Fluids Demonstrations III: Viscous Flow in Modified Thin Enclosures, Centrifugal Effect, Vortical Flow, and Turbulence

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Fluids Demonstrations III: Viscous Flow in Modified Thin Enclosures, Centrifugal Effect, Vortical Flow, and Turbulence

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Several new devices that demonstrate a variety of known phenomena in fluid dynamics are presented. These add on to a recent collection of demonstrations and follow the same design features as documented earlier (self-contained, easy to use, low cost).\(^1,2\) Descriptions are provided to enable replication by others, using readily available materials. The significance of each demonstration is outlined and background information on the relevant physics can be found in the cited references. The devices can be generally used in classroom lecture demonstrations, outreach activities, or other student-based projects. However, pedagogical details are left to readers’ discretion, depending on the scope of local interests and constraints. Video samples of demonstrations are available online.\(^3\)

Description

Acrylic sheet and round stocks were used to make the devices. All materials were sourced in the United States; therefore, dimensions are given in inches for brevity. Fabrication methods were the same as described earlier.\(^1,2,4\) Liquids used in the current devices included glycerin, water, olive oil, and mineral oil. The total material budget was US $240 as recorded in the appendix. With additional expenditure, polycarbonate could be used instead of acrylic as it provides better resistance to breaking, but it scratches easily. It should be noted that joining acrylic (or polycarbonate) parts requires special adhesive that works on the principle of chemical welding.

1. Flow in thin enclosures

A thin enclosure has served as an ideal device (i.e., self-contained and light) for a number of fluids-based demonstrations as reported earlier. The author has used olive oil, liquid soap, rheoscopic fluid, glycerin, and sand in such enclosures. Of these materials, glycerin is the best when considering long-term stability and number of phenomena that can be demonstrated. Furthermore, glycerin can be colored by adding and mixing a few drops of food color, and if needed diluted with water. In contrast, and in about 12 to 18 months of use, olive oil turns colorless, liquid soap thickens into gel, and rheoscopic fluid tends to lose its pearlescence property. Sand, although a stable material, is limited in the number of phenomena it can demonstrate.

Because the thin enclosure has been such a useful device, several modified enclosures are presented to complement and enhance the aforementioned collection. Also, the variety of enclosures described here may encourage interested readers’ participation in designing similar devices. All enclosures have frontal dimensions of 8 x 10 inches, and spacing of 1/16 of an inch between the back and front. They were designed primarily as visual objects to be used in outreach activities and museum settings. Furthermore, they also exhibit a variety of interfacial phenomena from surface tension to instability due to density differential.\(^5,6\)

The first group of enclosures are modified versions of a simple enclosure. The modification is the addition of a single or multiple partitions made of thin rods or blocks. The partitions’ role is to alter the flow in the enclosure. It was of interest to study the visual effect of such alteration, and four arrangements are shown as examples in Fig. 1. (A total of seven arrangements were tried.)

Each enclosure contains approximately equal volumes of glycerin and air. Glycerin is diluted with 10% water on volume basis and dyed with a few drops of food color. The store-bought glycerin is very viscous (~ 1000 cP), and its dilution was done to reduce its viscosity and hence speed up its flow in the narrow gap. Several percentages of dilution were tried, and the 10% was found to have

Fig. 1. Dyed glycerin in thin enclosures with partition(s) turned upside down: (a) single diagonal partition, (b) multiple parallel partitions, (c) nested rectangular partition with openings at two diagonal corners, and (d) multiple block partitions.
the overall best visual effect under a temperature range of approximately 15 to 25 °C. (For liquids, as temperature increases, viscosity decreases.)

In each enclosure, the flow starts from an unstable condition. This is established when the enclosure is turned upside down, and the heavier fluid, glycerin, is positioned on top of the lighter fluid, air. The altered flow (due to the partitions) in each of the enclosures was engaging; however, the most interesting was the one associated with the multiple parallel partitions, shown in Fig. 1(b). Glycerin flowing down and air pockets rising up create complex and intriguing patterns partly due to pressure fluctuations in the channels between partitions. The fluctuations are caused by random blockages in the channels by blobs of glycerin that momentarily disrupt air flow. This dynamic situation is readily seen in the sample video.³

Another enclosure has two separate layers, where glycerin is dyed with a different color in each layer. This is to enhance the demonstration by including the visual effect of additive colors. The glycerin in the front layer is blue and in the back layer yellow, resulting in green when overlapped, as shown in Fig. 2. When the enclosure is turned upside down, the instability due to density differential between glycerin and air is demonstrated. This instability takes the form of undulation at the liquid-air interfaces in each layer as marked by dashed lines in Fig. 2(b), and is known as Rayleigh–Taylor instability.

Two other enclosures contain different combinations of immiscible liquids and air. The first is shown in Fig. 3(a), which is an enclosure with colored water, olive oil, and air. When this enclosure is turned upside down, a number of fluid features are demonstrated. For example, air bubbles must pass through oil and water to reach the top. The speed of rising air bubble is markedly different in oil than water due to the large difference in their viscosities ($\mu_{\text{oil}} \sim 40 \text{ cP}$ and $\mu_{\text{water}} \sim 1 \text{ cP}$). Also, penetration of water into oil or vice versa creates fingering patterns due to viscosity and density differentials, see Fig. 3(b). The fingering is identified by dashed lines in Fig. 3(b).

Figure 4(a) shows another enclosure, made of clear acrylic sheets, with approximately equal volumes of glycerin and mineral oil and a small volume of air. The red dashed lines indicate the boundaries of the liquids, with glycerin at the bottom above which is mineral oil and above that is a thin layer of air. It is difficult to distinguish the two essentially clear liquids apart from each other. However, they have close but non-identical indices of refraction, and even a slight difference is sufficient to cause light to bend at the interfaces of the two liquids. Therefore, it is possible to detect their interaction by the shadows created at their interfaces, see Fig. 4(b). Of course, to visualize the shadows, a strong light source in front of the enclosure and a screen situated behind the enclosure are needed. A typical smartphone’s flashlight is sufficient to provide the light source, and an uncluttered wall or a large sheet of paper can serve as the screen. Glycerin can be easily colored if desired, but here the reliance is solely on shadowgraph.⁷

2. Two-in-one

Two phenomena, centrifugal effect and vortical flow and the resulting turbulence, are demonstrated with a disk-like enclosure that contains water and cosmetic mica powder, and an air bubble. The mica serves as an inexpensive tracer to make the flow visible, but it is heavier than water and quickly settles down if water is stationary. Therefore, just prior to each demonstration, the enclosure should be shaken to thoroughly mix the mica. Food color is added to the water for visual enhancement. (Earlier attempts to use commercially available rheoscopic fluid, which turned out producing very good results initially, failed because in most cases the fluid lost its pearlescence property after being sealed in an enclosure for a while, sometimes in a matter of several weeks. An inexpensive alternative to the rheoscopic fluid was recently documented.)⁸)

The enclosure is made of a small length (~ ¼ in) of 6-in acrylic tubing, which is covered by a 6-in disk at each end. A small hole on the side allows injection of water into the enclosure; the hole is then covered by a small square piece of acrylic and sealed.

The enclosure is held on a turntable, which is made of three parts. The bottom is a square piece of acrylic sheet. To this sheet, a plastic 6-in turntable is glued. An acrylic disk of 8-in diameter is glued to the top part of the turntable and has three pegs to retain the enclosure, see Fig. 5(a).

To perform the demonstration, the base is held by one hand, while the other hand spins the turntable. If the enclo-
Summary

The devices presented here can be set up instantly and used repeatedly without maintenance. More importantly, they can be easily replicated, requiring readily available materials and ordinary fabrication methods with a modest budget. Although simple in design, the devices demonstrate complexity (and beauty) of several types of fluid flows. They were exhibited at the 2019 AAPT Apparatus Competition in Provo, UT.

Acknowledgments

Special appreciation is extended to Dr. David Kardelis for his sponsorship, which enabled me to enter the 2019 Apparatus Competition, and for his willingness to set up and take down the demonstration devices on my behalf. I thank an anonymous reviewer whose comments helped improve the paper. My wife, Mahnaz, assisted with taking photographs in Fig. 5, while we were sheltering-in during the pandemic. Funding was provided by the Faculty Research Committee of the University of the Pacific.

References

4. For example, view instructional videos on cutting and gluing acrylic at: https://www.tapplastics.com/product_info/videos. Also, type “Acrylic Sheet Fabrication Manual” in your search engine to access a 36-page manual with the same title.
6. R. F. Benjamin, “Rayleigh-Taylor instability – Fascinating gate-


10. Apparatus Competitions are archived at https://www.aapt.org/Programs/contests/apparatus_home.cfm.

**Said Shakerin,** educated in Iran and the U.S., has been with the Department of Mechanical Engineering at University of the Pacific since 1986 and retired in September 2021. His recent scholarly activity included creation of water fountains with special effects and self-contained interactive demonstrations primarily related to physics of fluids. He still loves physics and recommends its study.

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**Appendix – Materials and supplies**

(All items were sourced in the U.S. and thus the English system is used to specify them. Prices were as of April 2019 and rounded up to the next dollar value.)

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Size</th>
<th>Source</th>
<th>Price, US$</th>
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</thead>
<tbody>
<tr>
<td>acrylic sheet, 1/8 in thick</td>
<td>15</td>
<td>10 x 8 in</td>
<td>plastic supplier*</td>
<td>15 @ 7.00 each</td>
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<tr>
<td>acrylic sheet, 1/16 in thick</td>
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<td>10 x 8 in</td>
<td>plastic supplier</td>
<td>5.00</td>
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<td>acrylic rod, 1/16 in diameter</td>
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<td>6 ft long</td>
<td>plastic supplier</td>
<td>1.00</td>
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<td>acrylic 6-in tube, 1/8 in thick</td>
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<td>¼ in long</td>
<td>plastic supplier</td>
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<tr>
<td>acrylic disk, 1/8 in thick</td>
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<td>6 in diameter</td>
<td>plastic supplier</td>
<td>2 @ &lt;4.00 each</td>
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<tr>
<td>acrylic square, 1/8 in thick</td>
<td>2</td>
<td>8 x 8 in</td>
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<td>plastic turntable</td>
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<td>5.00</td>
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<td>acrylic knife</td>
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<td>plastic supplier</td>
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<td>acrylic cement</td>
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<td>funnel &amp; trough ****</td>
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<td></td>
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<tr>
<td>applicator bottle</td>
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<td>2-oz bottle</td>
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<td>5-oz tube</td>
<td>plastic supplier</td>
<td>10.00</td>
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<tr>
<td>micro tip (for glue tube)</td>
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<tr>
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<td>grocery store</td>
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<tr>
<td><strong>Total</strong></td>
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<td></td>
<td></td>
<td>240.00</td>
</tr>
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* An example of plastic supplier is tapplastics.com.

** The edge strips are cut from this item. The supplier may cut the ¼-in wide strips upon request. Otherwise, cut the strips with a table saw equipped with a fine tooth blade.

*** Needed to score and cut thin acrylic stock.

**** Needed to fill applicator bottle with acrylic cement. Spillage is a sure thing without these.

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