(0.02m)]^{1/4}}\left(\frac{4(0.000355m\text{^}3)}{\pi(0.02m)^2(13\ s)}\right)^{1/2}$$

$$= 0.53$$

where g is the gravitational acceleration, D is the diameter of the bottle opening (2 cm), V is the volume of the bottle (12 fl. oz), and t is the time required for filling or emptying the bottle (13 s). I measured the diameter of the opening (2 cm) with a ruler. For the volume, I filled the bottle completely with water and then poured that fluid into a measuring cup (~12 fl. Oz = 0.000355 m^3). I calculated the time required for emptying the bottle using the elapsed duration for emptying calculated from the video (from timestamps 3 to 29 seconds at ½ x playback speed = 13 seconds in real time). I disregarded drips after the bottle appears mostly empty. For the density of the liquid, I took the average density of the fluid if one accounts for both the water and mineral oil in the proper proportions (933.33 kg/m^3). This density approximation not give us the most accurate representation of the flooding constant, however, because the denser fluid (water) will generally empty before the less dense fluid despite mixing. Therefore, we should consider this flooding constant a rough approximation. The calculated value of 0.53 for the Flooding Constant, *C*, is slightly lower than reported for less dense fluids like water (0.93) and sherry (0.98) in (Whalley, 1987, 1991). Our lower Flooding Constant indicates that the time to empty in this experiment is significantly slower than the time to empty for less dense fluids, which I expected because I used a more viscous fluid like mineral oil in these experiments.

Bubbles and Jets

Bubbles form when ambient gas (air in this case) is sucked into the neck of the bottle due to the lower pressure of the gas within the bottle. As the bubbles rise to the fluid surface, there are four distinct phases (shown in Figure 2): 1) First the bubble pinches off; 2) then an ejector jet forms and that jet punctures through the edge of the bubble; 3) then the jet penetrates top of the bubble; and 4) finally an annular bubble structure forms as the jet disintegrates or breaks through the surface (Mayer et al., 2022). To describe these bubbles, we use the Bond or Eötvös number, which characterizes the shape of bubbles moving through fluid ("Eötvös Number," 2023; Mayer et al., 2022).

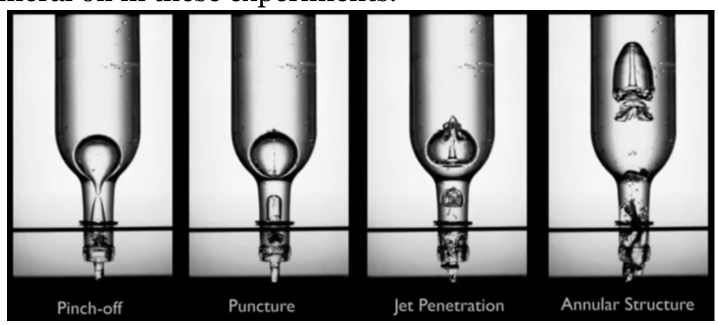


Figure 2 : *The four phases of bubbles go through when traversing the bottle (Mayer et al., 2022).*

$$Eo = \frac{\Delta\rho\, g\, L^2}{\sigma} = \frac{(933.33\ kg/m^3 - 1.225\ kg/m^3)\ 9.8\ m/s^2\ (0.002m)^2}{0.069\ N/m} = 0.529$$

where $\Delta\rho$ is the change in density between the gas and the liquid ($\rho_L - \rho_G = 933.33\ kg/m^3 - 1.225\ kg/m^3$), g is the gravitational constant, L is the characteristic length of the bubble (the volume equivalent diameter of the bubble – $0.002\ m$ estimated from the video frames), and σ is the surface tension of the fluid (averaged surface tension of mineral oil and water is 0.069 N/m) (Rohilla & Das, 2020). A Bond number of 0.529, which is on par with the observations from Rohilla and Das, 2020 for a bottle filled with silicon oil, indicates that we will likely see large bubbles due to the low surface tension of the mineral oil

Figure 3: *A jet forms on the surface of the mineral oil/water mixture.*

(Rohilla & Das, 2020). In this experiment, these large bubbles contribute to the formation of jets as shown in Figure 3.

MIXING

In the video, the fluid in the bottle mixes considerably. If the bottle contains a fluid like beer or wine, we may care about how much the fluid in the bottle mixes as the bottle empties because this mixing can affect the flavor and texture of the beverage. We can quantify this mixing with the Reynolds number, which is a measure of the ratio of inertial and viscous forces in the bottle. Since most of the mixing seems to occur when the bubble rises through the bottle, I have calculated the Reynolds number for the fluid flowing around the bubble. The characteristic length L is the bubble diameter (0.022 m), the velocity U comes from observing the bubble center traverses 1 cm over 3 frames (1 cm / (3 frames * 1/(120 frames/second)) = 40 cm / s).

$$Re_{Flow\ around\ bubble\ in\ Water} = \frac{\rho_{water} U L_{bubble}}{\mu_{water}} = 24{,}800$$

$$Re_{Flow\ around\ bubble\ in\ Mineral\ Oil} = \frac{\rho_{Oil} U L_{bubble}}{\mu_{Oil}} = 193$$

$$Re_{Flow\ around\ bubble\ in\ Mixture} = \frac{\rho_{Mix} U L_{bubble}}{\mu_{Mix}} = 661$$

These Reynolds numbers reveal that, when the bubble is moving through the water, the water flowing around the bubble is turbulent. When the bubble is moving through mineral oil only, the mineral oil flow is laminar. When the bubble moves through the mixture of mineral oil and water (e.g., after the fluid has already mixed a little), the flow is still laminar. A summary of the above dimensionless numbers is in the Appendix at the end of this document.

FLOW VISUALIZATION

The flow visualization technique illustrated within this video depends on the different indices of refraction among the air, water, and mineral oil. However, as the mineral oil mixes with the water, the mineral oil appears to mark the boundary between the air, and water –

Table 1: Camera and Video Settings

Camera	Olympus OMD E-M10 Mark II
Lens	M. Zuiko Digital 14-42mm 1:3.5-5.6
Light Source	Indirect sunlight at 10 am
Focal Length	42 mm
ISO Speed Rating	ISO 500
Aperture	Auto - unknown
F number	Auto – f/5.6
Frame Rate	120 fps
Playback speed	0.5x forward, 2x backward, 0.3x forward
Camera Modes	Video, HD 120 fps, Static AF + MF, Program Auto (P)
Raw Video Frame Size	640 x 480†
Edited Video Frame Size	Cropped 466 x 360, scaled by 825%, and padded with back background
Edited Video Resolution	3840 x 2160 output at 30p

† My camera can shoot at a higher resolution but not at 120 fps. For 1080p, you can only shoot at 60 fps. This was a tradeoff I had to make to capture the dynamics of this video.

becoming a sort of seeded boundary technique.

PHOTOGRAPHY

To capture this video, I used my Olympus OMD E-M10 Mark II camera with the kit lens – a M. Zuiko Digital 14-42mm 1:3.5-5.6. The lens was fully zoomed in at a 42mm focal length. For this video, I used the Manual focus (MF) mode. While my camera has a continuous focus (CF) mode for tracking motion during a video, in my trials using CF, I found that the CF tracking tended to defocus the motion in the bottle throughout the video. This video was filmed in the "slow-motion" 120 frames per second mode. On my camera, the native playback speed on the raw slow-motion video is played back at 60 frames per second (1/2 of real-time speed).

POST-PROCESSING

To edit this video, I used a free trial of Apple's Final Cut Pro. Unfortunately, during the filming of this video, a fly flew across the upper left corner of the frame. For this reason, I cropped the frame to make sure you could not see the fly in the video, and to center the bottle in the frame so it was the focus of the video. To increase contrast, I used the "Hard Light" filter set at 50% along with the "Vibrancy" filter also set to 50%. These two filters increased the contrast and highlight details in the frame. I played around with monochrome filters. However, I found the contrast in the colors of the light bouncing of the glass and the fluid mixture captivating. Monochrome filters failed to replicate the strike beauty found in the raw video. I feel the color spectrum present in this video augments the motion. This is why I chose to make only the still thumbnail frame black and white.

In this video, you see a variety of playback directions and speeds. The video begins with the forward direction bottle opening played at 1/2x speed (i.e., compared to real-time). After the bottle empties, I reversed the video at 2x speed. I found this reversal to be helpful in drawing attention to the mixing and the jets you see in the video. Then I replayed the video at 0.3x speed to emphasize some of the dynamics you see in the video – the jets, mixing, and bubbles. I close the video with a still frame of one of the more interesting bubbles I saw during the video.

I also trimmed some of the excess time at the beginning of the video when I was hesitating during opening the bottle and at the end of the video while the fluid drips from the edges of the bottle spout.

After adding a few title frames, transitions (i.e., fade in and out), and text overlays showing the playback speed, direction, and the composition of the fluid, I added music – Esther Abrami's *No. 10 A New Beginning* and aligned the final video frame to the resolution of the piece.

Conclusion

Bottle discharge and slugging is a gorgeous representation of a confluence of physical principles. When visualized in natural light, one sees striking images of turbulence, jets, and bubbles. I love the chaos illustrated in this video and how so many different fluid instabilities are represented in one bottle. If I were to perform this experiment again, I would try it with a higher speed camera and perhaps more controlled lighting. However, I think the refraction of the natural light off the natural surface around my setup were exciting additions to this video that enhance the art.

Acknowledgements

I would like to thank my co-authors and helpers. Thanks to Jill Murphey for supplying the mineral oil and various other liquids to try. She also helped me with positioning the camera, experimenting with lighting, and keeping our dogs away from the fluid collection bowl below the bottle setup. Finally, in many of the trials, Jill opened the bottle. While her hand is not the one captured in this particular video (that's my hand), I learned a great deal by watching her open the bottle and tried to apply her technique in the video presented here.

I would also like to thank my Team Chard teammates, Ben Clairday, Zach Turner, and Venkata Ramana Murty Durvasula. While they did not participate in the filming this video, they provided valuable feedback on this idea for which I am extremely grateful.

Finally, thank you to Esther Abrami for supplying the music for this video. I found Esther's music on the royalty-free YouTube Audio Library. The piece featured in this video is *No. 10 A New Beginning*.

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APPENDIX

FLUID PROPERTIES

	Density ρ (kg/m^3)	Dynamic Viscosity μ (Pa-s) at 25C	Surface Tension σ (N/m)
Water	1000	(1.05×10^{-3})	0.072
Mineral Oil	800	(1.08×10^{-1})‡	0.063
Air	1.225	(1.86×10^{-6})	-

SUMMARY OF THE CALCULATED VALUES AND DIMENSIONLESS NUMBERS

	Formula	Estimated Value	Units / meaning	Calculated from…
Velocity of Bubbles Rising	-	0.4 m/s	m/s	1 cm movement / (3 frames * 1/(120

‡ (*Mineral Oil Dynamic Viscosity Data.*, 2017)

				frames/second)) = 40 cm / s
Velocity of fluid exiting the bottle	$\bar{v} = Q/A$	0.0439	m/s	Initial volume of fluid (6 fl oz) over time to empty divided by the area at the outlet
Time to empty bottle	$t = elapsed\ time\ to\ empty$	13	s	Counting number of frames
Reynolds Number in Mixture	$Re = \frac{\rho U L}{\mu}$	661	*Dimensionless*	Flow around the bubble in the **mixture** of fluid
Bond or Eötvös Number	$Eo = \frac{\Delta\rho\, g\, L^2}{\sigma}$	0.529	*Dimensionless*	
Wallis Flooding Constant	$C = \frac{{\rho_G}^{1/4} + {\rho_L}^{1/4}}{[(\rho_L - \rho_G)gD]^{1/4}} \left(\frac{4V}{\pi D^2 t}\right)^{1/}$	0.53	*Dimensionless*	ρ_L is the volume-averaged density of all of the liquid in the bottle.

EQUIPMENT LIST

- 1x Cornucopia Clear 12 oz. Liquor Bottles with T-Top Synthetic Corks : https://www.amazon.com/12-Ounce-Liquor-Bottles-2-Pack-Synthetic/dp/B07BRBXHS8
- Walgreens Mineral Oil : https://www.walgreens.com/store/c/walgreens-mineral-oil/ID=prod6154213-product?ext=gooFY23_GOO_RET_RETAILDEMANDGEN_Performance%2BMax%2B-%2BHealth%2BCare_REV_SRC_PMAX_PMAX_NA_PMAX_ENG__pla_local&gclsrc=aw.ds&gclid=Cj0KCQjwpc-oBhCGARIsAH6ote_-3cXM5kpGKE35n5SQFUT4a4Gu6KySIllYdGEPGqnfIE1hKEcUB9saAjQQEALw_wcB
- Park Tool Home Mechanic Repair Stand: https://www.parktool.com/en-us/product/home-mechanic-repair-stand-pcs-9-3?category=Portable
- Donner Sheet Music Stand – 17 * 10.7 IN: https://www.amazon.com/gp/product/B0772MTRSH/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1