Flame Dynamics

MCEN 5151: Flow Visualization | Team Second Assignment | Nov. 2 2026

Author: Joy Wakimura

Team Members: Tegan Chander & Joshua Keller



Introduction

This assignment focused on leveling up our experimental setup to capture an interesting image. Tegan, Joshua and I were inspired by long exposure shots of fire with visible bright particles tracing through time. From this we decided to experiment with sprinkling cinnamon on top of a flame. After some trials, we discovered that spraying alcohol onto the flame also created interesting flame shimmers. For my image I intended to capture the combination of flame shimmers from alcohol spray and the traveling ignited particles.

Test Setup

The experiment setup was performed outside on a concrete patio shown in Figure 1. An empty metal can was placed upside down with cinder blocks to the right of it to manage the wind. To produce the flame, a small amount of 70% isopropyl alcohol hand sanitizer was placed on top of the can and ignited with a bic lighter. A bucket of water and a fire extinguisher were 5 ft away in case of unmanageable fire.

To produce the image a small amount of hand sanitizer was ignited as a base flame. Simultaneously, someone sprinkled ground cinnamon ~1 ft above the flame and sprayed the flame with 70% isopropyl alcohol from a spray bottle.

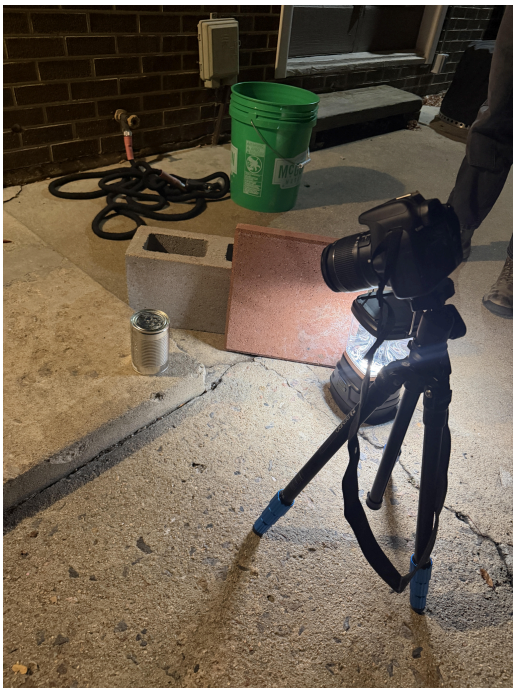


Figure 1: Test setup

Fluid Dynamics

One of the interesting flow phenomena happening is the combustion of isopropyl alcohol droplets seen in the blue plume in the image. Droplet combustion is a prevalent area of research due to its direct application to jet engines, rockets, boilers, and gas engines. All of these

applications (and more) involve igniting a liquid fuel to achieve their desired outcome. Droplet combustion occurs in three steps, droplet breakup, droplet evaporation, and droplet combustion (Kirkpatrick, 2025). The first two phases will be explored in this report.

In the droplet breakup phase larger droplets are broken into smaller droplets due to the shear forces between the surrounding gas and the surface. This phase is characterized by the Weber and Reynolds numbers defined as:

$$We = \frac{\rho_g u_d^2 d}{\sigma} \; ; \; Re = \frac{\rho_g u_d d}{\mu_g}$$

Where ρ_g is the surrounding gas density, u_d is the relative velocity between the droplet and surrounding gas, d is the droplet diameter, σ is the surface tension of alcohol, and μ_g is the dynamic viscosity of air.

Literature has studied droplet size of spray fixtures finding the diameter to be about 150 microns (Strien, 2024). Using this values and characteristics of isopropyl alcohol the calculated Weber and Reynolds numbers are:

$$We = \frac{(1.225\ kg/m^3)(17\ m/s)^2(150e{-}6\ m)}{(.0215\ N/m)} = 2.4$$

$$Re = \frac{(1.225\ kg/m^3)(17\ m/s)(150e{-}6\ m)}{1.81e{-}5\ Pa{*}s} = 172$$

As the Weber number increases for a fluid different types of breakup modes occur (Figure 2). For a Weber number of 2.4, no droplet breakup occurs.

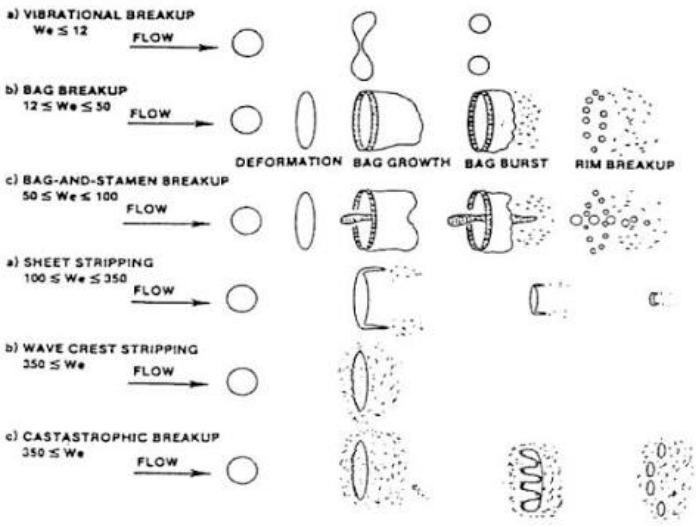


Figure 2: Liquid droplet breakup regimes

After the droplet breakup phase, fuel droplets undergo evaporation and combustion. If the Reynolds number is $Re > 20$ a boundary layer flow region exists in front of the droplet and a wake region exists behind the droplet. It is possible to evaluate the droplets' evaporation time and

combustion time using the energy equation, heat and mass transfer equations. This analysis will follow Kirkpatrick's derivation of the droplet's lifetime.

We will assume the droplet has uniform temperature equal to the surface temperature, no internal motion, and the Lewis number is 1. Additionally assume that $T_\infty = 900\ K$.

Calculate the Reynolds number using half the initial diameter to account for the droplet diameter decreasing with evaporation. All gas values are taken at $T_\infty = 900\ K$.

$$Re = \frac{\rho_g u_d d/2}{\mu_g} = \frac{(0.3868)(17)(75e{-}6)}{398.1e{-}7} = 10.2$$

Calculate the Nusselt number with the Ranz and Marshall relation.

$$Nu = 2 + 0.6Re^{1/2}Pr^{1/3} = 2 + 0.6(10.2)^{1/2}(.720)^{1/3} = 3.7$$

Calculate the Spalding heat transfer number B_T, a ratio of heat put into the droplet versus the heat required to vaporize the liquid.

$$B_T = \frac{c_p(T_\infty - T_s)}{h_{fg}} = \frac{(1050)(900-355)}{664000} = 0.86$$

The evaporation coefficient is then:

$$\beta_v = \frac{4kNu}{\rho_l c_p} ln(1 + B_T) = \frac{4(0.0448)(3.7)}{(858)(1050)} ln(1 + 0.86) = 4.56e - 7$$

Finally the droplet evaporation time is:

$$t_v = \frac{d_o^{\ 2}}{\beta_v} = \frac{(150e{-}6)^2}{4.56e{-}7} = 0.049\ s$$

$$t_v = 49\ ms$$

Additional work can be done to find the combustion time of the droplet.

Visualization Technique

Particles were used to capture the flow in this image, specifically ground cinnamon particles. Store bought ground cinnamon was sprinkled about 1 ft above the flame which ignited and traveled up through the air. The base flame was ignited 70% isopropyl alcohol hand sanitizer.

Little light setup was required for this photo as long exposure was used. The image was taken outside at 8:30 pm with no sunlight with the addition of someone's phone flashlight pointed at the flame.

Photographic Technique

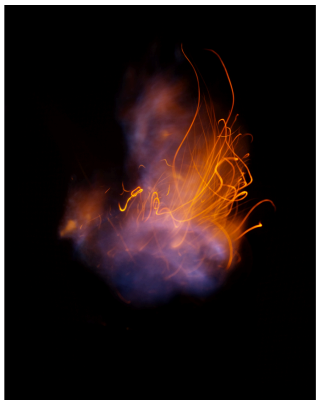
The image was captured in manual mode to have the most control over exposure and shutter speed. A long exposure time of 1 second was chosen to capture the flying particles without excessive motion blur in the image.

Camera	Canon EOS Rebel T7
Lens	Canon EFS 18-55mm
Aperture	f/5.6
Shutter Speed	1 sec
ISO	200
Focal Length	41 mm
FOV (Vertical, horizontal)	18°, 27°
Original Dimensions	6020 x 4015
Edited Dimensions	3018 x 4000

In post, contrast, color balance, and brightness were adjusted to remove the remnants of the can below the flame and make the blues pop and oranges pop. Additionally the image was cropped to portrait to highlight the flame in the middle of the image.



Before Image



Edited Final Image

Conclusion

Overall I'm very satisfied with the image I was able to produce. It's dynamic, well contrasted, and shows the movement of the flow. I like how the image reveals two different parts of flame flow, the diffusion flame and the air moving around it.

In the future I'd like to capture the fast diffusion flame of the alcohol spray along with the traveling cinnamon particles in a single image. To do this I theorize I'd have to take one image with a long exposure to capture the moving particles and merge it with a fast shutter speed image to capture the spray flame.

Sources

Chapter 4 fluid dynamics. (2003). https://ocw.mit.edu/courses/3-185-transport-phenomena-in-materials-engineering-fall-2003/8027e02c18951dca6d22e8a0254401ec_chap4.pdf

Kirkpatrick, A. T., & Kuo, K. K. (2024). *Principles of Combustion* (3rd ed.). John Wiley & Sons.

Surface tension. (2022). Lsu.Edu. https://macro.lsu.edu/howto/solvents/Surface%20Tension.htm

Van Strien, J., Vahaji, S., Lappas, P., Morton, D., & Inthavong, K. (2024). Spatial and temporal characterization of droplet diameter and velocities of a nasal spray atomization. *Aerosol Science and Technology*, *58*(6), 610–629. https://doi.org/10.1080/02786826.2024.2332633