“Team First” Report: Flow through Orifices

MCEN 5151-001 Flow Visualization, Fall 2025

Emma Wilder, 10/1/2025 (created alone)

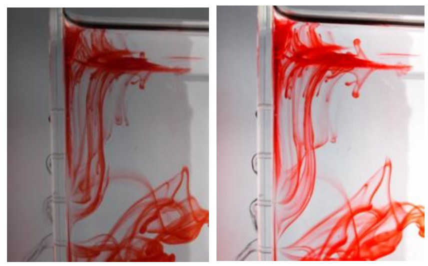

Fig. 1: Thumbnail of (A, left) the unedited video, and (B, right) the edited video.

Introduction

The video (represented by the thumbnail in Figure 1) was made to visualize the flow path of water passing through holes (or orifices) of the same diameter at various depths, and to compare experimental results of flow to theoretical predictions of flow. A transparent plastic vessel with drilled holes was filled with tap water and drops of food dye were added to trace the flow path. Since the different depths of the holes correspond with different pressures, the velocity between each of the holes differed, and the velocity at each of the holes decreased over time as the water level decreased. The flow path was made visible with the dye, showing the impact of pressure on flow patterns and speed, which also created an effective and aesthetically pleasing visual.

Flow Apparatus

The apparatus included a transparent plastic box (“vessel”) with five 1/16 in. diameter holes drilled into the side spaced ½ in. apart vertically (Fig. 2a). The holes were covered with tape to allow the vessel to be filled with tap water 1 in. above the top hole. The vessel was left for approximately 10 minutes to still water movement. The tape was then removed and drops of red and blue food dye (Kroger Food Colors, Assorted Colors) were dopped from approximately 1-2 in. above the water surface (Fig. 2a) so dye would disperse without dropping too rapidly.

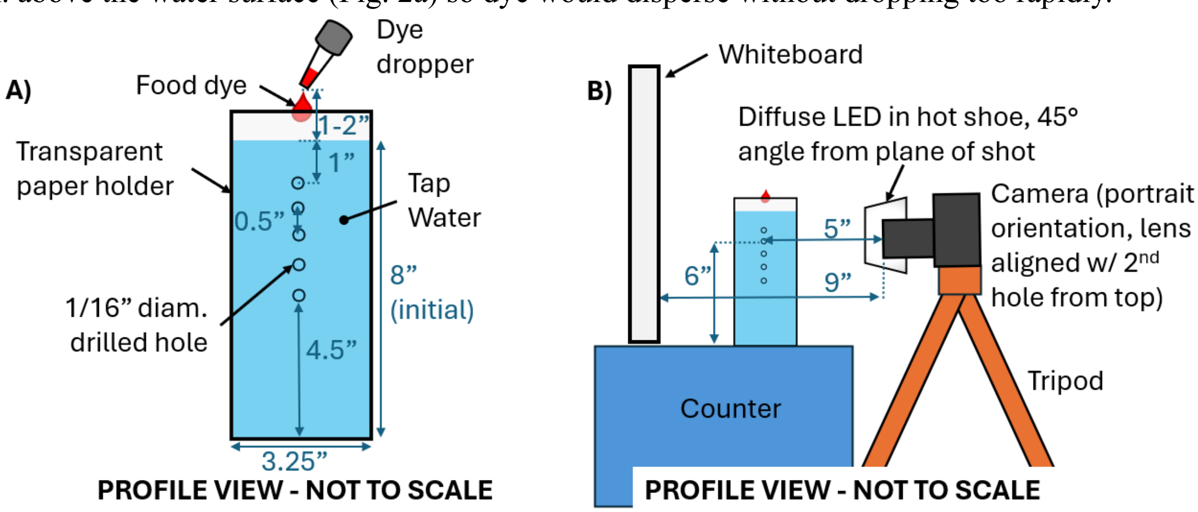

Fig. 2: Profiles of experimental setup including (A) a close up of the vessel, & (B) entire setup

Appropriate dimensions and placements are shown in Fig. 2a-b. The distance and camera placement were intended to capture the detail of the flow, and show both the bulk water in the vessel and the water exiting the vessel.

Scientific Explanation

Within a fluid, hydrostatic pressure increases with depth due to the weight of the fluid above it (Fig. 3a). This hydrostatic pressure of water provides the force that accelerates the water through the holes. The pressure inside the vessel is higher than atmospheric pressure, but the water jet is at atmospheric pressure after it exits the holes, and water flows from high pressure to low pressure. Assuming that the viscosity of water is negligible, the flow of water can be described with Bernoulli's equation (Eq. 1). Bernoulli's equation describes that along a flow path (e.g., Fig. 3b) energy is conserved, but the energy transforms between pressure energy (P), velocity energy ($\frac{1}{2}\rho v^2$, where ρ is the fluid density and v is the velocity), and gravitational potential energy (ρgh, where g is gravitational acceleration, h is the depth). A special case of Bernoulli's equation is Torricelli's law (Eq. 2; D'Alessio, 2021), which allows calculation of flow velocity through an orifice when the area of the water surface is much larger than the area of the orifice.

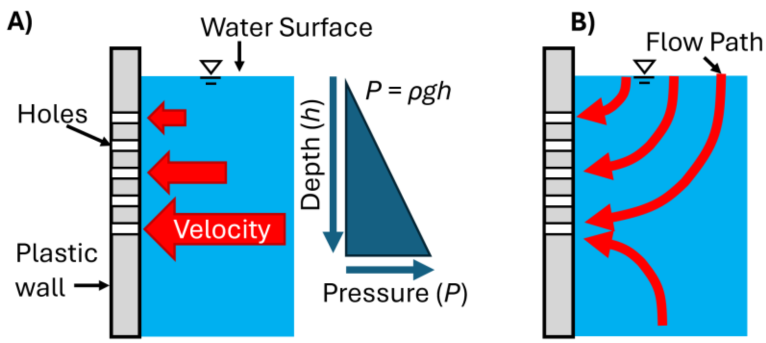

Fig. 3: Diagram of (A) pressure profile & (B) flow path.

$$P_1 + \frac{1}{2}\rho {v_1}^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho {v_2}^2 + \rho g h_2 \qquad \text{Equation 1}$$

$$v_{theoretical} = \sqrt{2gh} = \sqrt{2(9.8\,m/s^2)(0.0762\,m)} = 1.22\,m/s \qquad \text{Equation 2}$$

Using Eq. 2, the velocity of water through the holes can be predicted at t = 0 s, when the water surface is one inch above the top hole. Torricelli's law predicts flow velocities of 0.71, 0.86, 1.00, 1.12, and 1.22 m/s for the top through bottom holes, respectively (example calculation for the bottom hole given in Eq. 2), which is an average of 0.98 m/s for all the holes. These velocities correspond with Reynolds numbers (Re) of 1120-1940 (example calculation for the bottom hole given in Eq. 3), which are laminar but approaching the transition region to turbulence. The determination of laminar flow agrees with the observed flow patterns being predictable and non-chaotic. By the time that the water level dropped by one inch to the level of the top hole, the velocity within the holes is predicted to drop to between 0.00 to 1.00 m/s for the top through bottom holes, respectively, averaging out to 0.61 m/s. These theoretical velocities can be compared to the observed velocities which can be calculated with the vessel geometry and water level change. It took 130 seconds for the water level to drop one inch. Using the dimensions of the vessel, 600 mL were drained in this time, which corresponds with an average flow rate of 4.6 mL/s for all holes. Dividing this flow over the 5 holes and using the hole dimensions, the average velocity through each hole throughout the 130 seconds was approximately 0.47 m/s (Eq. 4). Since the predicted velocity through Eq. 2 is always higher than the observed average velocity, there are likely other forces at play. Eq. 2 does not consider viscous effects that cause head loss and thus a reduction in flow, as well as different potential velocity profiles within the hole (i.e., uniform vs non-uniform velocity, D'Alessio, 2021). The actual velocities are slower than predicted, which would also reduce the corresponding Re values to be fully in the laminar region. To account for energy losses (and thus flow reduction) in real systems, literature often includes a discharge coefficient (C_D, Eq. 5) (Chanson et al., 2002). To compute C_D (Eq. 6) for this system, we must compare the theoretical to the experimental velocity, using averages for simplicity. The theoretical average flow velocity can be approximated as the average of initial and final theoretical velocities (i.e., the average of 0.98 m/s and 0.61 m/s is 0.80 m/s). Since the observed average velocity is 0.47 m/s, C_D is approximately 0.59 (Eq. 6). This result fits within the typical range for a horizontal water jet from a large reservoir of 0.58-0.61 (Chanson et al., 2002), and means that friction and energy loss reduces the flow nearly in half compared to theoretical predictions for an ideal frictionless system.

$$Re = \frac{\rho v D}{\mu} = \frac{(1000\ kg/\ m^3)\left(\frac{1.22\ m}{s}\right)(1.59 * 10^{-3} m)}{(0.001\ Pa * s)} = 1940 \qquad \text{Equation 3}$$

$$v = \frac{Average\ flow\ per\ hole}{Area_{hole}} = \frac{\left(\frac{1}{5\ holes}\right)\left(4.6\frac{mL}{s}\right)\left(\frac{10^{-6} m^3}{mL}\right)}{\pi\left(\frac{1}{16} in. * \frac{1\ m}{39.4\ in.}\right)^2} = 0.47\frac{m}{s} \qquad \text{Equation 4}$$

$$v_{experimental} = C_D\sqrt{2gh} \qquad \text{Equation 5}$$

$$C_D = \frac{v_{experimental}}{v_{theoretical}} = \frac{0.47\frac{m}{s}}{0.80\frac{m}{s}} = 0.59 \qquad \text{Equation 6}$$

Since the flow velocity increases with depth, water is flowing faster towards the lower holes. This difference is visible in the video with the dye movement and how the water exits the orifices. The observed flow path (Fig. 1, Fig. 3b) can be explained by the following. The dye is slightly denser than water, which results in the dye sinking. As the depth increases, the velocity towards the holes to the left increases, resulting in a curved flow path, approaching horizontal near the holes. Some dye fell beneath the holes, resulting in an upwards flow path towards the holes because the hole is drawing in water from all directions.

Visualization and Photographic Technique

The visualization technique was a marked boundary technique using food dye to trace the flow path to contrast with the white background achieved with a whiteboard. The light source was a nine-inch diffuse LED light panel (NEEWER) which was attached to the camera hot shoe and pointed towards the vessel. The highest brightness setting and light placement were used for proper exposure and to avoid glare, and a color temperature of 5600 K was used to avoid yellow shades.

The photographic technique was developed to allow for calculations of flow velocity, to see the flow path, and to aesthetically appreciate this phenomenon. The flow was moving approximately 0.5 m/s at the hole exit, but much slower farther away, approximately 1 cm per second at least 1 cm away from the hole. Since the field of view is around 4 inches (around 10 cm) the flow speed is around 10% of the field of view per second, a shutter speed of 1/60 s would result in a movement of less than 0.2% of the image over the exposure time, which is adequate to capture the flow detail, although there may be some blurring right next to the hole as the velocity accelerates. The camera used was a Canon EOS Rebel T7 (digital DSLR) with an EF-S 18-55mm IS II Kit lens. A 33 mm focal length and 5 cm distance to the holes was used to capture the nuances of the flow pattern while showing the whole flow path. The video was captured at 30 frames per second with a 1/60 s shutter speed for a 180° shutter angle. A portrait orientation was used to capture the vertical flow path, and the camera shoots at a resolution of 1920 x 1080 pixels. An aperture of f/18 was used to have sufficient depth of field to prevent blurriness across the depth of the shot (3.25 inch thick vessel) and an ISO of 800 was used to achieve proper exposure while minimizing noise. Only slight cropping was used after slight rotation of the video for the wall to be vertical, but the video remained 1920 x 1080 pixels due to Davinci Resolve Software. Video composition was intended to follow the rule of thirds while also showing a significant amount of the water on the right and how the water jet exited on the left. Video editing processing in DaVinci Resolve involved increasing saturation and using an s-curve to increase contrast (Fig. 1a-b).

Conclusion

The video reveals the impacts of static head on velocity, the limitations of Torricelli's law without considering energy loss, and water flow paths, fulfilling the intent described above. I liked how striking the visualization turned out and that it also allowed calculations to be performed. I think the amount and placement of dye allowed the flow path to be visible and gave a good sense of relative velocity when paired with the exit jets being visible on the left. It was interesting that this simple experiment allowed for a calculation of C_D which agreed with literature. I think this idea could be developed further by placing particles that allow better visualization of the velocity of the water and a different perspective of the flow paths, by adding dye in controlled manner to clearly show the flow path, or by measuring the flow rate at each of the holes at multiple points in time to see how well they match up with Eq. 5 using the C_D calculated.

References:

D'Alessio, S. Torricelli's Law Revisited. *Eur. J. Phys.* **2021**, *42* (6), 065808. https://doi.org/10.1088/1361-6404/ac279a.

Chanson, H.; Aoki, S.-I.; Maruyama, M. Unsteady Two-Dimensional Orifice Flow: A Large-Size Experimental Investigation. *Journal of Hydraulic Research* **2002**, *40* (1), 63–71. https://doi.org/10.1080/00221680209499874.