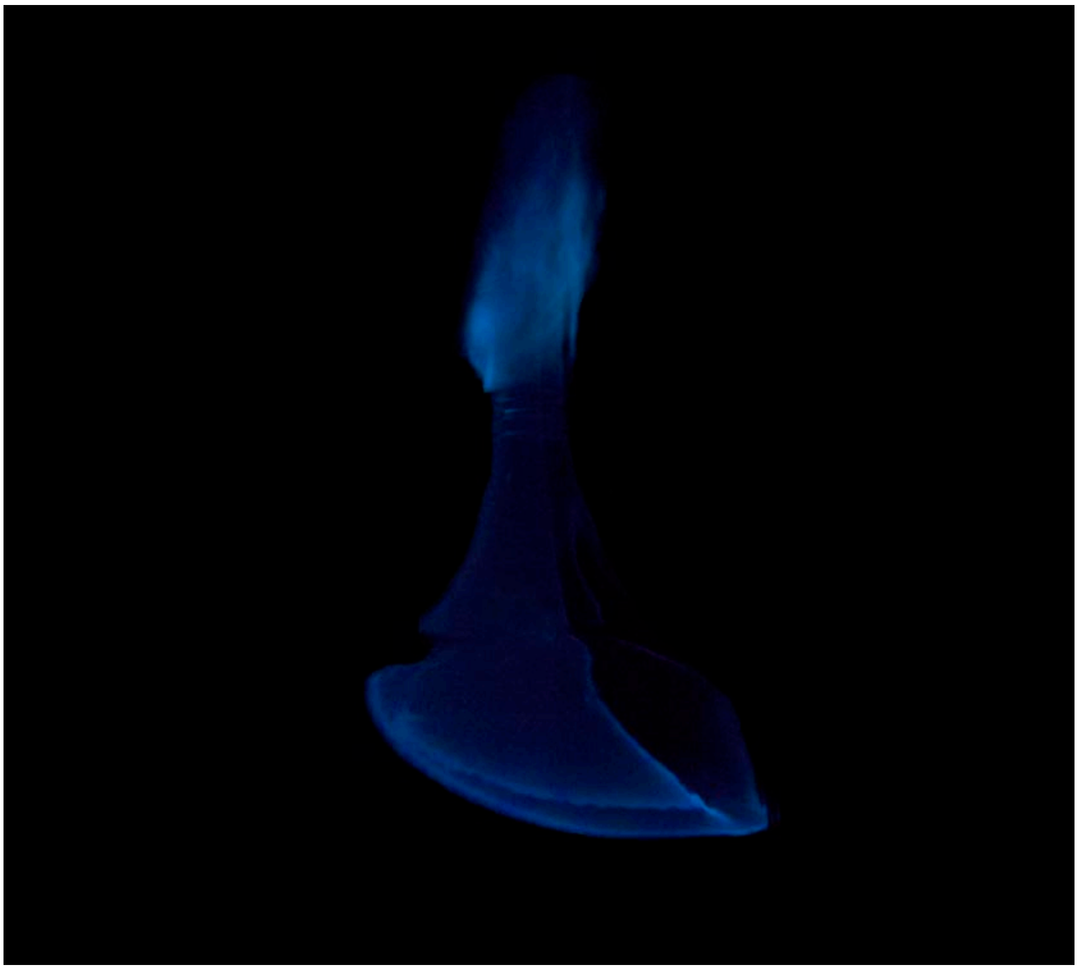
Group Project Two

Woosh Bottle Flame Propagation



MCEN 5151:Flow Visualization

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Introduction

The goal of the flow visualization group projects is to provide each student with a larger set of resources in order to produce more complex images. For this assignment, my group decided to study the flame propagation in a *woosh bottle* (Flinn Scientific, 2012). The goal was to try and capture a series of flames propagating though a glass bottle with Isopropyl alcohol (rubbing alcohol) on the walls. The vaporized alcohol was then ignited used a blowtorch and the group tried to capture as many images of the flames propagation as possible.

The Physics behind the Image

While there are hundreds of possible topics that could be detailed in this section, I have chosen to analyze the chemistry and flame propagation speeds observed when taking the images. The alcohol used to create the flames was Isopropyl alcohol. This alcohol is a secondary alcohol that has the hydroxyl group bonded to second carbon atom within the molecule. (Clark, 2013). Due to the relatively high vapor pressure of the alcohol at 33.1 mmHg (twice that of water), there is enough gaseous alcohol to begin the combustion process with a small ignition source (DOW Chemical, 2012). The chemical formula for isopropyl alcohol is C_3H_8O. With this chemical formula, we can begin to understand the reaction that is taking place within the bottle. Using Stoichiometry, one can calculate the resultant products as a result of the combustion of the alcohol with the surrounding air. The stoichiometric equation for the reaction captured in my image is below (Flinn Scientific, 2012):

$$2(CH_3)_2CHOH + 9O_2 \rightarrow 6CO_2 + 8H_2O \qquad \Delta H = -1{,}235\ kJ/mol$$

With this equation, we can begin to analyze the amount of combustible fluid that was within the jug by reviewing a video of flame propagation within the glass jug. With the glass jug measuring 12 inches tall and the body of the jug measuring 9 inches tall, we can review

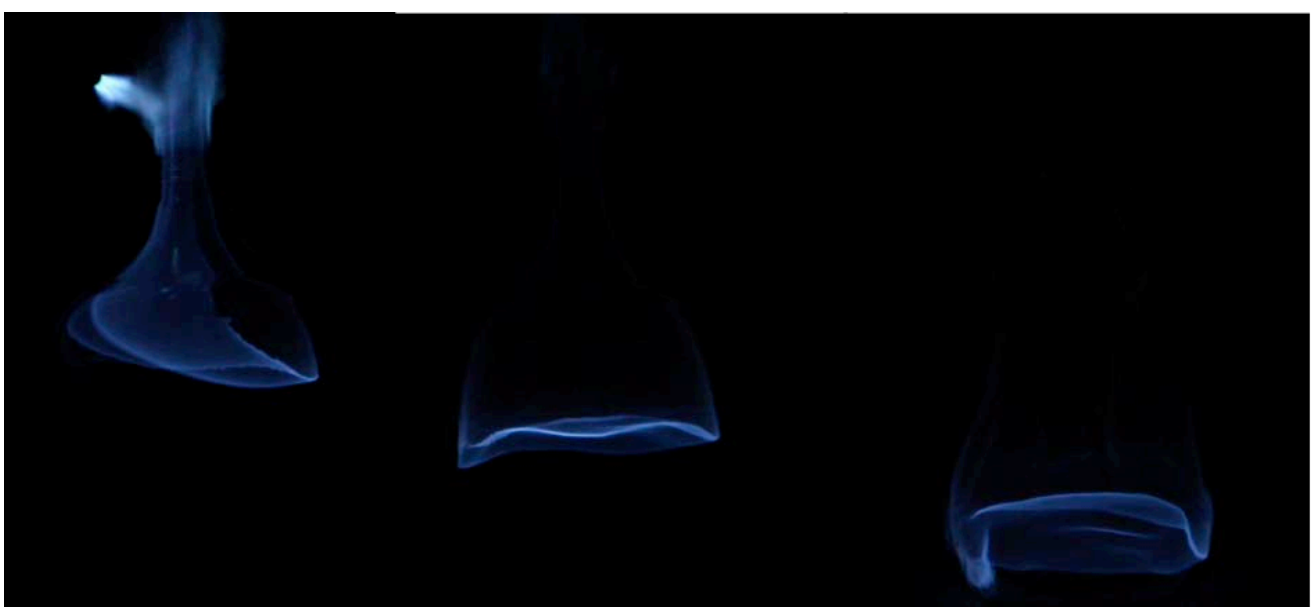

Figure 1-Flame Propagation within Bottle

the time the flame takes to travel from the top of the body to the bottom. Slowing down the video to 25% of the original speed, I found that the time from the far left flame to the far right flame in Figure 1 to be 4.58 seconds. When equating this time to real-time speed, we find that the flame takes 1.21 seconds to travel down the body of the bottle. Finally we can determine the velocity of the flame using the equation below:

$$V = \frac{\Delta x}{\Delta t}$$

Δx=position

Δt=time

Using this equation the velocity of the flame is found to be 0.19 m/s. Experimental data from a study on laminar flame speeds of n-propanol (Isopropyl Alcohol) found that with a velocity of 0.19 m/s an equivalence ratio of approximately 1.45 (Veloo & Egolfopoulos, 2011). The equivalence ratio is defined by the experimental fuel to oxygen ratio over the stoichiometric fuel to air ratio as seen in the equation below (ANDERSSON, HOLMSTEDT, & DAGNERYD, 2003):

$$\emptyset = \frac{\dot{m}_{fuel}/\dot{m}_{oxygen}}{(\dot{m}_{fuel}/\dot{m}_{oxygen})_{stoich}}$$

Assuming the air and fuel to be in a premixed solution we can find what the limiting product using the above equation when combined with the stoichiometric chemical balance as shown below where $x = \dot{m}_{fuel}/\dot{m}_{oxygen}$:

$$1.45 = \frac{x}{(2/9)_{stoich}}$$

After performing the calculations, the fuel to oxygen ratio is found to be 29/90. This means that there is more fuel than there is oxygen when compared with the stoichiometric air to fuel ratio within the bottle. This allows for the conclusion that oxygen is the limiting factor

Figure 2 - Unburnt fuel re-ignition

within the reaction. When reviewing the video, oxygen being the limiting factor makes complete sense as the flame continues to propagate downward not allowing more oxygen to enter from the spout between the flame front and the bottom of the bottle. Interestingly, once the flame reaches the bottom of the bottle, there is a re-ignition of the remaining unburnt fuel within the bottle as seen in Figure 2. This phenomenon was experienced on the majority of the trial runs that the team performed; but not all as the amount of fuel used varied from run to run. After analyzing the flame propagation velocity, it becomes rather apparent as to why there was more than just a single downward propagation. When performing the experiment the team also noticed a large amount of fluid in the bottle, after balancing the stoichiometric equation, it can be concluded that this fluid was in fact water, a product of the combustion cycle. Finally, this analysis was performed in order to gain a deeper understanding as to the reaction that occurred on the specific trial run in which I captured my image. The analysis allowed me to figure out how fast the flame was propagating (and why I did not see any motion blur within my $1/90^{th}$ shutter speed) as well as what the limiting factor was within the reaction. By determining the limiting factor, one is able to explain the continued reaction after the initial downward propagation.

Creating the Setup

To create this image, my group purchased the necessary components including a 1 gallon glass bottle, 70% rubbing alcohol (70% isopropyl alcohol), and a blow torch for lighting the system. Fortunately, this image setup was quite simple considering the beautiful results. With all of the necessary components, the team found a dark room to ensure that no light

Figure 3 - Experimental Setup

pollution ruined the blue flames being captured. Within the room, the team put up a black backdrop to ensure that any reflection off of it would be removed. This created a nearly invisible backdrop that allowed for great captures of the flames. The glass bottle was filled with approximately five tablespoons of ethanol and capped. With the bottle capped, the team shook the bottle to evenly distribute the alcohol on the walls of the bottle. Once this had been finished, the bottle's cap was removed, the bottle was placed on an elevated surface (to have the cameras at the same height) and the blowtorch was brought to the top of the bottle igniting the vaporized alcohol. Two cameras were used to capture both still images as well as video for later analysis and visualization.

Capturing the Image

Due to the extremely low light levels, the camera was set up in a very specific way in order to capture a clean, well-focused, well-lit composition. I took hundreds of images with many different trials of the flame propagation. After reviewing these photos, I felt that the chosen image captures the flames well. One of the biggest drawbacks to capturing these images is the high ISO required. The high ISO induced a significant amount of grain to the image. The chosen image had the smallest amount compared to the majority of the photos. The image was taken with a Canon EOS 10D; it has a 6.3 megapixel CMOS chip that is able to capture images at a resolution of 3072x2048 pixels (Canon USA, 2014). I used an ISO of 1600 to ensure that I could capture the image quickly while also having the flames create an adequate amount of exposure within the capture. Also as a result of the high ISO, I was able to use a relatively quick shutter speed of 1/90 second to capture the flames while

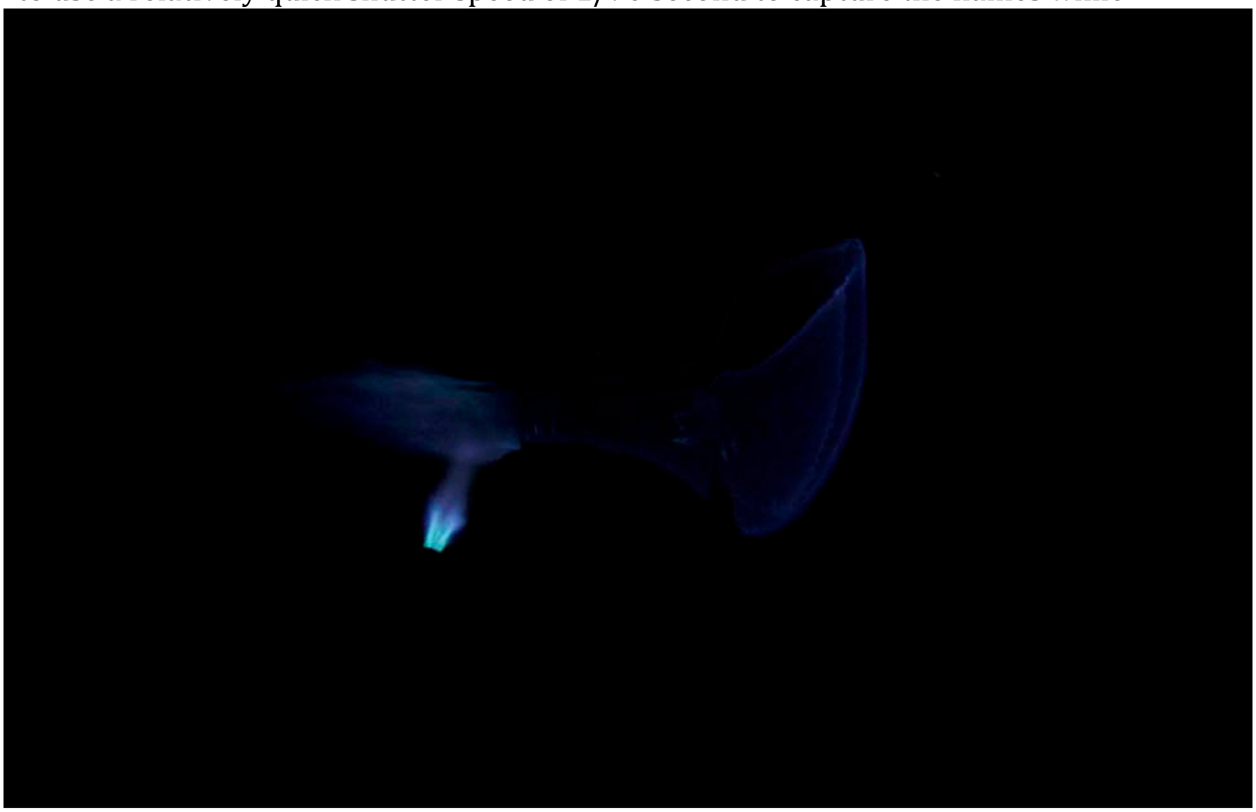

Figure 4-Original Captured Image

preventing any motion blur; allowing capture of clear, crisp images of the flames being propagated through the bottle. Since the depth of field required for this image was narrow, I used a relatively low f-number of 5.6 to allow for a larger amount of light through the shutter. The lens used was a large range lens allowing for a focal length between 28mm and 135mm. For this image, I used a focal length of 30mm to allow the camera to be somewhat close to the flame while also maintaining a relatively wide field-of-view. Overall, I am extremely satisfied with the flames that I captured in the image. Capturing the flames with enough light presented quite the challenge and it took many trial runs to find good settings that balanced high speed capturing (to prevent motion blur) and well lit compositions.

Post Processing

In order to get the most out of the captured image, I had to perform a few post process changes. I tried to keep the changes to only minor changes in order to keep as much of the natural effects as possible. The first change performed was removing the flame from the blowtorch. I felt that this part of the image subtracted from the actual bottle flame since it was brighter and more intense. I used the clone tool to turn this section of the image black. After removing the blowtorch, I selected the blue flames within the image and brightened and intensified the colors for easier viewing. This made the contrast with the black better and allows the user to see more of the intricate details within the flame. Next, I selected the background, which had a significant amount of grain, and changed the color to a solid true black. Finally, I cropped and rotated the image to remove a significant portion of the background. I felt that the combination of these changes allows for a better overall composition.

The Image

The captured image for this project is one that provides a clear composition consisting of little more than the flame itself. This was my intent, as I wanted to remove as much of the bottle's reflection as possible. While you can see small portions of the bottle used, the glare is very difficult to find. One finds the glare up near the neck of the bottle where the threads are located. I actually like that this is the one location that it is somewhat apparent as it allows the viewer to find a sense of perspective within the image. I love the captured image and believe that there are only a few changes that I would have liked to make when capturing. First, I would have enjoyed using a more modern camera that provided higher ISO settings without the high amount of noise seen in my image. I did my best to minimize the noise, yet it is still apparent. I would have also like to use a larger lens that would have allowed more light capture since the flame gave off such little light. Finally, I wish my camera had allowed for high image capture rates as I had large gaps between captures. One of my team's cameras allowed for nearly-simultaneous capturing that allowed him to capture nearly every stage of the flame's propagation though the bottle. This imagery was eventually turned into a video that was used in my analysis above. Overall, I believe my captured image is a unique representation on the *woosh bottle* that has been used in scientific demonstrations around the world.

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