Get wet report: Gravity Currents and Turbulent Structures Revealed by Dry Ice Fog

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1 introduction

The purpose of this report is to describe and discuss the image on the cover. High-resolution versions of the image are available on flowvis.org, along with many other inspiring flow images. This image was created for the Get Wet assignment in the MCEN 5151 Flow Visualization course in Fall 2025.

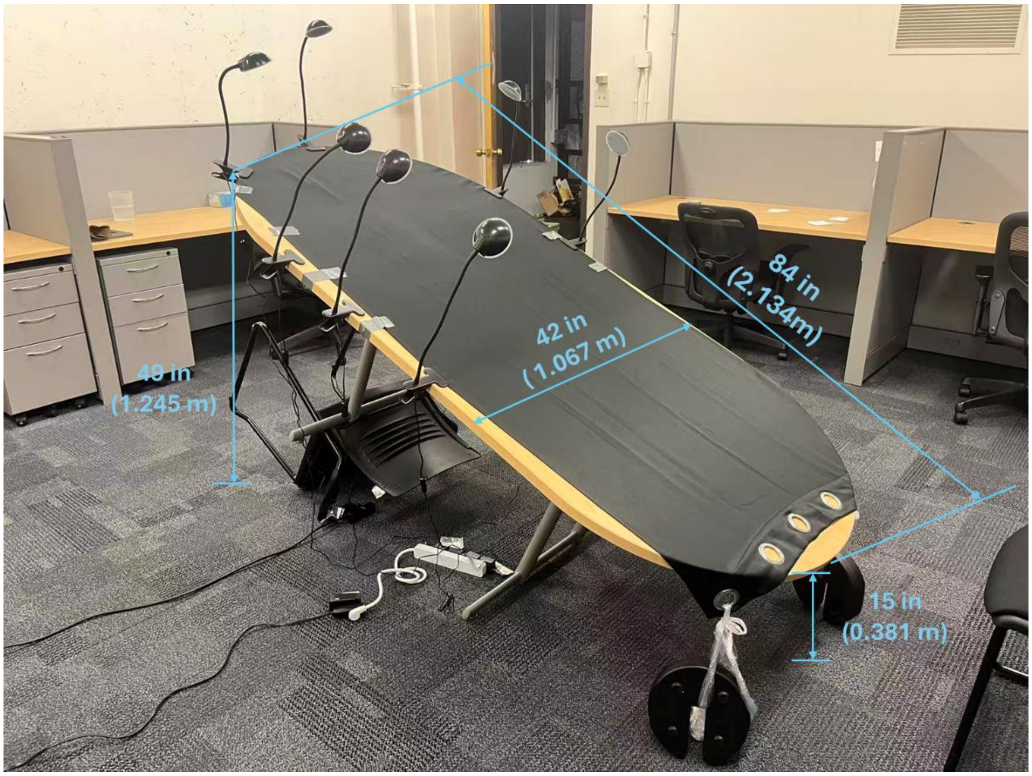
This photo is meant to study how a cold plume forms, sinks, and spreads across the surface. The sublimation of dry ice in the beaker produces cold CO_2 gas. This gas cools the surrounding air, condenses water vapor, and forms visible white fog. This fog makes the invisible flow phenomenon visible. In the water, the fog forms bubbles that rise and burst at the surface. Then the bubbles collect and spill out of the beaker. During this process, environmental disturbances, such as airflow from popping bubbles, room air currents, and buoyancy differences, trigger turbulent eddies and vortices. You can also see some small vortical rolls. Once the fog reaches the table surface, it forms a gravity-driven boundary flow. It stays close to the surface because it is denser than the surrounding air. In short, this is a cold plume that sinks and spreads horizontally.

2 Methodology

2.1 Test setup

This photo was taken in an office. The basic setup is shown in Figure 1, and all the materials and tools used are shown in Figure 2. The table is 84 in (2.134 m) long and 42 in (1.067 m) wide. One side of the table was raised, so the higher edge was 49 in (1.245 m) above the ground, while the lower edge was 15 in (0.381 m) above the ground. The tabletop in the photograph is tilted, forming an angle of about 23.8° with the level ground. A black curtain cloth was placed on the tabletop to provide a plain black background that highlights the white fog. Its size is 40 in × 90 in (1.016 m × 2.286 m), and the material is 225 GSM polyester fabric. Four weight plates were used to stretch the cloth and reduce wrinkles.

The liquid container was a plastic measuring cup with a rim diameter of 5 in (12.7 cm) and a height of 6 in (15.24 cm). Each experiment used 600 mL of warm water at 40 °C. A total of 8 lb. of dry ice was used over about 20 experiments, with about 0.4 lb. per experiment. To make the reaction between dry ice and warm water stronger and to produce more fog for clearer visualization, the dry ice was cut into small pieces before being placed in the water. The ambient temperature during the tests was 20 °C. During the experiments, the measuring cup was placed along the table's centerline, 8 in (20.32 cm) from the edge, and its base was taped to the tabletop. The light source consisted of seven LED clip lamps, each with 200 lumens and a total power of 35 W. Their arrangement is shown in Figure 1(a), at a height of about 45 cm above the table surface. The camera position is shown in Figure 1(b).



(a)

(b)

Figure 1. Experimental setup: (a) Table and lighting arrangement. (b) Measuring cup and camera position. The camera was 2 3/4 in (6.985 cm) above the table surface, and the lens was 17 in (43.18 cm) from the measuring cup.

2.2 Flow discussion

In this experiment, dry ice (solid CO_2) placed in warm water sublimated rapidly, producing cold CO_2 gas. This gas cooled the surrounding air, caused saturation, and led to the condensation of tiny water droplets, forming visible fog. Because this CO_2-rich cold air is denser than the ambient air at 20 °C, it overflows the rim of the cup as a negatively buoyant gravity current. It then flows onto the tabletop, moves downslope along the inclined surface, spreads outward, and generates intermittent billows. The downslope component of gravity accelerated the layer, while the normal component slightly compressed it. The structures observed along the cup rim and in the surface layer are classic Kelvin–Helmholtz (KH) shear billows. They were formed where the dense, fast outflow slid beneath the lighter room air. When two fluid layers with different velocities slide past each other, the velocity shear at their interface can amplify small disturbances. These disturbances then grow into wavy structures known as Kelvin–Helmholtz (KH) waves.

This phenomenon changes clearly over time. First, the sublimation rate is not stable. Influenced by water temperature and the contact area of dry ice, the sublimation rate is high at the beginning when the water is warmer. Large amounts of CO_2 are released, which cool the surrounding air and condense water vapor into droplets. As a result, a large volume of fog is produced. When bubbles burst at the water surface, they create local jets and disturbances. These make the fog move with irregular airflow rather than accumulate peacefully. In addition, after the fog overflows the rim, its higher density makes it form a gravity current along the tabletop. At the shear layer with the surrounding air, Kelvin–Helmholtz instability develops and produces visible billows. As the dry ice is consumed, the sublimation rate decreases, and the water temperature gradually drops. Fewer bubbles are produced, the fog becomes calmer, less fog escapes from the cup, and billows appear less frequently.

Another reason this phenomenon changes over time is the intrinsic growth and merging of KH instabilities. The downslope fog flows at about 0.1 m/s, while the overlying room air is nearly stagnant. This contrast creates a strong velocity shear. The ragged, wave-like patterns observed at the fog–air interface are KH billows. Initially, many small vortices appear. Over time, they merge into fewer but larger structures.

To quantify the fog current dynamics, characteristic geometric, velocity, and fluid property scales were estimated based on the photographic setup and physical conditions. In the image, using the cup height as a reference, the fog layer thickness was estimated to be about 1–3 cm. Therefore, a representative layer thickness of h = 0.020 m was chosen. For a shallow gravity current on an incline with angle θ, the velocity scale was chosen following the method described by Benjamin [1].

The downslope motion is driven by the along-slope component of gravity, $g' \sin\theta$, which pushes the current into a supercritical state (Fr > 1). Here, a conservative value of $\Delta\rho/\rho=0.03$ is used. Then, the reduced gravity was estimated as:

$$g' = g\frac{\Delta\rho}{\rho} = 9.8 * 0.03 = 0.294\ m\ /s^2$$

With h=0.020 m and θ=23.8° (cosθ = 0.914), the internal wave speed, represents the natural propagation speed of gravity waves within the dense layer, is given by:

$$c = \sqrt{g'h\cos\theta} = 0.074\ m/s$$

The velocity scale for the downslope current was taken as U≈0.1 m/s, slightly larger than the internal wave speed because of the slope-induced acceleration along the surface.

Dimensionless parameters are used to identify the flow regime and to compare it with classical theory. The Reynolds number (Re), Froude number (Fr), and Grashof (Gr)/ Rayleigh (Ra)numbers were estimated as follows.

$$Re = \frac{Uh}{\nu} = \frac{0.1\ \times 0.02}{1.5\ \times\ 10^{-5}} = 1300$$

This result indicates a transitional flow regime. At the scale of the fog layer, large coherent vortices form; however, the turbulence cascade is not yet fully developed. In thinner shear layers, the local Reynolds numbers are likely higher, which enables Kelvin–Helmholtz billows to roll up and persist.

$$Fr = \frac{U}{c} = \frac{0.1}{0.074} = 1.35$$

A Froude number greater than 1 confirms that the flow is in a supercritical state. In this regime, disturbances cannot propagate upstream. As a result, the head of the current advances rapidly downslope, and strong shear instabilities are generated continuously.

$$Gr = \frac{g\beta\Delta T L^3}{\nu^2} = \frac{9.8\ \times 3.4 \times 10^{-3} \times 15 \times (0.02)^3}{(1.5 \times 10^{-5})^2} = 1.8\ \times 10^4$$

$$Ra = Gr\ \times Pr = 1.8\ \times 10^4\ \times 0.71 = 1.3\ \times 10^4$$

Where: Thermal expansion coefficient: $\beta = \frac{1}{T} = 3.4\ \times 10^{-3}\ K^{-1}$ (air at 20 °C),

Temperature difference: $\Delta T = 15K$ (fog at 5 °C vs. ambient at 20 °C),

Length scale: L=0.02 m (chosen as a representative vertical dimension),

Kinematic viscosity: $\nu = 1.5\ \times 10^{-5} m^2/s$,

Thermal diffusivity: $\alpha =\ 2.1\ \times 10^{-5} m^2/s$.

These values show that thermal buoyancy is modest compared with composition-driven buoyancy caused by CO_2 enrichment. Thus, the primary driving mechanism is the density difference caused by CO_2, rather than temperature gradients.

The nondimensional numbers reveal that the flow regime is dominated by buoyancy and interfacial shear, rather than by viscosity. The Reynolds number suggests a transitional flow with large KH billows, whereas the Froude number indicates a supercritical gravity current moving downslope. These findings are consistent with the visual observations of coherent billows forming, growing, and merging.

3 Visualization techniques

In this study, fog generated by the sublimation of dry ice in warm water was used as a natural flow tracer. The cold CO_2 released during sublimation cooled the surrounding air and caused water vapor to condense into micron-sized droplets. These droplets scattered visible light and followed the motion of the ambient air, making the otherwise invisible flow field directly observable. A black polyester curtain was placed on the tabletop to provide a plain background, which maximized contrast and ensured that fine structures such as shear-layer billows and vortex roll-ups were clearly visible. Illumination was provided by seven LED clip lamps arranged above the table to produce uniform lighting and to enhance droplet scattering. Images were captured with a Nikon D3500 digital camera using a short exposure time (1/640 s), a wide aperture (f/4), and a high ISO setting (3200). These parameters allowed transient features to be recorded sharply without motion blur.

Overall, this image was obtained using direct fog visualization with light scattering, complemented by background contrast and short-exposure photography. This approach is simple yet effective in revealing the dynamics of gravity currents and interfacial instabilities in air flows.

4 Photographic techniques

The photographic setup was designed to capture fine structures in the fog flow with high contrast and sharp resolution. A Nikon D3500 DSLR camera equipped with an 18–55 mm f/3.5–5.6G lens was used. The lens was set to a focal length of 18 mm, with an aperture of f/4. A short exposure time of 1/640 s and a high ISO setting of 3200 allowed transient flow features to be recorded sharply without motion blur.

Size of the field of view (FOV) calculated as:

$$FOV_{Width} = D \times \frac{W_{sensor}}{f} = 432 \times \frac{23.5}{18} = 56.4\ cm$$

$$FOV_{Height} = D \times \frac{H_{sensor}}{f} = 432 \times \frac{15.6}{18} = 37.4\ cm$$

Where: sensor size 23.5mm x 15.6mm (Nikon D3500 DSLR)

Focal length: 18 mm

Object distance (camera–cup): 17 in = 432 mm

The camera was positioned 17 in (43.2 cm) from the plastic measuring cup, corresponding to a field of view of approximately 56.4 cm × 37.4 cm at the subject plane.

The original photo is shown in Figure 3, and it was processed using the Darktable software. The original image resolution was 6000 × 4000 pixels. After cropping, the final processed image size was 5710 × 3806 pixels, which corresponds to a reduction of about 5% in both width and height. Then, the retouch function was used to remove background artifacts. However, the result was not fully satisfactory, as a perfectly uniform black background was not achieved. The tone curve was adjusted to enhance the visibility of the white fog. Local contrast was also adjusted, with the parameter “detail” increased from 125 to 147 and “highlight” increased from 50 to 100.

Figure 3 Original image

5 Conclusion

The image reveals the development of a downslope gravity current formed by CO_2-rich cold fog overflowing from the container. The fog layer clings to the inclined tabletop, and clear Kelvin–Helmholtz waves can be seen along the upper interface, highlighting the role of shear instability in the mixing process. I particularly appreciate how the dark background and strong illumination create a sharp contrast, allowing the wave structures and flow stratification to be captured clearly.

What is interesting in this image is the variety of flow phenomena that can be observed. One particularly striking aspect is that the image almost shows different stages of mixing, depending on where the flow is located. This is especially compelling because sharp lines can be seen between the fog and the background immediately after it emerges from the cup. Further downstream, molecular diffusion becomes more apparent, producing a blurred region. This progression highlights how the visualization captures both sharp interfaces and gradual mixing. The compositional choice are effective, the tilted framing draws the viewer's eye upward, while the flow spilling over the glass aligns near the one-third line, creating a visually engaging composition. Regarding the lighting of the photograph, one improvement could be to reposition one or more light sources directly behind the fog. By carefully adjusting the angle so that the lights are blocked by the measuring cup or other objects, they would remain out of the frame while creating a stronger glowing effect in the fog. During shooting, a plain black background, such as a poster board, could be used to make the background cleaner. In post-processing, adjusting the exposure can help achieve a more uniform and consistent background color.

References:

[1] Benjamin TB. Gravity currents and related phenomena. Journal of Fluid Mechanics. 1968;31(2):209-248. doi:10.1017/S0022112068000133