Team First Report

MCEN 4151: Flow Visualization
Team First Assignment
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Figure 1: Final Image of flame with post-processing

Context and Purpose

This image was produced for the Team First assignment in MCEN 4151: Flow Visualization. My team, consisting of Curtis Dunford, Isaac Rodriguez, and myself, planned the setup together, though I ultimately captured the final shot on my own due to illness. Our collective intent was to achieve a crisp visualization of a flame using a homemade fuel source. From an artistic perspective, we wanted to capture the organic shape and motion of fire in a way that highlighted both its structure and unpredictability. From a physics perspective, the goal was to explore how buoyancy-driven convection, combustion chemistry, and environmental conditions such as airflow influence the visible features of a flame.

While the setup was simple, the image demonstrates the complexity of fluid motion and heat transfer that arise even in everyday combustion phenomena. This intersection of art and physics is the core purpose of the course: to translate unseen forces into visible forms through careful experimental and photographic technique.

Apparatus and Flow Description

The flame was created by burning a homemade gel fuel mixture. To prepare the fuel, calcium carbonate (from chalk) was reacted with vinegar (acetic acid). Upon heating, water was reduced from the mixture, isolating calcium acetate, which acted as a gelling agent when later combined with isopropyl alcohol. This process yielded a stable gel fuel that could be safely burned in small quantities. The gel was placed in the lid of a standard mason jar, which had a diameter of approximately 7 cm and a depth of about 1 cm. When ignited, the flame extended upward roughly 10–15 cm.

The environment of the experiment strongly influenced the flame dynamics. The test was conducted on a balcony enclosed on three sides, with one side open to the outdoors. The flame, while rising vertically due to buoyancy, was consistently deflected toward the open side of the balcony. This suggests that a draft was pulling cooler ambient air into the space, modifying the flame shape and creating asymmetry in its motion.

The physics of the flame can be understood through the interaction of buoyancy, viscosity, and inertial forces. Hot gases produced by combustion have significantly lower density than the surrounding air. This density gradient produces a buoyant force that drives the upward motion of the flame. As gases rise, they entrain cooler air, leading to shear layers and vortices at the flame boundary. This results in the undulating motion visible in the image, where smooth laminar regions give way to turbulent fluctuations.

A sketch of the experimental setup is provided in **Figure 1**, showing the placement of the mason jar lid, the balcony enclosure, and the camera position relative to the flame.

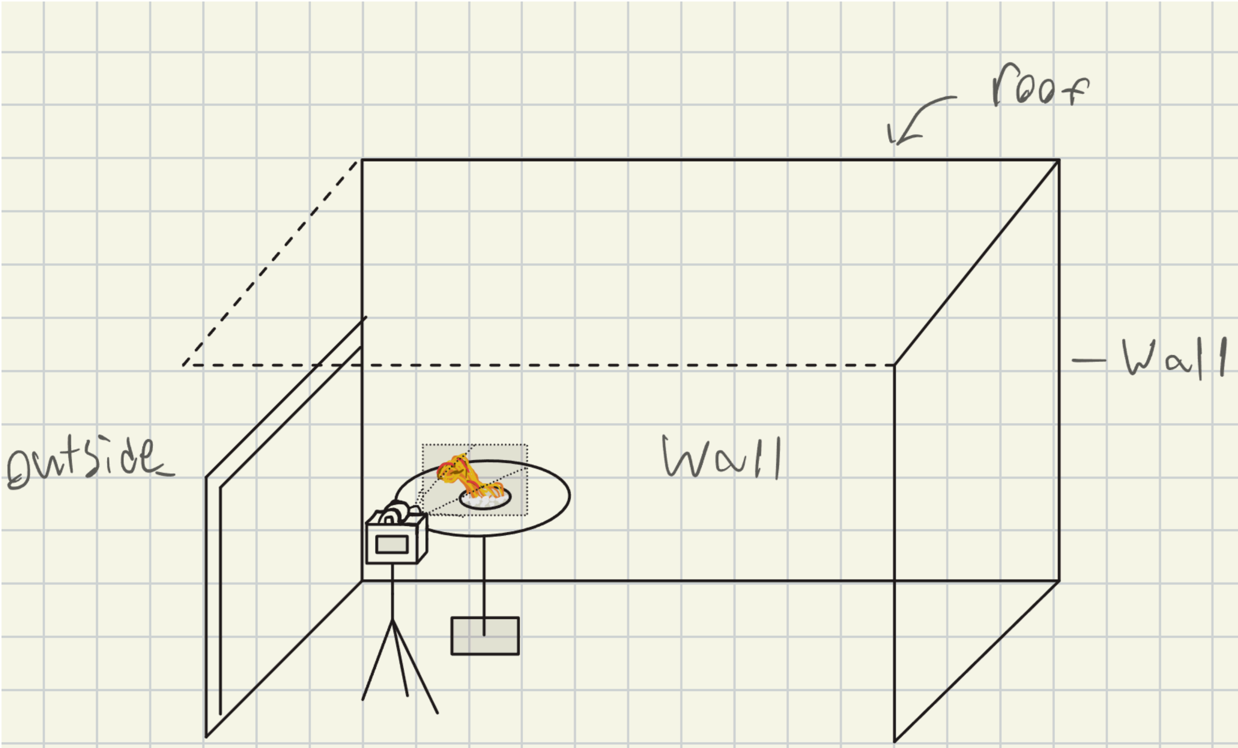

Figure 1: Schematic of setup on balcony enclosure

Nondimensional Analysis

To characterize the flow regime, nondimensional numbers can be estimated. Assuming a characteristic velocity of **0.5 m/s** for the upward flame gases (a typical order-of-magnitude estimate for small pool flames [1]) and a length scale of **0.1 m** (the flame height), the Reynolds number is:

$$Re = \frac{UD}{\nu} = \frac{(0.5\,\mathrm{m/s})(0.1\,\mathrm{m})}{1.5 \times 10^{-5}\,\mathrm{m^2/s}} \approx 3300$$

where v is the kinematic viscosity of air at elevated flame temperatures (~1000 K) [3]. This value indicates a transitional flow, consistent with the observed large-scale oscillations in the flame without complete breakdown into small turbulent eddies.

The Grashof number, which measures the relative importance of buoyancy to viscous forces, can also be estimated:

$$Gr = \frac{g\beta\Delta T L^3}{\nu^2}$$

With $\mathrm{g} = 9.81\mathrm{m/s}^2, \beta \approx 1/T \approx 0.0033\,\mathrm{K}^{-1}, \Delta T \approx 600\,\mathrm{K}, L = 0.1\,\mathrm{m}, \text{and } \mathrm{v} = 1.5{\times}10^{-5}\,\mathrm{m}^2/\mathrm{s}:$

$$Gr \approx 8.7 \times 10^7$$

This very large value confirms that buoyancy forces dominate the flow. Such high Grashof numbers are typical in natural convection flames [2] and explain why the flame structure is highly sensitive to surrounding drafts and air currents.

Visualization Technique

The visualization relied on the intrinsic luminosity of the flame. Hydrocarbon flames emit visible light primarily through blackbody radiation from incandescent soot particles and through chemiluminescence of combustion intermediates such as CH and C2 radicals [3]. In this case, the homemade fuel produced a bright yellow/orange flame, characteristic of incomplete combustion with significant soot formation.

The flame was captured in a naturally dark environment on the balcony at night, with no additional lighting introduced. The only illumination was the flame itself, which provided strong contrast against the background and allowed the flame contours to be sharply resolved. No additional visualization materials such as dyes, smoke, or tracer particles were required since the flame was inherently self-illuminating.

Photographic Technique

The image was taken with a Canon EOS 2000D DSLR. The lens was placed approximately 30 cm (1 ft) from the flame. Camera settings included an aperture of **f/5.6**, shutter speed of **1/160 s**, and ISO appropriate for low-light conditions. These parameters were chosen to freeze the motion of the flame while still allowing enough light exposure to capture its internal detail.

The field of view was approximately 15 cm across, centered on the mason jar lid. The image was later cropped to emphasize the structure of the flame and its interaction with the surrounding air. Contrast adjustments were applied in post-processing to increase the visibility of flame edges and highlight smaller flow features.

Figure 3: Original Photo before post-processing

Image Analysis and Reflection

The final image captures both the artistic beauty and scientific complexity of a flame. The leftward tilt of the flame demonstrates how sensitive buoyant flows are to environmental drafts, even in a semi-enclosed space. The flame itself shows regions of smooth laminar flow near its base and progressively larger instabilities as it rises, consistent with a Reynolds number in the transitional range.

What I like most about the image is the visible layering within the flame: brighter inner zones surrounded by more diffuse outer edges. This highlights the structure of a diffusion flame, where fuel and oxygen mix primarily at the interface rather than premixed throughout the volume.

If repeated, I would adjust the framing to include a wider view, capturing the full extent of the flame's bursts and interactions with the air currents. Additionally, including high-speed video could further illuminate the time-dependent oscillations that are only hinted at in a still image.

Overall, the experiment fulfilled its intent: to capture a crisp visualization of a flame that conveys both its aesthetic qualities and underlying fluid physics. The exercise demonstrated how even a simple setup, when documented carefully, can reveal the deep interplay of buoyancy, turbulence, and combustion chemistry.

References

[1] Tamanini, F. (1993). *The structure and properties of pool fires*. Fire Safety Journal, 21(1), 1–19.
[2] Bejan, A. (2013). *Convection Heat Transfer*. John Wiley & Sons.
[3] Turns, S. R. (2012). *An Introduction to Combustion: Concepts and Applications*. McGraw-Hill.