University of Colorado - Boulder

MCEN 5151
Flow Visualization

# Get Wet: Assignment 1 Report

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# 1 Introduction

## 1.1 Summary

The purpose of this report is to describe and discuss the image presented on the report cover; high-resolution versions of the image can be found on flowvis.org along with lots of other inspiring flow imagery. This image was created for the first assignment of the MCEN 5151 Flow Visualization Fall 2024 class. It was captured using a Canon EOS 6D Mark II with an EF 50mm f/1.8 STM lens, shot at ISO 500, f/2.8, and a 1/4000 second shutter speed. The RAW image is 6264x4180 pixels, and the final cropped image is 5005x3337 pixels. The image, taken from above, captures a flame jet impinging upon the surface of a still pool of water. Careful inspection of the image reveals water droplets being thrown up above the flame.

## 1.2 Motivation

This image is largely motivated by the many excellent images of rocket nozzles firing on test stands and during rocket launches. Those pictures often exhibit flow phenomena such as mach diamonds, under or over-expansion of supersonic flow exiting nozzles, or flow mixing as the exhaust interacts with launchpad exhaust suppression systems. It is generally difficult to get access to rocket engines; much more common are heavy-duty propane torches, sometimes called weed burners, which mix pressurized propane with ambient air in a mixing nozzle to create relatively long flames. Firing the flame into water was partially motivated by curiosity (what will happen?) and partially by safety: it is quite hard to light a concrete pool deck on fire, let alone the water itself.

# 2 Methodology

## 2.1 Test Setup

The test setup includes only two items: the imaging camera and the flame source. In this case, the camera is a Canon EOS 6D Mark II with an EF 50mm f/1.8 STM lens; the wide aperture of this camera is helpful for the dark setting, but the lack of zoom capabilities limits the scale at which images of the flow can be captured. The flame source is a high-output propane torch, sometimes called a weed burner. It consists of a combustion-chamber-nozzle combination attached to the end of a long, rigid pipe, a flow control valve and throttle handle, a long, flexible tube, and a propane tank. The flexible tube links the propane tank to the handle, and the long rigid pipe connects the handle to the nozzle. The handle flow control nob limits the low-flow rate of fuel, while the throttle allows the user to raise and lower the flow from that low-flow rate. The nozzle is a thin cylinder open at the end, with a fuel outlet port in the center back surrounded by 3 to 4 fluted inlets on the back face of the nozzle bell. The bell extends from there for 4-5 inches in a cylindrical shape with a 3-inch diameter. The shape of the nozzle primarily serves to direct the flame away from the operator and to create a low-pressure zone around the fuel port, which induces airflow

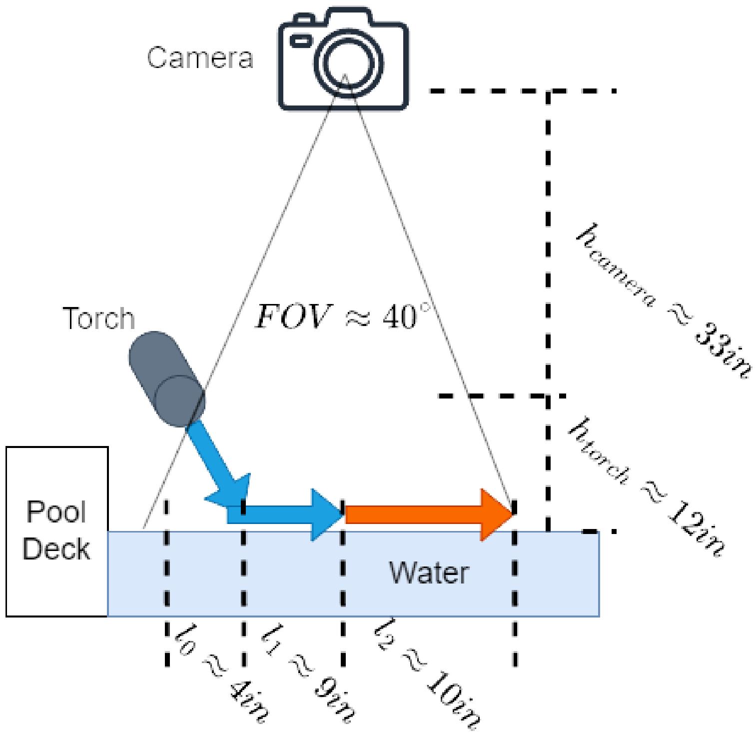


Figure 2.1.1: Test Setup Diagram

through the rear inlets. This airflow provides cooling to the nozzle body and serves as the oxygen source for the combustion.

Also important to the test setup is the testing environment. These images were taken at an outdoor pool to avoid the combustion and fume risks associated with operating a torch indoors. The images were taken on a night with a new moon and some cloud cover, to limit the amount of light entering the image from sources other than the flame itself. Additionally, the choice of the pool has important safety ramifications: the pool deck was cement and kept clear of any flammable items.

The test setup is infrastructure light; because of the dynamic nature of the propane fire flow, both the camera and the torch nozzle must be easy to move around. This allows for angles and depths to be changed easily, which is helpful from an artistic perspective. The freedom to move all equipment around is also important to safety: Tripods for the camera and stands for the torch would make the pool deck cluttered and the setup cumbersome. Risks associated with such a setup include participants tripping, possibly into the flame or the pool, as well as apparatus being knocked into the pool.

In lieu of mounting setups, both the camera and torch are hand-held. The torch is plumbed into the propane tank via a long, flexible tube. This helps prevent the weight of the tank from encumbering the test participant in charge of positioning the nozzle. A camera strap was used at all times to ensure that the camera, if dropped, didn't fall into the flame or the water.

Figure 2.1.1 shows the specific setup geometry used to capture the cover image. The camera was held out above the flame front and pool surface, pointed approximately directly downwards. The relative distances are estimated based on the focal length of the lens, the

Figure 2.1.2: A different perspective

known diameter of the nozzle in inches, and the apparent pixel diameter of the nozzle in the final image. The camera was held approximately three feet off the surface of the water, which is about two feet above the torch nozzle. The nozzle was pointed down into the water at an approximate angle of 71.6° up from the surface of the water. In general, the flame output from the torch used for the image is between three and four feet long. In this image, the flame extends about two feet horizontally away from the torch and expands sideways to a width of just under one foot. Figure 2.1.2 shows a shot of a similarly placed flame from the side rather than from above.

## 2.2 Visualization Technique

There are no formally named techniques at play in this image. The most important aspect here is the lighting, that is, the lack of any. The lack of ambient light in the test area made the water and pool area quite dark, which made the flame front stand out well. It is crucial that very little other light enters the frame, as there is very little light available in the first place. It is desirable to avoid using high ISO settings to limit noise in the image. Similarly, a fast shutter speed helps reduce blurring of the quick-moving flame patterns, and a smaller aperture is useful for getting more of the flame front in focus while shooting with a hand-held camera. All three of these setting choices decrease the amount of light the sensor will capture, thus it is important that whatever light is captured is actually from the flame.

Figure 2.3.1: A compressed JPEG of the original, unedited RAW image.

## 2.3 Photographic Technique

### 2.3.1 Image Capture

As mentioned previously, the image was photographed using a hand-held camera positioned above the flame, pointing approximately straight down. The image is fully manual: the auto modes on the camera are just not tuned for this sort of imaging. ISO was picked largely through trial and error, taking images at various levels to find a compromise between speed and noise. Shutter speed was picked in a similar matter. The aperture was mostly kept pretty wide, prioritizing a fast shutter and slow ISO over a deep focal plane; the cover image was shot at f/2.8, 1/4000 second shutter speed, and ISO 500. Focus was set using a variety of techniques. It was somewhat helpful to allow the auto-focus to find the surface of the pool when lit by the flame. This provided a baseline for manual focusing. The final focus was then set by getting the nozzle into focus. From there, the camera was raised and lowered slightly above the flame to capture images at slightly different distances, in the hopes that some of the images would be well-focused.

### 2.3.2 Image Processing

A jpeg of the original image is shown in Figure 2.3.1. The final image is somewhat cropped in both directions, mostly to remove space. A fair amount of editing went into producing the colors and clarity of this image. The exposure was bumped up a fair amount to reveal more of the flame front. Highlights and whites were both attenuated to create a more even lighting across the image. Shadow-zone light was amplified and blacks were attenuated, both to bring out more of the flame and to create a steeper contrast between the flame and the background. The image vibrancy is increased some, and the saturation is turned down slightly. No color grading, transformations, or effects were applied, other than a lens profile correction to remove some slight fish-eye effect and physical vignetting from the lens in the hopes of better estimating the physical size of things using the nozzle as a reference object. An Adobe Lightroom Classic denoising algorithm was used to remove high ISO-related noise from the image.

## 2.4 Safety Considerations

Safety was a primary consideration for this photo shoot, as the propane flame could pose a danger to test participants, and any runaway fire could spread and cause larger problems. The class Combustion Experiment Guidelines were carefully considered; the following directly addresses how each of the guidelines was Incorporated into the photo shoot:

1. The whole session was conducted in a non-combustible location: The flame never reached beyond the edges of the pool water, which was itself surrounded by a large concrete pool deck, which was swept clean of any potentially flammable debris.

2. Both a fire extinguisher and sand were on hand, as well as a water hose and of course, the pool water itself.

3. There were, at all times, 5 individuals present during the experiment. Generally, one held and operated the torch, one operated the camera, and the remaining three observed the process, ensuring nothing unexpected went uncaught. All participants had cell phones and were prepared to give directions to the shoot location.

4. No PPE was deemed appropriate for this shoot. The fuel is contained throughout the process until it is burned, so there is no need for fuel-handling PPE. The burner nozzle is attached to the control valve by a long pipe and is kept somewhat cool by the inflow of ambient air through the back of the nozzle, so there was no need for thermal protection PPE.

5. Shielding was not appropriate for this setup, as the subject was large enough and cool enough that the camera and operator were not at risk of being burnt. Similarly, the burner operator is always several feet behind the nozzle and flame. Additional participants were physically distant from the flame due to its proximity over the pool: all individuals were on the pool deck at all times.

# 3 Flow Discussion

## 3.1 Visual Observations and Descriptive Heuristics

Lots could be said about the flow captured in this paper, some of which could potentially support far more rigorous study than is within the scope of this class. What follows is largely an attempt to find scientific explanations for the most easily observable flow features captured in the image. Firstly, it is important to have a general understanding of what is, and isn't, fire.

### 3.1.1 What is Fire, Anyways?

Often people think about fire as a complete, unique thing in and of itself. What is fire but the bright, hot thing you observe when looking at a candle or bonfire? Fires at any scale are made up of flames, one in the case of a candle or many for a bonfire. A flame though is not just one thing either; what people see as a flame is a more complicated flow field containing reacting gases, heated air, and cooling soot. Flame is produced when a fuel and an oxidizer undergo a chemical reaction called combustion, by which fuel and oxidizer break apart and recombine in an exothermic reaction, emitting energy across the light spectrum. An "oxidizer", or source of oxygen molecules, is required for combustion to happen. In most cases observed on a day-to-day basis, the oxidizer is just ambient air. In more controlled combustion processes, like in rocket engines, a oxidizer fluid is mixed with fuel at a carefully controlled ratio in the process of generating thrust.

The ratio of fuel to oxidizer is the most important factor in determining things like the heat output of a flame. If the fuel and oxidizer being combusted are mixed at the ratio that yields a perfect reaction, meaning all of the fuel and oxidizer are used up in the combustion reaction, then the mixture is called "stoichiometrically balanced"; the stoichiometry of a chemical reaction is the ratios of the various reactants and products of the reaction; literally how much oxygen and propane are burned, and how much of the various outputs are released by the burn. A combustion process in which there is relatively less fuel than oxidizer is called fuel-lean, and one with relatively more fuel is called fuel-rich. This is just a rough summary; for a more detailed explanation please read something like Chung K. Law's "Combustion Physics", the main reference for most of the information on combustion contained in this report [1].

What is most commonly thought of as "flame", the yellow-orange glowing part of a candle flame, is the leftovers of the combustion going on at the base of the flame. The orange glow you see when looking at a candle is the "soot", the exhaust of the combustion, radiating away all the energy it picked up as it left the combustion front and stopped burning. The existence of soot in a flame flow is usually indicative of a fuel-rich combustion mixture; in a stoichiometric or fuel-lean mixture, there is sufficient oxygen for the complete combustion of the fuel. This combustion is cleaner and produces little to no soot. A pure blue flame, like one coming from a gas stove, is well mixed, meaning it is not fuel-rich, and so the fuel completely burns. This is why gas stoves don't usually produce visible smoke or soot. The flame in this image is, at least initially, a "premixed" flow: the fuel is sufficiently mixed with an oxidizer (the ambient air) before reaching the combustion front. As it's burning, it never becomes fuel-rich and burns with a bright blue color. This kind of combustion happens in fluids already in motion when they reach the flame; not the sort of thing that usually happens with candles or log fires (For more on premixed swirling flames like the one imaged here, see Paul Palies' textbook, "Stabilization and Dynamic of Premixed Swirling Flames" [2]).

A quick summary of what's really important for understanding the topic image: Combustion, the burning chemical reaction, is visually a blue-hued color. Soot, exhaust from incomplete combustion, glows orange as it cools down. Soot forms from fuel-rich combustion flow, that is, when there is unburnt fuel left over after the chemical reaction stops.

#### 3.1.2 Observable Flow Phenomena

There are a few things the image immediately offers. The flame is, for the most part, blurred slightly in the direction of motion. The camera was set to its shortest shutter time of 1/4000th of a second, but the fire is still blurry; this indicates it is flowing quite quickly.

Figure 3.1.1: Fire impacting water

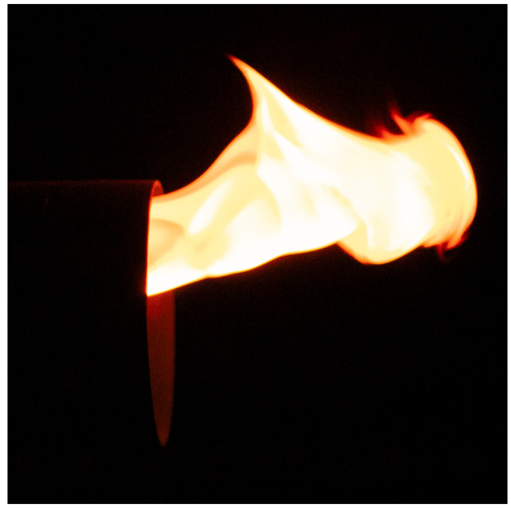

Figure 3.1.2: Fuel-rich propane flame

Lots of the flame is also actually out of focus, which is disappointing but does not hamper observation of the flow phenomena. On the left of the image, there is a clear area below the nozzle where the flame is impacting the surface of the pool, and bouncing off. The spread of the flame around this point shows a clear, sharp change in direction. Most of the flame continues to move to the right, indicating that the conserved horizontal velocity is somewhat high. A steeper flame, or one with less momentum, might appear to spread out more evenly around the impact sight. There is also a reasonably clear line between the actively combusting flame and the radiating orange soot, indicating a strong cooling effect, likely from interacting with the cool water below.

### 3.1.3 Premixed Turbulent Flow: Temperature and Color

The most striking thing about the imaged flow is the two colors: There is a clear blue flame on the left and a bright orange flame on the right. It was stated before that the flame is premixed, and should be fuel-lean, so why is there so much soot formation? Likely, this is the result of the rapid cooling of the flame by the water, which is just underneath the layer of combusting flow. The impact zone, where the flame initially hits the water, is visible on the left of the image; see Figure 3.1.1 for a close-up.

The flame seems to bounce off the surface of the water, changing directions from down and to the right to mostly just to the right, along the surface of the water. If a combusting flow rapidly loses heat, the chemical reaction can be terminated before all of the fuel is completely reacted; this is why the ostensibly lean premixed flow coming out of the nozzle ends up generating so much soot. The combustion is cut short as the flow is rapidly cooled through some interaction with the water's surface. Blue propane flame generally has a temperature around 1900 °C, while a yellow-orange propane flame is more like 1000 °C. This temperature (color) change is not typical for the flame flow produced by the torch used in the experiment. When the nozzle valve is mostly closed, it produces a small yellow flame; see Figure 3.1.2. When not impacting the water, a full flame from the nozzle is typically a deep blue with some purple-like on the left of Figure 3.1.3. The red soot on the right eventually gives way to a flame like that in the middle; it might be a leftover from the transitional period between the full yellow flame and the fast and turbulent blue flame. It is also possible that the flow stoichiometry is fairly unstable, and so some of the flow is lean while other parts are fuel-rich; this may explain persistent orange areas in the flow, or maybe contribute to the purple hue.

Figure 3.1.3: Full flow premixed propane flame, does not impact water

### 3.1.4 What About the Water Droplets?

Although it is clear that the flame is changing directions (again see Fig. 3.1.1), the impact sight doesn't reveal much about how strongly the two fluids are interacting. Is the flame hitting the surface of the pool? Looking closely at the middle of the image, water droplets are floating above the flame; see Figure 3.1.4. The drops look almost still compared to the motion-blurred fire below. They were probably thrown up from the pool in the initial splash from the high-velocity flame impacting the still water. It is mostly luck that they are in focus at all; the wide-open aperture used for this image left a lot of detail uncaptured. Later in the flow on the right side of the images, there are plenty more water drops, but they are less easily spotted because they are largely out of focus. Figure 3.1.5 shows a close-up of some of these; there are a couple in focus, but there are lots of drops here that are only identifiable by the way they act as lenses, focusing the light from the soot below so that they show up as bright, blurry, elliptical splotches.

# 4 Conclusion

## 4.1 Potential Avenues of Study

There is a lot in the title image which could bear a closer inspection. A detailed analysis of the specific colors of each area of flame may reveal the actual fuel-oxidizer ratio of the

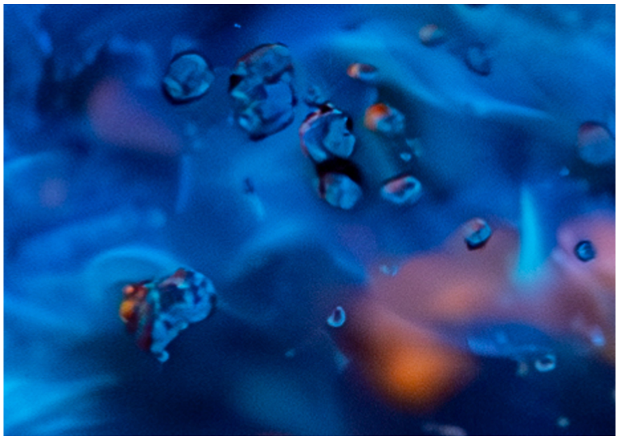

Figure 3.1.4: In focus water drops

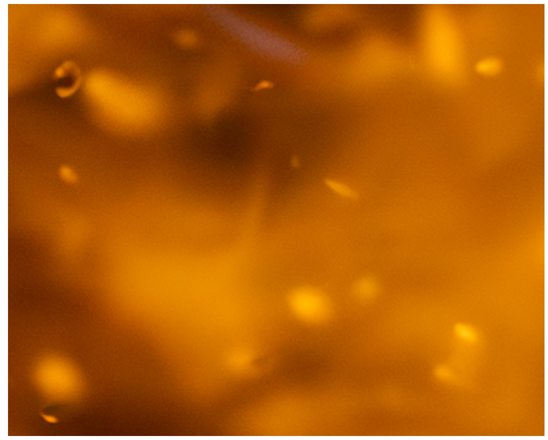

Figure 3.1.5: Out of focus drops

premixed turbulent flame, and it may be possible to compute a temperature field plot of the whole flow. It could also be revealing to compute a velocity field plot for this image; how much of the flow's energy is lost simply from displacing water and changing direction? How does this compare to the change in temperature necessary for the combustion to stop where it does? It would be interesting to attempt to model the flow mixing in the nozzle and the subsequent flame propagation using computational fluid dynamics tools; comparing a CFD analysis with what is observable from this image may lead to further insights.

Some things should be done in an additional photo shoot: a faster shutter speed and wider depth of field would both contribute to a better snap-shot in time of the whole flow field, though getting enough light would be a challenge. A more controlled setup, in which the angle, elevation, and position of the nozzle are more consistent would allow for less hand-wavy analyses of the relative distances, speeds, sizes, etc. of the combustion flow, water drops, and glowing soot.

## 4.2 Revelations

This image makes me feel a lot of things: the full power of the propane torch is on display in the scale of this flow field (several feet across, even though it's bouncing off of cold water). The splashed-up water is all over the place, as though something solid hit the pool, but it's just a jet of burning propane. It's not often that household flames create any meaningful thrust, but there is a decent amount of force being imparted during the impact. This is somewhat inspiring to me. Sometimes it feels as though the things we use to go to space are too complicated, or too "sciency", to be fully appreciated in day-to-day life; this image brings rocketry down to Earth a little bit for me. I have a first-hand feel for what flowing turbulent combustion involves, and it's not all that mystical. The image is also beautiful; I have looked at it (and other shots from that night) for hours and hours now, and I keep noticing new things. I set out to try and capture the beauty of fire, and I believe I succeeded. I was inspired by creators like Smarter Every Day and The Slow Mo Guys, who excel at visualizing scientific phenomena in stunning ways. They always nail it; I feel as though I haven't found my quintessential propane-flame-hitting-a-pool shot yet, and I maybe never will. I'd like more to be in focus, and I'd like a faster shutter, or maybe even a high-speed video, but all of that takes great practice, patience, and probably money. What I have done, though, is taken a big step down the path of curious creation. I said yes to a big "what if", I invested emotional energy into a piece of art, and it inspired me to delve into and learn about an entirely new-to-me science discipline. Before writing this report, I knew very little about combustion. The outcomes of this project are twofold, then. First of all, I have come to know more about science, scratching the curiosity itch. That is important but can be done without creating art. I have also come to know more beauty, which is sometimes missed in the world of engineering. Bringing the two together is what makes flow visualization such a powerful pastime.

# 5 Acknowledgements

# References

[1] Chung K. Law. *Combustion Physics*. Cambridge University Press, 2010. DOI: 10.1017/CBO9780511754517.003.

[2] Paul Palies. *Stabilization and Dynamic of Premixed Swirling Flames*. Academic Press, 2020. DOI: 10.1016/C2019-0-00497-9.