The Crescent Flame

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Team 3 Image Project, MCEN 5151, Boulder, Colorado
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INTRODUCTION

The intent of this photographic experiment was to image an interesting fluid phenomenon that was worth photographing. The submitted photograph was the sixth image assignment called "Team Assignment 3" for a class called Flow Visualization. Specifically, the objective of this particular image was to capture the movement of a flame burning in open air. The flame here was created using rubbing alcohol and was contained in a small bowl. The flame was controlled using two small incense sticks as will be discussed later. Once the flame has been created, wind and heat transfer will be the governing forces that cause the shapes of the fire. The shapes and movement were relaxed by the addition of the incense sticks. Many different phenomena could have been photographed for this third team image; it was the task of the photographer to create a flow worth submitting. The idea for this image came from seeing other flame shots shown in class. After being tasked with creating a team image this idea sounded like a great way to end the semester.

FLOW APPARATUS

Creating this flow was very easy. A small dish and rubbing alcohol were used. The amount of rubbing alcohol used was very small at first (about 25mL) but then after learning that the flame would last longer with more fluid (125ml) the procedure changed. The amount of fluid did not however affect the size of the flame.

The flame was then initiated using a lighter. This is not a hot reaction, but was performed outside on concrete ground in a safe environment. At first the flames were very mobile and moving too fast to image properly. The wind was tearing through the flame and not allowing shapes to take form and last. To counteract this, small incense sticks were used to control the flame. After putting the incense sticks across the top of the bowl the flames moved slower and actually took on true form. An image showing this is below.

Figure 1: Incense Sticks in Flame

To get different shapes from the flame the incense sticks were separated further, or laid on top of one another. Another benefit to having the incense was that it seemed to increase the height of the flame, allowing the photographer to get an even wider array of flows.

FLOW & REACTION ANALYSES

There are many different forces acting on the flame that can produce a multitude of

flame shapes. These forces are due primarily to the wind in open air, heat differences and gravity. The most powerful of these is most likely the wind. Whenever even a slight gust would come the shape of the flame would completely change.

The isopropyl alcohol burning is a chemical reaction. First it degrades into methane and ethane. Then the ethane experiences dehydrogenation creating ethylene. There are other products within the rubbing alcohol, which go through oxidation [2]. These processes are what actually create the visual flame.

Once the flame has been created and its beginning is understood the flow can be analyzed. The flow of flames is very complicated and the equations used to describe flame flow require many variables. One common equation used to describe flame flow is the Navier-Stokes equation for viscous-compressible flow [3]. This equation along with convection considerations can be used to describe the boundaries seen below.

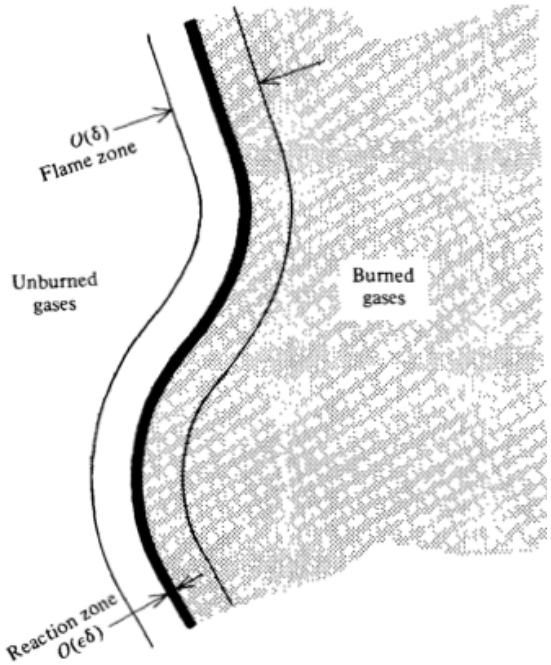

Figure 2: Boundaries seen on flame [3]

The Navier-Stokes equation is an arduous calculation however, with many constants and differential relationships. It can be seen below. Also, this equation would have to be solved for multiple locations along the flame to find the velocity at those points.

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(\rho r u_r) + \frac{1}{r}\frac{\partial(\rho u_\phi)}{\partial \phi} + \frac{\partial(\rho u_z)}{\partial z} = 0.$$

Equation 1: Navier-Stokes

In this equation $\boldsymbol{\rho}$ represents density, t represents time, the rest of the variables (*Φ, r, and z)* are the positions in a cylindrical coordinate system. Different velocities at different points of the flame would result in different shapes. The null on the right side of this equation is due to the assumption there are no other forces acting on the flame [4]. This of course, is not the case; convection forces and air movement are acting on this flame.

The air movement during any particular moment can be very hard to characterize due to its general unpredictability at small scales. It can be assumed however that since this is the main driving force of the flow that the wind in this picture is moving from left to right towards the bottom. This would cause the convex shape seen on the flame.

The color and temperature of flames is dependent on the chemicals being burnt. Different combinations of chemicals will emit different wavelengths when going through self-sustained oxidation. In this case the rubbing alcohol and incense sticks are burning reddish yellow. The diagram below shows different colors from different materials being burnt. The chemicals from left to right are methane, calcium sulfate, calcium phosphate, sodium chloride, potassium phosphate, and sodium borate.

Figure 3: Different Colors With Different Materials [6]

IMAGING TECHNIQUE

The rubbing alcohol was purchased from a nearby grocery store, and was 91% isopropyl alcohol. The incense was purchased at an Asian market in Denver, it is a sandalwood flavor designed for slow burning. The bowl used in the photograph holds about one cup of liquid.

The image here had about 125mL of rubbing alcohol in the bowl. The size of the flame was very dependent on rubbing alcohol up to a certain point, which was nearly 125mL. If there was less than this the flame would be much smaller, it was possible even to get the flame to not rise above the rim of the bowl. Presumably this is due to the fact that as you add more liquid there is more surface area for the oxidation to occur, but once you add 125mL the surface area really is not increasing by a noticeable amount.

The number of incense sticks also had an effect on the image. If more incense sticks were used the flame became very plain, but if just one was used it was rather uncontrolled. The shape of the flame could further be altered by separating the incense sticks by different amounts, widening the flame or increasing its height if they were brought together.

PHOTOGRAPHIC TECHNIQUE

This photo was taken from approximately three meters away and the flow was nearly 0.15 meters tall. This photo was taken with a digital Nikon D3000. It provided a (3872x2592) pixel resolution that, after editing, resulted in a (1765× 3633) pixel resolution. The D3000 is a digital single lens reflex camera (DSLR). When the image was taken the ISO was set to 3200 due to the bright sunlight, the lens focal length to 40mm to get a wide view, shutter speed to 1s/640 for a sharp image, and aperture set at f/5.6.

After importing the original raw image it was clear what the center of the picture should have been. By cropping out the sides and bottom of the picture the true subject stood out. Besides the cropping job the image was also edited to make the image black and white. Also, the image was very grainy due to the high ISO. To counteract this a sharpening tool was used along with an edge smoother. This helped the flame get its good edges.

CONCLUSION

This image shows great flow visualization. The reaction occurring here has fascinated me for a while and this is a great image of the phenomenon. The physics of this reaction are very clearly shown. The flame rises from the rubbing alcohol and is calmed by the incense sticks. It is obvious what is going on and where the flame came from.

One question that lingers post assignment is what other factors cause the flame shape. I am curious if the ambient heat of the atmosphere has a large affect on the fluid shape as well. My main interest in this project was how fun it was to create the actual fire. It would be really fun to make this a larger reaction with greater fluid height.

My intent for this project was not only to capture an interesting flow that showed physics at work, but also to make it look stunning. This photograph encompasses both of those goals well and I am very proud of the picture.

To improve on this image I would like to have a high-speed camera to take a high definition video of this event. This would be to really focus in on the creation of the flame. I feel as though some of the image is clearly out of focus and a video would contribute to the understanding of this a lot. I would also like to somehow understand the environmental conditions much better to estimate how they might affect the flame shape. Overall I feel accomplished with this photograph.

REFERENCES

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APPENDIX

Figure A 1: Unedited Image (2592 × 3872) Pixels

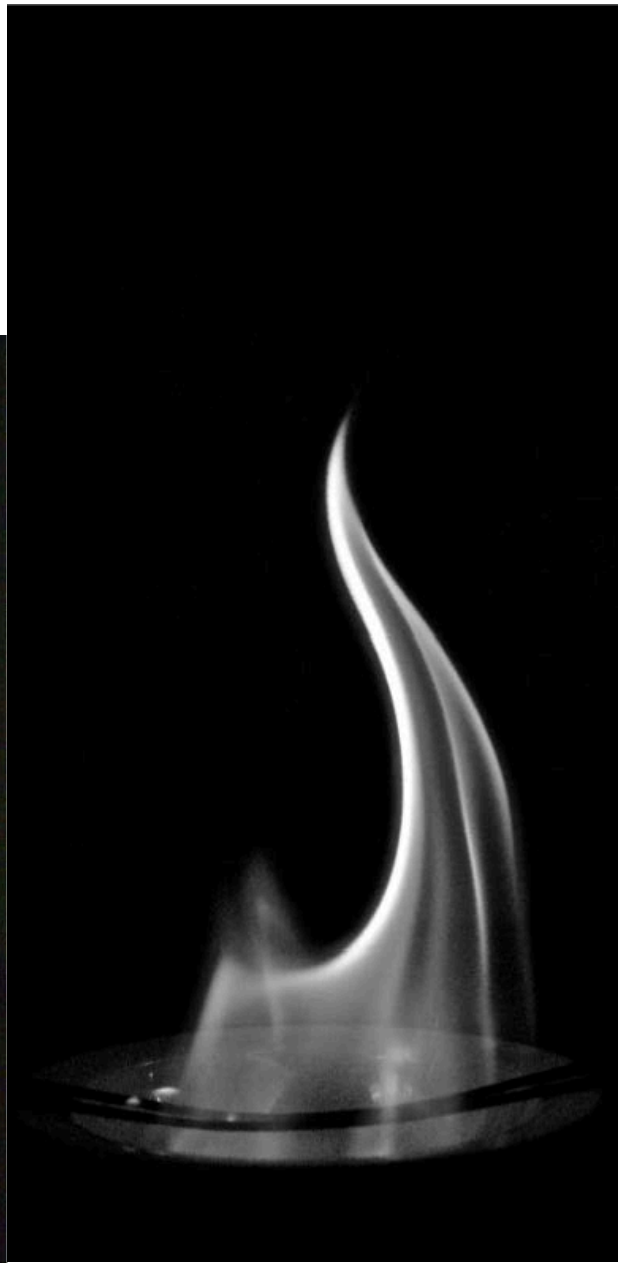

Figure A 2: Edited Image (1765 × 3633) Pixels