MCEN 5141: Flow Visualization
Get Wet

Andrew A. Van Der Volgen

1 Introduction

The purpose of this project was to become familiarized with the techniques necessary to create a fluid flow that illustrates a fluid mechanic phenomena, as well as how to image it effectively. Although several different fluid flows were considered, fire was eventually settled on as a subject for the image.

Methanol was chosen as a fuel source for the fire as it is relatively clean burning, easy to source, and produces an aesthetically pleasing blue flame. However, experimental photographs of pure methanol flames were of poor quality due to the low intensity light emitted. As a result, strategies for chemically altering the fuel in order to emit more intense light were investigated. Many of these strategies can also alter the color of flame emitted when methanol is burned. For aesthetic reasons, the decision was made to utilize two strategies that produce distinct colors in order to introduce contrast to the photograph.

While testing strategies the phenomena known as a *fire whirl* was observed forming spontaneously. This inspired the ultimate goal of the project: to photograph a fire whirl mixing two different color flames.

2 Creating the Fuel

2.1 Sourcing Methanol

Methanol is used in a wide variety of consumer grade products and can typically be sourced locally without trouble. Local race tracks or hardware stores are likely to carry pure methanol, but typically in volumes of one gallon or more. This project required only a small amount of methanol and so it was purchased in twelve fluid ounce bottles of a product called HEET®, which can be purchased from most major auto parts stores. HEET® is marketed as a vehicle gas line anti-freeze additive and is 99% methanol. The remaining 1% of the solution is safe for combustion and does not alter the color characteristics methanol when burned.

2.2 Modifying Methanol Flame Colors

2.2.1 Green Flame

Green was selected for the first modified flame color because it is unique and easy to produce. Green flame is generated when methanol containing boric acid is burned. The intensity of the green is dependent upon the amount of boron in the solution. Small amounts will fail to mask the blue flame of methanol, and so for this project, boric acid was added to methanol until it was saturated. The solution was mixed in batches of 150ml of methanol, which requires roughly 2 tablespoons of boric acid to saturate.

Boric acid is widely available in pure form online, but can also typically be found locally at pharmacies or hardware stores. For this project, boric acid was obtained from a hardware store within the product Zap-A-Roach™, which is 100% boric acid and is marketed as a roach and ant pest control agent.

2.2.2 Red Flame

Red was chosen for the second flame color because the material needed to produce it is available on the consumer market and the result is a strikingly brilliant red color. Red is produced through the addition of lithium to methanol.

Lithium salts are available online and obscure sources of free lithium metal do exist, but for convenience during this project lithium metal was obtained from Energizer Ultimate Lithium® AA batteries. The lithium from one of these AA batteries is capable of treating approximately 175ml of methanol, which is reduced by chemical reaction through the release of hydrogen gas to approximately 150ml.

3 Safety

3.1 Boric Acid

Boric acid is a relatively benign substance that is sold for use in multiple household applications. Nevertheless, if severely mishandled, it can pose a health risk [6]. Before working with it, a Material Safety Data Sheet (MSDS) was consulted and precautions were taken to ensure safe handling.

All interaction with the substance was done outdoors in a well ventilated area while wearing rubber gloves and safety glasses. Care was taken to avoid ingestion, inhalation of boric acid dust, or direct contact. When boric acid is added to methanol, the following reaction takes place [10]:

$$\underset{\text{boric acid}}{H_3BO_3} + \underset{\text{methanol}}{3CH_3OH} \rightarrow \underset{\text{trimethyl borate}}{B(OCH_3)_3} + \underset{\text{water}}{3H_2O}$$

When the products are burned, the relevant combustion reaction is [10]:

$$\underset{\text{trimethyl borate}}{2B(OCH_3)_3} + \underset{\text{oxygen}}{9O_2} \rightarrow \underset{\text{diboron trioxide}}{B_2O_3} + \underset{\text{carbon dioxide}}{6CO_2} + \underset{\text{water}}{9H_2O}$$

According to their respective MSDSs, trimethyl borate and diboron trioxide are also relatively innocuous, but should be handled with precautions similar to those appropriate for pure boric acid [8] [9]. Accordingly, suitable personal protective equipment (PPE) was worn while working with them and care was taken to avoid direct contact, ingestion, or inhalation of fumes during combustion.

3.2 Lithium

Energizer's Ultimate Lithium® Product Safety Sheet was consulted prior to extracting any lithium. The batteries operate on a lithium iron disulfide chemistry. Iron disulfide is a solid state electrolyte making this particular brand battery relatively safe and non-toxic to disassemble when compared to a lead-acid or lithium ion chemistry battery. Nevertheless, there are hazards associated with disassembly [3].

As a result of those hazards, and to reduce the need for lithium, sodium chloride (table salt) was used to dope batches of methanol for test photos until the process had been perfected. Methanol with sodium chloride produces yellow flame which provided the necessary color contrast for test photos. Only then was lithium obtained in order to produce the final image's red flame. This reduced the lithium necessary to achieve the final photo to the amount contained within two batteries.

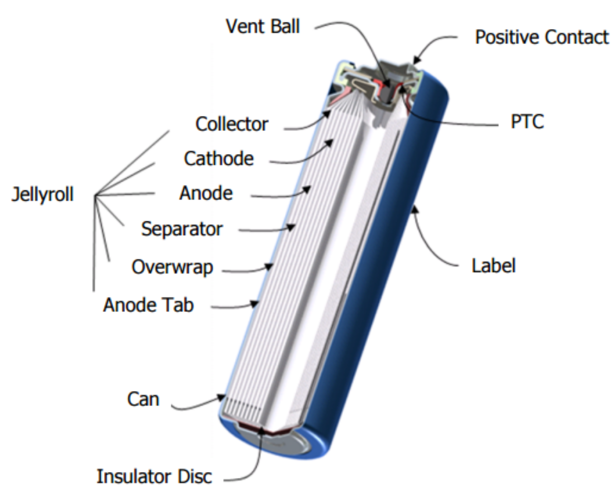

Figure 1: Energizer Ultimate Lithium Battery [2]

The batteries were disassembled outdoors in a well ventilated area while wearing rubber gloves and a face shield. First, the battery's *can* (Figure 1) was cut through near the center of its length with a pipe cutter. Care was taken to pierce only the can, and not penetrate any of the *jellyroll*, which could cause a short. One half of the can was then pulled off the jellyroll with a pair of pliers and the jellyroll was removed (with pliers) from the remaining half of the can. The jellyroll can then be unraveled to reveal a sheet of lithium foil. The remaining portion of the jellyroll is a combination of aluminum foil, iron disulfide electrolyte, and separator sheets.

Care was taken to avoid inhaling electrolyte fumes or making direct contact with any portion of the battery. Although the AA battery design should not contain enough electrical energy for spontaneous combustion in the case of a short, disassembly was conducted on a concrete pad in case of fire. Additionally, although lithium can react violently with water, each AA battery contains $\leq$2g lithium and does not meet any federal government criteria under 40 CFR 261.2 for reactivity [3]. This makes it highly unlikely that the lithium contained within one battery would spontaneously ignite if exposed to water. Nevertheless, the battery was handled under conditions where a spontaneous fire could be allowed to burn itself out harmlessly.

The unused portions of the battery are not hazardous waste per the United States Resource Conservation and Recovery Act - 40 CFR Part 261 Subpart C, however, they were disposed of within a leak and fireproof container and in accordance with federal, state, and local laws [3].

The recovered lithium was introduced to 175ml of methanol and the following reaction occured [4]:

$$\underset{\text{lithium}}{2Li} + \underset{\text{methanol}}{2CH_3OH} \rightarrow \underset{\text{lithium methoxide}}{2CH_3LiO} + \underset{\text{hydrogen}}{H_2}$$

Lithium methoxide's MSDS reads similarly to that of the boron compounds from the previous section [7]. Accordingly, care was taken to avoid contact or inhalation of the methoxide solution and fumes produced by its combustion were avoided.

3.3 General

A dry chemical fire extinguisher was available throughout the project along with a water hose and the process was conducted on a concrete pad, away from flammable objects, where any fire could be allowed to burn itself out if necessary.

4 Execution

One 150ml green and one 150ml red batch of methanol were prepared. A Canon Powershot A640® (7.3-29.2mm focal length) camera on a JOBY Gorrilapod Original® tripod was set up 1.5m upwind of the intended location for a pool of methanol on an outdoor concrete pad. The photos were taken well after nautical twilight with zero moon illumination and minimal cultural lighting nearby.

The camera was prepared by placing an object in the center of the intended methanol location and manually focusing on the object. The object of focus was then removed and the methanol was poured into distinct pools (red/green) with an attempt to have them join at the center of the camera's field-of-view. Additional volume of methanol was poured at the junction of the two color pools in order to promote higher air temperature, and therefore larger updraft, at the intersection of the two colors of flame. The camera was set to *Shutter Priority* mode with 1/320s shutter speed, ISO400, a resolution of 3648x2048, and programmed to take ten consecutive pictures when activated.

The methanol was ignited from a distance with a propane torch while simultaneously activating the camera. Even at their brightest, the resultant flames gave off a level of light that the camera's auto-exposure program determined to be under exposed at the camera's largest aperture stop of f/2.8. As a result, all photos were taken at the f/2.8 stop. This procedure was repeated until an acceptable image was captured (Figure 2).

The image was then post-processed in Adobe Photoshop®. The image was cropped slightly, and the *Clone Stamp* tool was used to remove several artifacts resulting from dead pixels and dust on the camera lens. The background was painted black with the *Paint Bucket* tool to eliminate small amounts of grainy ISO noise. Finally, from the *Curves* window, mid-range RGB colors were brightened to enhance the contrast of the flames against the background. The resultant image, which depicts a scene measuring roughly 150 $\times$ 84cm at the object plane, can be seen on the title page of this document.

Figure 2: Final Image - Raw

Note that post-processing adjustments were subtle and Figure 2 may not be distinguishable from the title page at the sizes displayed within this document.

5 Fluid Dynamics

In Figure 2, a fire whirl is just beginning to form at the intersection of the two colors of flame. This phenomena is promoting the mixing of the red and green flames and is dependent upon temperature induced buoyancy gradients as well as angular momentum imparted by surrounding air. As air is heated by the flame its density decreases and its buoyancy relative to the surrounding ambient temperature air increases. This creates an updraft which drives the flames upward. As the heated air rises it creates a low pressure zone at the base of the fire. Surrounding air rushes in to fill the low pressure zone, is heated by the flame, and the updraft process repeats itself [1]. If, by chance, there happens to be rotational motion in the environment surrounding the fire, it can impart angular velocity to the fire's updraft as it rushes in to fill the low pressure region created by the fire. When this process becomes self-supporting, a persistent fire whirl develops [1].

The development of a fire whirl involves a significant increase in fuel burn rate with an associated increase in flame height. Although flame height correlations aren't universally agreed upon, one proposed model predicts a fire whirl's height, z_f, in centimeters as [5]:

$$z_\mathrm{f} = \frac{(r_\mathrm{p})(\mathrm{Pe})}{4\ln[1/(1-Z_\mathrm{st})]}$$

where
r_p is the fuel pool radius (cm)
Pe is the system's characteristic Péclet number
Z_st is the stoichiometric value of fuel mixture fraction

For methanol pools on the order of size that generated the final image, this equation predicts fire whirls will attain heights ≈ 3 times greater than that exhibited by the same system's basic pool fire dynamics (i.e. without vortical motion). Accompanying this increase in height is the vortical mixing motion desired by the project.

Pouring a larger volume of fuel around the intersection of the pools of methanol helps to create the highest air temperature, and therefore the strongest updraft, at the focal point of the image. This increases the probability that if a fire whirl were to form, it will form at the intersection of the colored flames.

There are artificial methods by which rotational flow can be added to the environment surrounding a fire in order to force formation of a fire whirl, but in the environment that this project was conducted they formed naturally with regularity and were able to be imaged without artificial manipulation.

6 Conclusion

The final image captures only the beginning of the formation of a fire whirl. Photos taken after the fire whirl had fully developed exhibited large amounts of motion blur due to the increased flame speed in the vortex. This was largely a shortcoming of the camera used to image the flames. Increasing ISO to the camera's maximum setting of ISO800 (which allowed near equivalent exposure at 1/400s shutter speed) introduced unacceptable levels of noise with only marginal reduction in motion blur. A higher quality camera with usable ISO settings well above 800 or aperture stops below f/2.8 would allow for significantly faster shutter speeds at equivalent exposure values. This would make imaging a fully developed fire whirl possible. Nevertheless, the settings used for the final image produced an aesthetically pleasing result that highlights many of the fluid dynamics associated with fire and fire whirls.

References

[1] Francine Battaglia, Ronald G. Rehm, and Howard R. Baum. The Fluid Dynamics of Fire Whirls – An Inviscid Model. Technical report, National Institute of Standards and Technology Building and Fire Research Laboratory, 2000.

[2] Energizer Battery. Lithium Iron Disulfide: Handbook and Application Manual. Technical report, Energizer Holdings, Inc., 2013.

[3] Energizer Battery. Lithium Iron Disulfide: Product Safety Data Sheet. Technical report, Energizer Holdings, Inc., 2015.

[4] William A. Hart, O. F. Beumel, and Thomas P. Whaley. *The Chemistry of Lithium, Sodium, Potassium, Rubidium, Cesium, and Francium*. Pergamon Press, 1973.

[5] Yasuhiro Hayashi, Kazunori Kuwana, and Ritsu Dobashi. Influence of Vortex Structure on Fire Whirl Behavior. *Fire Safety Science*, 10:671–679, 2011.

[6] Acros Organics. Material Safety Data Sheet: Boric Acid. Technical report, Fisher Scientific, 2014.

[7] Acros Organics. Material Safety Data Sheet: Lithium Methoxide in Methanol. Technical report, Fisher Scientific, 2015.

[8] Acros Organics. Material Safety Data Sheet: Trimethyl Borate. Technical report, Fisher Scientific, 2015.

[9] Fisher Scientific. Material Safety Data Sheet: Boric Oxide. Technical report, Fisher Scientific, 1997.

[10] S. Zumdahl. *Introductory Chemistry: A Foundation*. Cengage Learning, 2003.