

Team First Report — Flow Visualization



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MCEN 5151-001

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10/3/2026*

Nomenclature

A	= Surface area of the glass pane, cm^2
d_c	= Camera distance from the glass pane, cm
g	= Gravitational acceleration, m/s^2
h	= Drop height of the dye above the glycerin surface, cm
h_f	= Thickness of the glycerin film, m
L	= Characteristic length scale, m
t_D	= Diffusion time, s
U	= Representative spreading velocity of the dye, m/s
V	= Volume of glycerin, mL
v_i	= Impact velocity of the drop, m/s
W	= Side length of the glass pane, cm
D_m	= Molecular diffusivity of the dye in glycerin, m^2/s
ℓ	= Spreading distance, m
μ	= Dynamic viscosity of glycerin, $\text{Pa}\cdot\text{s}$
ν	= Kinematic viscosity of glycerin, m^2/s
ρ	= Density, kg/m^3
$\Delta\sigma$	= Surface tension difference between glycerin and alcohol, N/m
τ_v	= Viscous diffusion time, s
Pe	= Péclet number
Re	= Reynolds number

I. Introduction

For our Team First visualization, my team and I set out to capture what happens when a thin, alcohol-based dye is dropped into a very thick fluid. We released a drop of blue alcohol ink into a thin layer of clear glycerin spread on a transparent pane of glass and filmed the result from above against a solid red backlight from an iPad screen [1].

Our original plan was to use glycerin to slow the mixing down enough to watch diffusion between the two fluids. What the video shows is different, but arguably more interesting: the dye does not diffuse in any visible way over the length of the clip. Instead, the drop punches through the glycerin to the glass, spreads outward underneath the glycerin to the edges of the pane, and then rises up around the sides to the surface, where it slowly forms bubble-like shapes that hold until the alcohol evaporates. Because glycerin is so viscous, this flow happens at a very low Reynolds number, the same regime seen in nature in many forms, such as lava creeping downhill or honey crawling off a spoon, where viscosity dominates and inertia is almost irrelevant [2].

1.1 Equipment

The equipment used is listed below. A clear glass pane measuring 4 in $\times$ 4 in (10.2 cm $\times$ 10.2 cm) and 2 cm thick was covered with about 5 mL of Humco USP glycerin, giving a layer roughly 0.5 mm deep (see Section 2.2). One drop of blue alcohol ink was released above the center of the pane using the dropper tip on the ink bottle. An iPad displaying a full-screen solid red image was placed screen-up beneath the glass pane as the only light source.

Materials:

- Humco 103116001 Glycerin, USP, 16 oz
- Alcohol ink set, 12 $\times$ 0.35 oz (10 mL) concentrated alcohol-based colors for epoxy resin art (blue used)
- Apple iPad (11th generation), 11-inch display, used as a solid red LED backlight
- Clear glass pane, 4 in $\times$ 4 in $\times$ 0.78 in (10.2 cm $\times$ 10.2 cm $\times$ 2 cm)

USP-grade glycerin was chosen because its viscosity depends heavily on purity. Glycerin is hygroscopic, meaning it absorbs water from the air, and even a little water makes a large difference: a 95% glycerin solution has roughly a third of the viscosity of pure glycerin at 20°C [3]. Viscosity is also sensitive to temperature, falling from about 1.41 Pa·s at 20°C to about 0.95 Pa·s at 25°C [3]. The bottle was kept sealed until use, and the experiment was run at a room temperature of about 21°C.

The alcohol ink's dropper tip produced repeatable drops. Assuming a typical dropper volume of about 0.05 mL, each drop of alcohol dye is roughly 4.6 mm in diameter. The iPad uses an LED-backlit IPS LCD with a maximum brightness of about 500 nits and a resolution of 2360 $\times$ 1640 at 264 pixels per inch [4].

Following the safety plan, gloves were worn while handling the ink and glycerin, the work was done in a ventilated room because of the alcohol vapor, and the ink was kept away from any open flames or heat sources.

II. Discussion

2.1 Flow Apparatus

As shown in Figure 1, the dye was released from a drop height $h \approx 12.7$ cm above the glycerin surface onto the center of the glass pane, which has a side length $W \approx 10.2$ cm and a surface area of about 103 cm^2 . The iPad was laid directly beneath the pane, and the camera was positioned above the pane at a distance $d_c \approx 12.7$ cm, looking down through the glycerin and glass toward the light. This backlit setup turns the dye dark and gives the video its high contrast.

The drop height determines how fast the drop is moving when it reaches the surface. If air drag is neglected, the impact velocity v_i can be determined using Equation 1.

$$v_i = \sqrt{2gh} \quad (1)$$

For a drop height of $h \approx 12.7$ cm, this gives $v_i \approx 1.58$ m/s. This entry speed is what drives the dye through the glycerin layer to the glass, where it begins spreading outward underneath the glycerin. Using a flat pane of glass instead of a container meant there were no walls, so the dye could spread all the way to the edges of the glycerin and rise around them freely. The camera was placed above the pane so that both the entry point and the full area of the spreading flow were in frame.

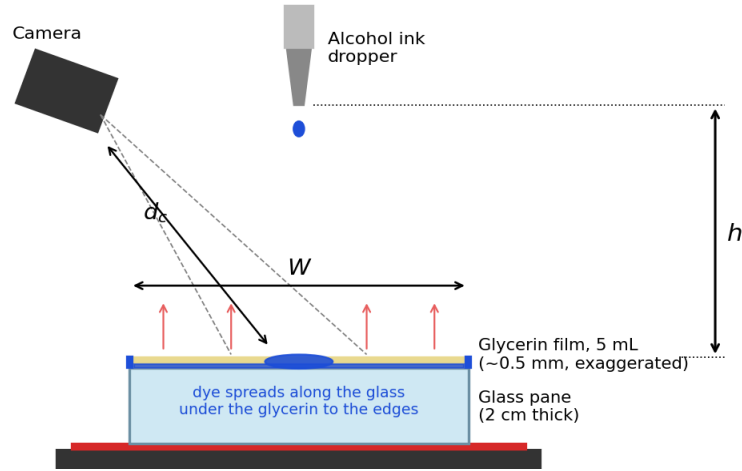


Figure 1: Glycerin and Dye Apparatus, dye drop point, camera, and backlight placement

2.2 Analysis

Glycerin is roughly 1,400 times more viscous than water, with a dynamic viscosity of about $1.41 \text{ Pa}\cdot\text{s}$ and a density of about $1,260 \text{ kg/m}^3$ at 20°C [3]. Its kinematic viscosity is found using Equation 2.

$$\nu = \frac{\mu}{\rho} \quad (2)$$

This gives $\nu \approx 1.12 \times 10^{-3} \text{ m}^2/\text{s}$. The alcohol carrying the dye is much thinner and lighter, with a density of approximately 790 kg/m^3 [5]. The depth of the glycerin layer is also important, since it sets how much room the dye has to move. Spreading a volume V over the area A of the pane gives the film thickness, Equation 3.

$$h_f = \frac{V}{A} \quad (3)$$

With $V \approx 5$ mL and $A \approx 103$ cm², the glycerin layer is only about $h_f \approx 0.5$ mm deep. The 4.6 mm drop is therefore about ten times larger than the layer is deep, which is why it passes straight through the glycerin and reaches the glass instead of being suspended in it. How quickly the viscosity is able to dampen the motion of the drop can be estimated using the viscous diffusion time found in Equation 4.

$$\tau_v = \frac{L^2}{\nu} \quad (4)$$

Using the film thickness as the length, $L = h_f \approx 0.5$ mm, gives $\tau_v \approx 2 \times 10^{-4}$ s. Any motion within the layer is damped in a fraction of a millisecond, so the drop's impact energy is absorbed by the glass and the viscous film. This is why the drop does not show a splash into the glycerin.

After impact, the flow is driven by the differences between the two liquids. The alcohol has a much lower surface tension than glycerin, about 23 mN/m compared to about 63 mN/m [6]. As a result, the alcohol spreads along the glass and slides underneath the glycerin, moving outward from the impact point toward the edges of the pane [7]. Once it reaches the edges, it is free to rise around the sides of the film to the surface, which matches the motion seen in the video. At the surface, the lower surface tension of the alcohol pulls it into the bubble-like shapes visible near the end of the clip, which persist until the alcohol evaporates; isopropyl alcohol evaporates readily at room temperature, while glycerin is non-volatile [5].

We can find a rough estimate of the spreading speed from balancing the surface tension difference, $\Delta\sigma \approx 40$ mN/m, against the viscous resistance of the thin film over a spreading distance ℓ , Equation 5 [7].

$$U \sim \frac{\Delta\sigma h_f}{\mu \ell} \quad (5)$$

Taking $\ell \approx 5$ cm, the distance from the center of the pane to its edge, gives U on the order of 0.1 to 1 mm/s, which is consistent with the dye's slow spread across the pane. A representative value of $U \approx 1$ mm/s is used below.

To characterize the flow, I used the Reynolds number, Equation 6 [8], to compare inertial effects to viscous effects. Because the glycerin layer is so thin, the film thickness h_f is the appropriate length scale.

$$Re = \frac{U h_f}{\nu} \quad (6)$$

$$Re = \frac{(0.001 \frac{m}{s})(0.0005 m)}{(1.12 \times 10^{-3} \frac{m^2}{s})} \approx 4 \times 10^{-4}$$

A Reynolds number of order 10^{-4} is far below one, which places this flow where viscous forces completely dominate inertia [2]. This explains why the dye moves smoothly and why there is no turbulence.

To check whether diffusion plays a role in the flow behavior, I compared the rate at which the flow carries the dye to the rate of molecular diffusion using the Péclet number, which is calculated using Equation 7 [9].

$$Pe = \frac{Uh_f}{D_m} \quad (7)$$

$$Pe = \frac{(0.001 \frac{m}{s})(0.0005 m)}{(10^{-11} \frac{m^2}{s})} \approx 5 \times 10^4$$

A Péclet number on the order of 10^4 to 10^5 means that the flow moves the dye thousands of times faster than diffusion spreads it. The time for the dye to diffuse across the thickness of the glycerin layer can also be estimated directly using Equation 8 [9].

$$t_D \approx \frac{h_f^2}{D_m} = \frac{(0.0005 m)^2}{10^{-11} \frac{m^2}{s}} \approx 2.5 \times 10^4 s \quad (8)$$

This is about 7 hours, far longer than the video or the time it takes the alcohol to evaporate. That is why the edges of the dye stay sharp for the entire video: the dye's spreading is not due to diffusion into the glycerin, but to the flow itself.

2.3 Visualization Technique

The dye used was the undiluted blue color from a 12-color alcohol ink set sold for epoxy resin art. The dye is introduced into the fluid and its movement is tracked visually, a marked-boundary technique [10]. The visualization relies on two optical effects. First, blue dye absorbs most of the red end of the spectrum, so wherever the dye sits it blocks the red backlight and shows up dark. How dark it appears depends on how much dye the light passes through, so the thick core of the drop appears nearly black while the thin, stretched parts of the dye appear lighter, which gives the image a sense of depth. Second, the alcohol and glycerin have different refractive indices, about 1.38 for isopropyl alcohol and 1.47 for glycerin [5], so light bends slightly at the edges of the dye and helps outline its shape.

Backlighting was chosen over front lighting because the glycerin is clear and the dye is semi-transparent, so light passing through the fluid shows the dye's shape far better than light reflecting off it. The iPad was used as the backlight because its LCD gives a uniform field of light without hot spots, and because its color can be changed easily to test different backgrounds. Red was chosen because it contrasts strongly with blue, which gives the dye the darkest possible silhouette. A continuous source was required because the flow was recorded as video, and the room lights were turned off so the iPad was the only source of light, which kept reflections off the glycerin's surface to a minimum.

2.4 Photographic Technique

The field of view of the video was approximately 5 cm across, with the camera 12.7 cm above the glass pane. The video was captured using an iPhone 16 Pro Max with its 24 mm f/1.78 main lens at a resolution of 3840×2160 px [11]. Shutter speed and ISO were set automatically. The video was recorded at 60 fps and is played back at 60 fps. Post-processing was limited to increasing the saturation slightly.

Exposure and focus were locked on the drop point before releasing the dye to keep the background brightness and sharpness constant throughout the clip. The focus was set on the dye at the surface of the glass pane rather than on the iPad screen, which kept the dye sharp while softening the screen beneath it.

Motion blur was not a concern for most of the clip. With a 5 cm field of view across 3840 pixels, each pixel covers about 13 μm . At a spreading speed of about 1 mm/s, the dye moves roughly 0.017 mm, or about one pixel, during a 1/60 s exposure, so blur is negligible. The only fast part of the flow is the moment of entry, when the drop is moving at over 1.5 m/s and the first frame after impact is likely blurred. Since the viscous analysis shows that this fast phase is damped almost instantly, a higher frame rate would add very little to the overall motion captured in the experiment.

III. Conclusion

The video shows a blue alcohol dye spreading through a thin layer of glycerin in the creeping-flow regime, with a Reynolds number of order 10^{-4} and a Péclet number of order 10^4 to 10^5 . The drop passes through the half-millimeter glycerin layer, spreads along the glass beneath it, and rises around the edges to the surface, driven by the alcohol's lower surface tension and density. Together these numbers explain why the flow appears smooth and slow, with no turbulence, and why the dye boundaries stay sharp until the alcohol evaporates.

We initially set out to film diffusion with this experiment and instead captured a slow, viscous flow driven by surface tension and buoyancy, in which diffusion plays essentially no role. This clearly shows how much the fluid properties control what a flow looks like.

The iPad backlight worked well, turning the dye into a dark silhouette with crisp edges, and it was an easy, cheap way to get a uniform colored background. However, for about 1.5 seconds of the video the individual pixels of the screen become visible, due to refraction caused by the moving glycerin. Although the video fulfilled the intent of the experiment, using a diffuser over the screen or an alternative light source may improve these visuals.

In future experiments I would like to compare several drop heights to see how entry speed changes the time it takes for the dye to spread, and to try a dye that is denser than glycerin so the drop sinks instead of fighting buoyancy. Gently warming the glycerin in a warm water bath, away from the alcohol ink, would lower its viscosity and show how much faster the dye spreads when viscous resistance is reduced. Varying the glycerin volume to change the layer thickness would also show how much the thin film controls the flow. I would also like to film a long time lapse over several hours to see whether any diffusion becomes visible.

References

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