Group Photo #3:

Michael Chilton

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Flow Visualization 2012

Introduction

For this assignment, I wanted to successfully create and capture the properties of an Isopropyl bottle rocket. I had first seen this experiment performed in my high school chemistry class and knew it would be a good contender for Flow Visualization. As the original experiment is very basic, I wanted to guide the focus of my image towards the exit flame and try to get a macro image of the properties of the flame just as it exits the bottle. I knew there would be some interesting phenomena occurring just at this exit point, and knew I would need a better camera than the point and shoot I had so digital camera from Durning Lab was checked out. As I began researching how to best create this experiment, I looked into rocket propulsion design and what effect different nozzle shapes had on the flow. Following this, I decided it would be interesting to try and create a nozzle for the bottle and compare flows. What I found upon testing was that the nozzle design significantly changed the flow in a violent and loud way, while also burning less of the fuel and leaving a hazy gas mixture in the bottle after combustion. This was an extremely fun experiment to set up and test, and I am very happy with the final image I was able to produce. For future iterations of this experiment, it would be great to utilize the slow motion camera and really study the differences in how the flame ignites and propagates through different nozzle geometries and designs.

Experimental Set-up

The flow apparatus used for this study was a store-bought 5 gallon water cooler bottle. The nozzle/shroud was made from plastic food storage container. To fit the nozzle/shroud over the water bottle, a hole was cut in the container's bottom and was then fit over the spout of the bottle. Two tablespoons of 99% Isopropyl alcohol was then measured out and poured into the bottle. After researching online how to properly conduct the experiment, care was taken to fully coat the inside surface of the bottle with the alcohol. This was accomplished by gently spinning the bottle and preventing the alcohol from pooling at the bottom. Once applied to the inside surface, a match was struck and placed into the bottle from the spout. As the match enters the bottle, it ignites the evaporating gas, causing a quick and severe expansion within the bottle resulting in a jet of flame travelling up through the open spout and through the nozzle/shroud. The bottle is 10 inches in diameter at its widest point, and tapers down to a 1.625 inch diameter spout opening which is 3 inches long. The bottle's length, excluding the spout, is 16.5 inches. The nozzle/shroud attachment is 5.5 inches long, 3.5 inches in diameter at its base and gradually expands to 4.5 inches at its opening. The nozzle/shroud attachment was placed over the bottle's spout in such a way so that the spout traveled up within the nozzle/shroud for a distance of 2.5 inches. The experimental set-up, along with a detailed image of the nozzle/shroud attachment is shown in Figure 1.

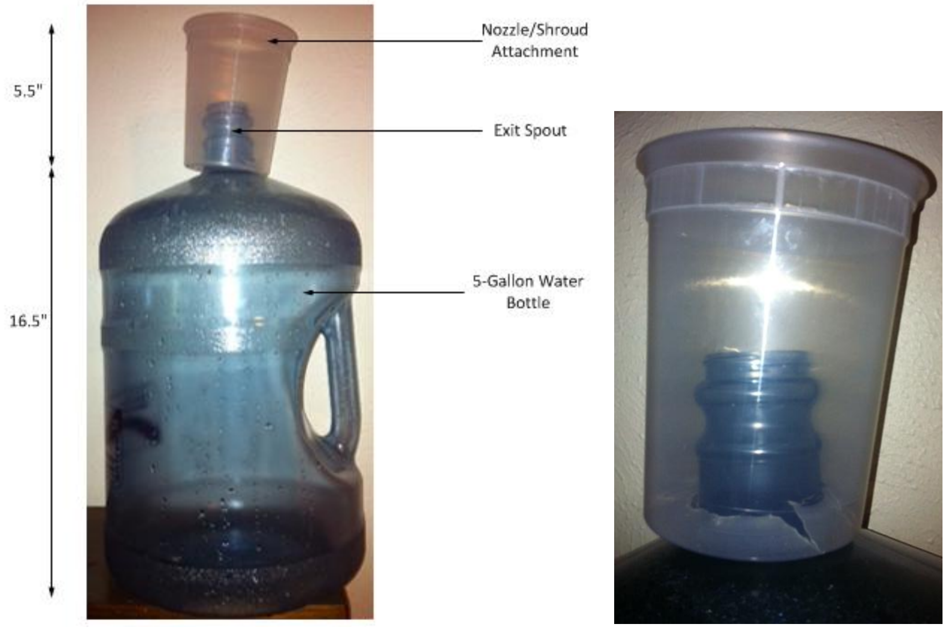

Figure 1: (Left) Entire Experimental Set-up, (Right) Close-up Detail of Nozzle/Shroud Attachment

Flow Analysis

The flow being studied is assumed to be similar to a typical rocket engine design, shown in Figure 1, only without the continual delivery of oxidizer and propellant or the optimized geometry of the nozzle exit. A goal of this experiment was to test the difference in flow when using a "nozzle" design and compare the results to that of a un-nozzled design. The experimental set-up follows what was described before, using the food storage container as "nozzle" for the exiting spout of the water bottle (for simplicity, the addition of the food storage container will be described furthermore as the nozzle-design, even though final results show it may have not produced nozzle behavior in the flow). The nozzle used was crude in design and installation, and my hopes were not high to see much of a difference in flow. After igniting both designs, I was extremely surprised at how much the nozzle altered the flow. The amplification in the sound of the jet with the nozzle was enough to send echoes through my neighborhood and compared to the sound made by the typical design, it was a clear indicator that the flow had been altered.

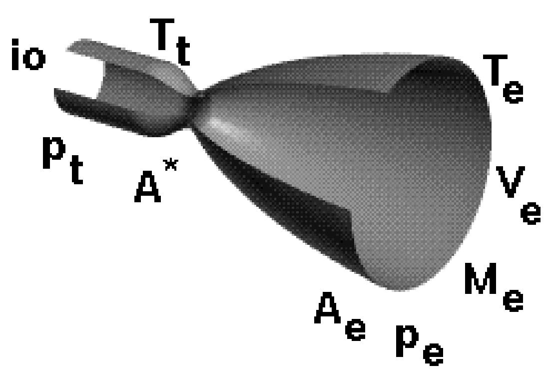

Figure 2: Rocket Nozzle Design Parameters [1]

During testing of the un-nozzled design, the jet was a faint blue which lasted for approximately 3-4 seconds with 2-3 secondary puffs of flame following the initial, primary combustion phase. Once extinguished, there was no noticeable gas left inside the bottle. Attempts to re-ignite remaining gas did not result in any form of combustion. When testing with the nozzle design, the jet was a much brighter and intense blue color, however, it lasted for a fraction of the time. The jet appeared much more powerful and resulted in noticeable movement of the bottle. The sound created by the jet was also much louder with a much sharper pitch than the un-nozzled design, which created more of a "whoosh" sound. *Once* extinguished the bottle's volume was filled with a cloudy white gas which was found to be combustible after throwing in a test match, as was done with the un-nozzled design. These observations clearly show there was some sort of change in the combustion process and/or flow when using the nozzle design. To support the observations made during the experiment, the internal temperature and pressure will be estimated and the exiting temperature and pressure will be calculated from these values. I will then determine if the set-up simulated a "choked flow" scenario and if there was any supersonic characteristic of the nozzled design.

To begin analysis, properties of Isopropyl Alcohol (C_3H_8O) were first found and are shown in Table 1.

Table 1: Properties of Isopropanol Alcohol

Molar Mass	60.1 g/mol
Density @20C	0.786 g/cm^3
Heat Capacity Ratio	1.13

The temperature and pressure within the bottle during combustion was then determined. Because the gas burnt under after removal of the ignition source the flash temperature was surpassed. Also, because the gas was lit with an ignition source, the autoignition temperature would not be applicable. Instead, the Adiabatic Flame Temperature would need to be used. The exact value for Isopropanol could not be found, however the values for Gasoline and Ethanol were determined.[X] Isopropanol is expected to lie somewhere in between these two values, and will be guesstimated for further calculations to be 2261 K or 1987 degrees C. Using the Ideal Gas Law, the pressure within the chamber during combustion can be calculated to be 245 GPa, which would not be possible without catastrophic failure of the plastic bottle, and is clearly impossible. It is likely the flame is at a much lower temperature or that the pressure is immediately released through the bottle's throat.

To eventually find the thrust generated by the combustion reaction, the mass flow rate, exit temperature and pressure, and exhaust velocity must be calculated. These equations are shown below.

Mass Flow Rate: $$\dot{m} = \frac{A^* P_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \quad (1)$$

Exhaust Temperature: $$\frac{T_e}{T_t} = \left(1 + \frac{\gamma-1}{2} {M_e}^2\right)^{-1} \quad (2)$$

Exhaust Pressure: $$\frac{P_e}{P_t} = \left(1 + \frac{\gamma-1}{2} {M_e}^2\right)^{-\frac{\gamma}{\gamma-1}} \quad (3)$$

Exhaust Flow Velocity: $$V_e = M_e \sqrt{\gamma R T_e} \quad (4)$$

Thrust: $$F = \dot{m} V_e + (P_e - P_o) A_e \quad (5)$$

Without an accurate measure of the combustion temperature and pressure, these values cannot be properly determined. One parameter which can be determined without the use of the temperature or pressure values, is the Mach number as a result of the ratio between the throat and exit areas, as shown in Equation 6. This equation is meant more so for the smooth expansion geometry of a De Laval nozzle design, however it should give a reasonable approximation of the what's possible with the geometry.

$$\frac{A_e}{A^*} = \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{\left(1+\frac{\gamma-1}{2}{M_e}^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M_e} \quad (6)$$

Solving for the Mach number, M_e, it was found that the exiting exhaust gases in the nozzle design travel at a Mach number of 2.927.

An online applet estimating phenomena occurring within the nozzle design was used to generate the results shown in Figure 3. It is interesting to note that the results from Figure 3 show there to not be a shockwave present within the jet, but rather an expansion wave. The lower plot demonstrates the Mach number throughout the nozzle, which also correlates well with my computed results.

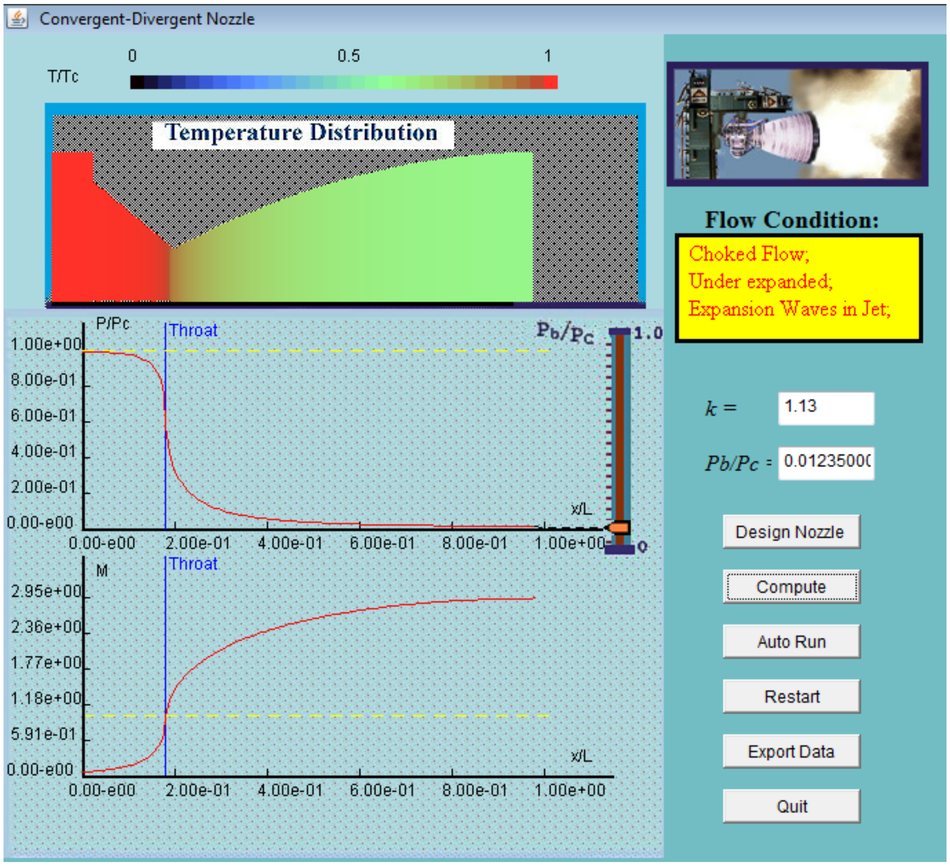

Figure 3: Convergent-Divergent Nozzle Flow Simulation [4]

It is still not clear to me why a cloudy, white combustible gas was left within the chamber, following combustion with the nozzle design. My hypothesis for this is that the shockwave or expansion wave which was created within the nozzle either kept oxygen from circulating back into the combustion chamber or generated enough force to extinguish the reaction. The sound and force generated from the reaction was evidence enough to show that some sort of powerful pressure wave was created, and the Mach number determination shows there was a potential for sonic flow. From studying the image further and looking through the individual frames of the videos taken, it is possible the flow is subsonic as there is no indication of a shockwave. It is difficult to determine the actual change in flow due to the inclusion of the nozzle, as flow at the throat exit does not appear to be expanded in any way.

Visualization Technique

Following directions found online for similar experiments, I used no special visualization techniques other than shooting at night to get the best flame image. The isopropyl alcohol was purchased at a local drug store and is labeled as 99% alcohol. An important aspect of setting up this flow was to make sure the bottle was re-filled with air following combustion, which took generally 20-30 minutes without the use of fans or forcing of air into the bottle. If the bottle was not properly re-filled with air following combustion, there would be no oxygen within the bottle to maintain combustion and the flame would not be able to start. Another important part of the set-up was to fully coat the inside surfaces of the bottle with a thin layer of alcohol. This was done by turning the bottle in a horizontal orientation and slowly rotating it so that the alcohol is not pooled at the bottom. This technique allows for the alcohol to not only evenly coat the surfaces, but to evaporate into a gaseous state for improved combustion.

Photographic Technique

Because of the speed of the combustion reaction, I was not able to take still images and instead used the camera's built in video recording feature to capture the flow. Individual frames were taken from this video to create the still image used for submission. The video's quality was not high enough to justify its submission and I lacked any video editing software as well. The camera used for this image was a digital Canon EOS Rebel T3 with a standard 18-55mm lens. Because the image was captured through video, the only info that was recorded onto the image was the pixel dimension, which was 720 by 1280. When captured the camera was set up on a tripod approximately three feet from the bottle. The camera was positioned so that its focal point was focused onto the bottles spout. The camera was placed in portrait orientation so as to capture as much of the vertical jet as possible. The field of view within the image is approximately 24 in. by 16 in.

I performed no post processing to the image, as I felt it was very well balanced in its original form. The blues were very well pronounced and there were no other colors interfering with the image's composition. The contrast between the blue and black tones came out naturally as I would have adjusted it anyway.

Conclusion

I am extremely happy with the final image as it required no post-processing and is clearly defined. I would have liked to have been able to film the flow using the slow motion camera, and by the success of my experiment, I may try this sooner than later. This experiment was a lot of fun to conduct and tweak, the only thing that was a bit tedious in the set-up was waiting for the bottle to "re-charge" and fill back up with oxygen. The only questions I have following this experiment are related to how the nozzle played a role in the overall efficiency of the combustion and how to more accurately calculate the generated thrust. The remaining gas within the chamber lead me to believe the combustion was incomplete, but it would be nice to have a more defined reason for why this occurred. I would also like to know why the remaining, un-burnt gas was of a white color. Going further with this experiment, I would like to try out different nozzle designs and manufacture them from stiffer materials with more defined and designed geometries. If possible, I would like to stay with a translucent material, such as glass, so that the flow entering the nozzle from the throat was visible and could be studied.

References

[1] "*Rocket Thrust Equations."* Space Flight Systems Mission Directorate. *Web. 01 May 2012. <http://exploration.grc.nasa.gov/education/rocket/rktthsum.html>.*

[2] *White, Frank M.* Fluid Mechanics. *4th ed. New York: McGraw-Hill, 1986. Print.*

[3] *Kar, Kenneth, Wai Cheng, and Kaoru Ishii. "Effects of Ethanol Content on Gasohol PFI Engine Wide-Open-Throttle Operation." SAE Int. J. Fuels Lubr. (2009). Print.*

[4] *"Converging Diverging Nozzle."* Converging Diverging Nozzle. *Web. 07 May 2012. <http://www.engapplets.vt.edu/fluids/CDnozzle/cdinfo.html>.*