

A Burst of Flame: Schlieren Visualization of a Butane Lighter Plume

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MCEN 5151 Flow Visualization - University of Colorado Boulder

5 October 2026

Introduction

This video, titled *A Burst of Flame*, was my individual submission for the Team First assignment. Our group of three used a single-mirror schlieren system and a high-speed camera to image the hot gas rising from a lit butane utility lighter. Schlieren imaging makes differences in air density visible, so heated gas, which is invisible to the eye, appears as light and dark patterns. The intent was to capture how the plume develops after ignition, from ignition to rising column to turbulent mixing. The mirror was borrowed from Professor Jean Hertzberg and the camera was reserved from the Integrated Teaching and Learning Laboratory (ITLL) at the University of Colorado Boulder. Each of us brought different objects to try, and the lighter in this video was mine. I lit the lighter while Ryan Cross and Jay Hall operated the camera; we took turns at the camera, holding objects, and contributing ideas. The video is at <https://www.youtube.com/watch?v=UPD60PxVH1o>.

Apparatus and Flow

The setup is sketched in Figure 1. A 12 in (30 cm) diameter concave mirror stood on one table, with the lighter held about 10 to 15 cm in front of its face and with the nozzle angled upward, seen in Figure 2. About 16 ft (4.9 m) away, on a second table, the camera sat on a tripod beside the light source. Light travelled from the source to the mirror and back to the camera, passing through the plume twice.

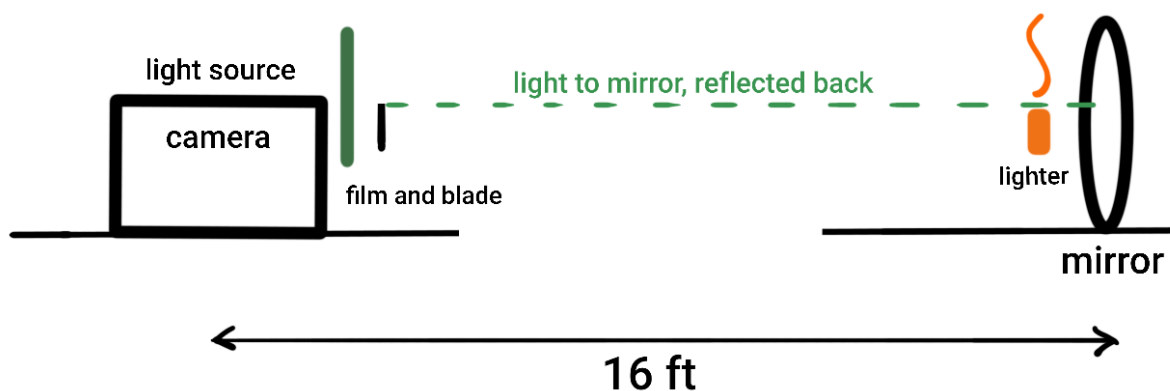


Figure 1. Sketch of the single-mirror schlieren setup (not to scale).

The flame heats the gas around it, making it lighter than the room air. Gravity has a greater effect on the cooler air because of its density, which pushes the hot gas upward and forms a buoyant plume [2]. In the video, the nozzle is only leaking butane until the flame ignites at about 0:20, after which the plume develops in three stages. First, a cluster of round lobes rise from the nozzle. This is a Rayleigh-Taylor instability, which occurs when a lighter fluid lies beneath a heavier one. Any ripple on the

boundary grows, because the heavy fluid sinks and the light fluid rises into it [5]. Second, a smooth column of gas rises from the nozzle, and farther up its edges expand into lobes that curl along that column. These look like a Kelvin-Helmholtz instability, which occurs when two layers of fluid slide past each other at different speeds and the boundary between them curls into spinning rings [5]. Here, the hot gas rises faster than the room temperature air at its edges. Third, about 9 cm above the nozzle, the lobes separate into small cells and the flow becomes turbulent. As a plume rises, the Grashof number based on height increases with the cube of the height, so buoyancy becomes increasingly important relative to viscosity higher up.

This captures the transition from laminar to turbulent flow. Near the nozzle, the flame's high temperature increases the kinematic viscosity of the local air, which keeps the initial flow smooth and maintains a laminar flow. As the plume accelerates upward and meets the cooler room air, shear spins the edges into vortices. By the time the plume reaches a height of roughly 9 cm, these structures break down into turbulent mixing. Evaluated at the breakup height $x = 0.09$ m using the same temperature difference, the local Rayleigh number is $Ra_x = Ra(x/L)^3 = (2 \times 10^5)(0.09 \text{ m} \div 0.04 \text{ m})^3 \approx 2 \times 10^6$. This likely overestimates the true value, since the plume gradually cools as it mixes with room air. For a heated vertical surface, this transition typically requires $Ra \approx 10^9$ [6]. This is only a rough benchmark for a plume, but a gap of three orders of magnitude suggests buoyancy is not the only explanation for the breakup. Instead, it is likely caused by shear between the rising gas and the still room air [5], combined with effects from the initial ignition.

To evaluate the flow of the plume, I estimated three dimensionless numbers. The plume width $L \approx 0.04$ m was measured from the column in the video. The velocity scale $U \approx 0.25$ m/s is the rise speed of the leading edge of the plume, which moved about 26 mm per second of video. The footage was recorded at 2,871.91 frames per second, played at 30 frames per second, and sped up 10 $\times$, so one second of video is $10 \times 30 \div 2,871.91 \approx 0.10$ s of real time. The gas temperature near the nozzle was assumed to be $T_{\text{plume}} \approx 600$ °C (unmeasured), and the room was $T_{\infty} = 20$ °C. Some air properties at the average temperature of 310°C (583K) from the Engineering ToolBox [4] are the expansion coefficient $\beta = 0.00171$ K $^{-1}$, kinematic viscosity $\nu = 5.12 \times 10^{-5}$ m ^{2} /s, and Prandtl number $Pr = 0.688$.

$$Re = \frac{UL}{\nu} = \frac{(0.25 \text{ m/s})(0.04 \text{ m})}{5.12 \times 10^{-5} \text{ m}^2/\text{s}} \approx 2 \times 10^2$$

$$Gr = \frac{g\beta(T_{\text{plume}} - T_{\infty})L^3}{\nu^2} = \frac{(9.81 \text{ m/s}^2)(0.00171 \text{ K}^{-1})(580 \text{ K})(0.04 \text{ m})^3}{(5.12 \times 10^{-5} \text{ m}^2/\text{s})^2} \approx 2 \times 10^5$$

$$Ra = Gr \cdot Pr = (2.4 \times 10^5)(0.688) \approx 2 \times 10^5$$

Re compares inertial and viscous forces, and $Re \approx 200$ is low, so the flow starts out smoothly, consistent with the column near the nozzle. Gr compares buoyancy and viscous forces, and $Ra = Gr \cdot Pr$ adds the effect of heat conduction. Both are large, therefore buoyancy drives the motion [2]. Because the temperature is an assumption and the speed is measured from the video, these are estimated values. For resolution, the 12 in (305 mm) mirror spans 550 of the 600 pixels in the frame height, or 0.55 mm per pixel, so the field of view is about 0.44 m $\times$ 0.33 m. Air moving at 0.25 m/s travels $0.25 \text{ m/s} \div 2,871.91 \text{ frames/s} \approx 0.09$ mm between frames, and $U \cdot t_{\text{exp}} = (0.25 \text{ m/s})(342 \times$

10^{-6} s) ≈ 0.09 mm during one exposure. Both are about 0.15 pixels, so the motion is, for our purposes, frozen in each frame.

Visualization Technique

Schlieren works because the speed of light in air depends on air density, so light passing through warm air bends slightly relative to light passing through cool air [1, 3]. The light source was a utility LED flashlight covered in foil with a small hole cut in it, to provide a small dot of light. The mirror sent this light back and focused it into a small spot near the flashlight. A razor blade was placed at the spot where the light focused to its smallest size and was then moved in until it covered half of the spot. Bent rays that fall on the blade are blocked and others pass, so density differences become brighter and darker regions in the image. Seen in Figure 1, a green film was placed over the lens, which gives the video its green tint. I chose this cool color to contrast with the typically warm colors associated with fire.

Photography and Processing

Video was recorded with a Chronos 1.4 high-speed camera (ISO 320 [7], 3200 K white balance) and a zoom lens at $f/1.2$ to maximize the amount of light collected during the short exposure. The lens was set at about 30-35 mm and focused at 3.5 m, with the camera about 4.9 m from the mirror. The settings were 800×600 pixels at 2,871.91 frames per second with a 354° shutter angle. This gives an exposure of $342 \mu\text{s}$. The cut recorded clip lasted about 5.6 s of real time.

In CapCut, I cropped the information strip from the bottom of the frame, trimmed the video, and sped the cut up by $10\times$, so it plays for 53.3 s at about $9.6\times$ slow motion (Figure 2). I added a title card and two background music tracks from the CapCut royalty-free library (“dark ambient drone 60 seconds edition” by low and “sad and painful live performance of violin and piano” by ishinuki). No brightness or contrast adjustments were made. The final video was exported at 1440×1080 pixels (upscaled from 800×600) and 30 frames per second.

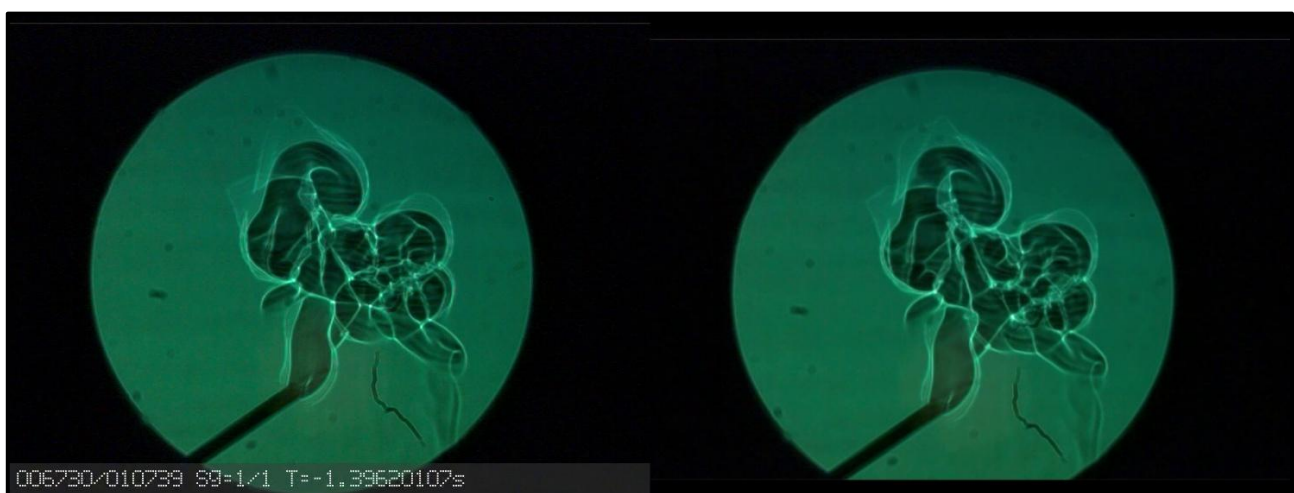


Figure 2. Unedited raw frame (left) and final edited frame (right).

Discussion

The video shows the plume going from a sudden burst of round lobes, to a smooth rising column with twisting lobes, to turbulent mixing at the top. Slow motion makes these stages easy to follow. The dark background and small, bright source give good contrast between hot and cool air. Limitations are the small 800×600 frame and the lack of any direct measurement of plume temperature. Overall, the video meets the intent of making the invisible structure of the plume visible. A possible continuation is to experiment with different lighters to test whether the turbulent flow is from the initial ignition or not.

References

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