Team Second: Flow Visualization

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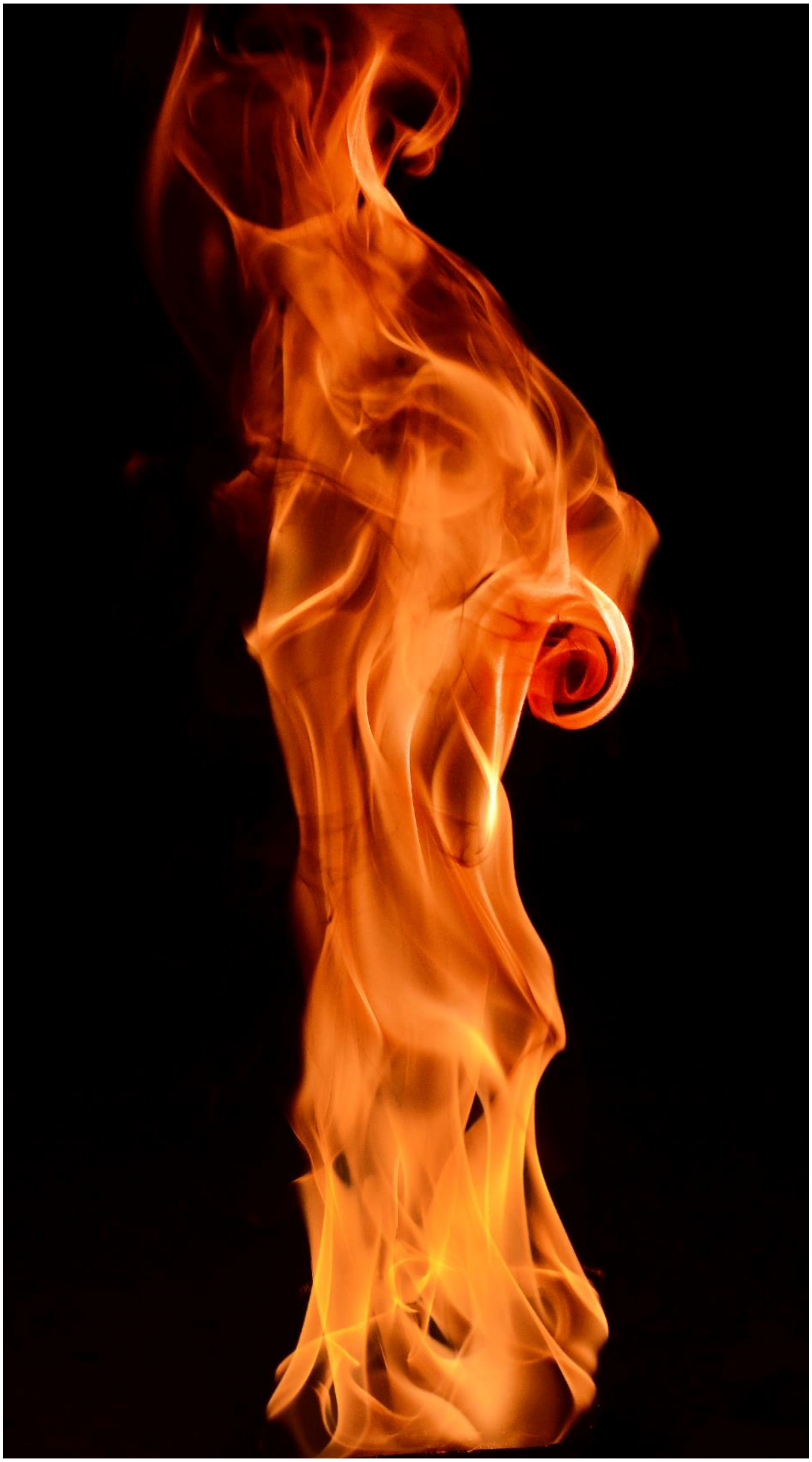


Introduction

Having visualized cloud flows, oil and liquid flows, and vapor flows, our group decided to pursue flame flows for our second project. I think most people feel drawn to fire, and for good reason. Flame is dramatic, exciting, beautiful, and difficult to understand. Team members Branden and Preston have some experience with juggling and spinning fire, which we thought could make a compelling image and dramatic flows.

Setup

The initial goals for this image were fairly broad and undefined. The goal was to play with fire in various ways and attempt to capture a striking image. To do this, we brought flaming juggling torches, kerosene, spinning poi, lighters, and a big water bucket to the alley behind my house and started trying things. Using a tripod, we took a variety of long exposure images of Branden and Preston spinning and juggling flames. While striking, these images had a lot of motion blur, were blown out, and could be very confusing. A couple examples of these images are shown below.

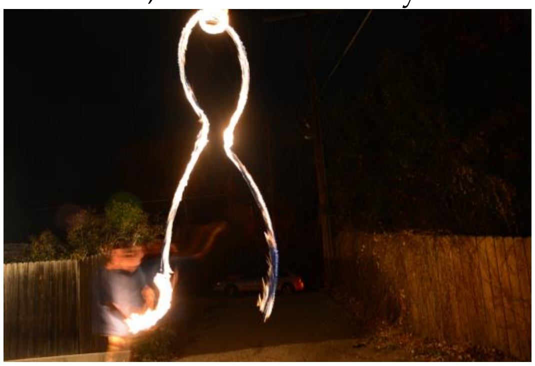


Figure 1: Juggling flame

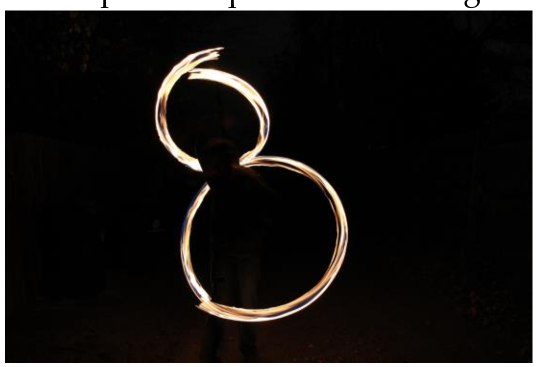


Figure 2: Spinning flame 1

As a team, we captured nearly 100 images of the spinning and juggling flames, but none of them really caught our interest. After this disappointment, we started taking high shutter speed images of a more stable flame. The final setup used in the image was an aluminum baking tray with about 75 mL of kerosene in the bottom of it. Because the evening was so calm when we captured these images, the burning kerosene produced a tall, nearly vertical column of flame. At its peak, the flame column reached nearly 1.5 meters in height. The kerosene fuel burned very steadily and for about 2 minutes before it had all combusted. A very striking element of this specific picture is the spiral swirls on the right side of the flame column. In order to fully understand the flame column and these spirals, we must examine the combustion reaction.

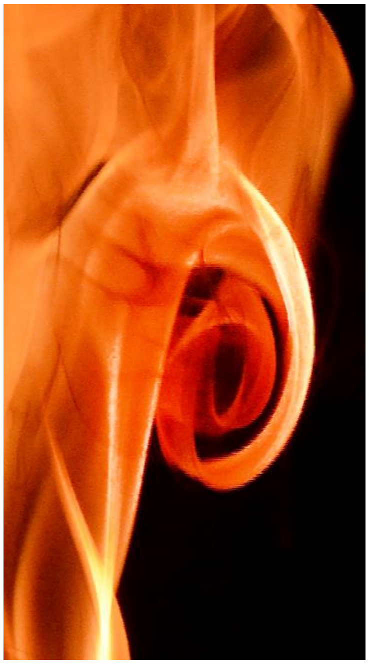
Flow Phenomenon

Kerosene fuel is typically a mixture of dodecane ($C_{12}H_{26}$), tridecane ($C_{13}H_{28}$), tetradecane ($C_{14}H_{30}$), and pentadecane ($C_{15}H_{32}$). This set of hydrocarbons is what combusts when the flame burns. The exact chemical composition varies based on the source, but typically each hydrocarbon contains between 12 and 16 carbon atoms. These long chain hydrocarbons burn steadily and release a large amount of energy, resulting in a bright flame. The combustion reaction of each hydrocarbon generally follows the formula:

$$[hydrocarbon] + nO_2 = mCO_2 + pH_2O$$

Equation 1

Because these hydrocarbons must atomize before they combust, they are nearly in gas form during combustion. Therefore, we can safely compare this flow to a methane jet study done by Viswanath R. Katta and W. M. Roquemore in 1998. In this study, Katta and Roquemore studied vortices in methane jets that closely mimic the vortices in this image. Shown here is the study images and the vortices observed in our teams experiment.



Katta and Roquemore determined that the vortices were a result of hot gasses accelerating upwards along the side of the flame column. As the hot gases encounter colder gases above, they develop a vortex. The hot gases then interact with the flame surface and cause it to coil in upon itself. Katta and Roquemore determined that in a methane jet, the vortices appear at a frequency of 12 Hz. Based on my observation of the kerosene flame column we created, this frequency is substantially lower, probably around 1 Hz.

Another interesting flow phenomenon seen in the image is the soot particles obscuring some of the flames. The dark streaks throughout the image are streams of soot particles being carried upwards by the hot gases around the flame column. The prevalence of the soot is likely a result of the kerosene burning inefficiently. Kerosene (and all fuels) burn best with a good supply of oxygen. Because the fuel in this experiment was in a 3 inch deep container, there was no good airflow to the fuel mixture, and caused very inefficient burning of the fuel. Another indication of this is the dark orange colors of the flame, indicating a low flame temperature. A kerosene flame with good air flow and high temperatures burns a bright white, which is why kerosene was traditionally used as a lamp fuel to provide light.

Photographic Technique

This photo was taken on teammate Katie Yarnell's Nikon D7100 DSLR camera with a 62mm focal length. The camera was about 8 feet from the flame basin. We had to use a tripod to avoid motion blur. The photo was taken with an ISO of 800, which meant little noise, and an aperture of f/10. This aperture gave us a wide depth of field that allowed the whole flame to be in focus. The high f stop was also beneficial in getting the image in focus. In fact, focusing the image was a particular challenge because the flames are not easy to focus on, and focusing can only be done while the flames are burning, because without the flames there was no light. In order to get the time domain fully resolved, we used a shutter speed of 1/1600th of a second. Most of these settings were set by the camera, which was on aperture priority.

Figure 3: Original

Figure 4: Edited

Post processing was an easy process for this image. Because the background was so clean, all that was needed was cropping the image, and dodging the areas I wanted to highlight. I upped the brightness a little, and then used Photoshop to dodge the uppermost vortex, and the vortex halfway up the image. Because flames are so complex, this process took a lot of time because going overboard with the dodge tool looked very bad.

Final Thoughts

I like this flame image a lot, mostly for its scale. We had spectacularly calm wind conditions for shooting outside, and a safe place that allowed up to really push our flame sizes. While most people are accustomed to seeing flames out of a campfire, such a tall (nearly 5 feet!) natural flame column that is less than a foot in diameter is not as common. Like with a lot of these shoots, the conditions that led to this phenomenon were mostly an accident, but gave a great flow. The tray we used severely limited airflow to the fuel, and gave a beautiful orange color to the flame and provided the interesting soot streaks. In fact, this inefficient fuel burning is what really provided a lot of the detail in the flow. Had the flame been much brighter, I suspect the image would just have been blown out. The stability of the flame column also revealed the vortex shedding on the outside of the flame layer, which was striking as well. While this image is far from our initial intent, the results are more interesting than what I had in mind when we started the project.

To develop this flow further, I would like to take a similar setup (kerosene fuel in a pan) into an indoor environment where we have total control of the airflow. With just a few well placed fans, we could manipulate the air supply to the flame column and reveal some interesting phenomenon. Interesting ideas to try would be a fire tornado, cross wind effects, upward forced convention, or using the fans to alter the pressure and create shapes with the flame column.

References

Katta, Vinswanath R., and W. M. Roquemore. "Simulation of Dynamic Methane Jet Diffusion Flames Using Finite Rate Chemistry Models." *AIAA Journal - 36(11):2044 - PDF (AIAA)*. AIAA Journal, 11 Nov. 1998. Web. 16 Nov. 2016.

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