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MCEN 5051-001

Flow Visualization Assignment #4 - Report

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The purpose of this video is to aesthetically capture the burning characteristics of an easy to make solid rocket fuel. The artistic intention was to create an otherworldly type scene that was as dramatic as possible but also calm. The original experimental intent was to capture an image of a rocket's exhaust flame. Unfortunately, this came with marginal success of getting a clear image and the project was pivoted to burning rocket fuel in the open. A slow-motion video proved to provide the most detail of the flow. As such the final video is of a small pile of rocket fuel burning in ambient air. This proved for very interesting characteristics where the powder fuel would clump up into liquid spheres which would flow around the pile of fuel and burn until they dissipated and returned to solid form.

The fuel used for these experiments is a mixture of potassium nitrate and sucrose. Potassium nitrate (KNO_3) served as the oxidizer for the sucrose. It was found as Hi-Yield brand Stump Remover which is nearly pure potassium nitrate crystallized into approximately 1mm balls. Generic brand confectioners' sugar was used as the fuel. This contains nearly pure fine ground sucrose with a few percent anti caking agent – likely corn or potato starch.[1] The fuel was combined in a 13:7 ratio of oxidizer (KNO_3) to fuel ($C_{12}H_{22}O_{11}$) by mass.[6] 65 grams of oxidizer was blended with 35 grams of fuel into a relatively homogenous mixture using a small food processor.

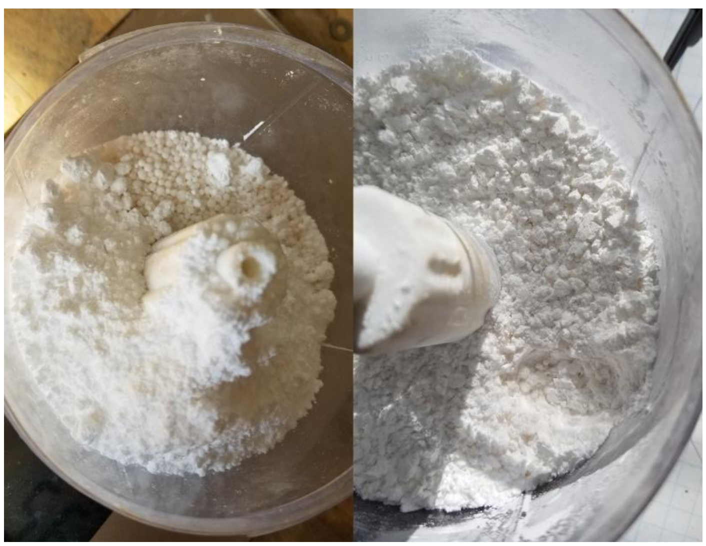

Figure 1. Precursors on the left. Completed fuel on the right after blending.

For the best performance, the fuel would then be melted together and then cast into the final shape to recrystallize.[6] For ease and safety the fuel was left in the powdered state with a grain size on the order of about 100 microns. Dr. Abhijeet Singh describes the theoretical combustion for the rocket fuel as follows:

$$48\,KNO_3 + 5\,C_{12}H_{22}O_{11} \longrightarrow 24\,K_2CO_3 + 24\,N_2 + 55\,H_2O + 36\,CO_2.$$ [6]

Other than the water, carbon dioxide, and nitrogen, one of the resulting compounds is liquid potassium carbonate. The liquid potassium carbonate is almost certainly a significant constituent of the molten orbs that are visible in the video. In addition, Singh lists KOH, or potassium hydroxide as a product of the combustion.[6]

Figure 2. Chips resulting from the fuel combustion. As with the orbs, they are likely potassium carbonate, possibly with some concentration of potassium hydroxide.

The agglomerates or the liquid orbs similarly have some fuel and oxidizer in them.[3] These pockets are likely the cause of the jet outbursts which can be seen shooting from the orbs. An example of one of these jets can be seen below in Figure 3.

Figure 3. A flame jet shooting out from one of the molten orbs. Circled in red for visibility.

In this case the rocket fuel burns at approximately 2,600°F [6] which is able to melt both potassium carbonate and potassium hydroxide which have melting temperatures of 1,650°F and 680°F respectively.[4][5] In order to estimate the Reynolds number for the orbs the viscosity must unfortunately be estimated visually as molten potassium carbonate does not have an easily found viscosity. Assuming a viscosity of an egg yolk by inspection, they Reynolds number for the orbs flowing down the pile is very roughly:

$$Re = \frac{\rho u D_{orb}}{\mu} = \frac{2000\ \left[\frac{kg}{m^3}\right]^{[4]} * 0.01\ \left[\frac{m}{s}\right] * 0.02\ [m]}{0.2\ \left[\frac{kg}{m * s}\right]^{[2]}} = 2$$

This very low Reynolds number implies laminar flow, however there may be significant convection or other flow within the orbs which could induce turbulence.

To visualize the flow a pile of approximately 30 grams of fuel was placed on to a 4” wide steel bar. This was set on a concrete floor in an open garage. The fuel was then lit with a MAP gas torch. About 10 large CFL bulbs provided some ambient light however the flame emission light became dominant during the burning.

An approximately 12” wide region makes up the field of view for the video. It was captured on a Samsung Galaxy Note 8 phone located approximately 15” from the fuel. The 12-megapixel camera has a fixed aperture of 1.7 and a focal length of 4mm. The video was recorded in slow motion with a 1080 x 720 resolution at 240 frames per second. The shutter speed and ISO settings were auto selected and auto adjusted during the filming. The camera did not record these values.

As for post processing, the video begins with an 8 second section at 1/8th speed as a title slide. Next is a 6 second section in real time as the fuel ignites. A 7 second clip at half speed is then followed by 10 seconds at 1/8th speed. The video goes back up to half speed for 8 seconds as the visibility of the orbs is limited due to an increased amount of flame present. Once the flame decreases a bit the video is slowed back down to 1/8th speed for 26 seconds. The final 25 seconds of the video are at half speed as the fire dies out. This was edited we the built in Windows video editor. An original music composition is added in addition to the sounds of the combustion. No additional post processing was used.

This video reveals a very interesting process where the products of solid rocket fuel combustion agglomerate into molten orbs which flow around, jet out hot flame, before eventually cooling and solidifying into hard chips. I do like the overall composition and the contrast with the burning rocket fuel and very slow music. The orbs themselves I find to be quite beautiful and very intriguing. Overall, this does fulfill the original intent however there are some areas with potential improvements. A better camera with control over the ISO and shutter speed would have allowed the exposure to be dialed in to better show the orbs. A tripod would have helped to steady the camera as opposed to the handheld videography. Finally, a cleaner background would have resulted in a more professional looking shot. To further develop this idea, many potential additives to the fuel such as aluminum powder can change the characteristics of the combustion[3] and would be worth investigating their effects. For this project I wanted to create an interesting combustion-based experiment for my final flow visualization submission and overall I believe the video is satisfying and curious.

Works Cited

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[3] - Dupays, Joël. "Two-phase unsteady flow in solid rocket motors." Aerospace Science and Technology 6.6 (2002): 413-422.

[4] - National Center for Biotechnology Information. "PubChem Compound Summary for CID 11430, Potassium carbonate" PubChem, https://pubchem.ncbi.nlm.nih.gov/compound/Potassium-carbonate. Accessed 6 December, 2020.

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[6] - Singh, D. Abhijeet. "Sugar Based Rocket Propulsion System-Making, Analysis & Limitations." International Journal of Engineering Trends and Applications (IJETA) Volume 2 (2015).