UNIVERSITY OF COLORADO AT BOULDER

Figures in Flame

MCEN 5228 – Flow Visualization

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Introduction:

Fire, when contained and non-threatening, amazes and entrances as it dances against a dark background. The basic premise of the experiment conducted is that the interesting natural interactions that occur as flames move and propagate on the surface of a thin pool of fuel can be captured on a digital camera. The fuel chosen was methanol with table salt (NaCl) added because of its relatively clean combustion into CO_2 and H_2O, ease of procurement, and colorful flame output. [4]

Procedure (Adapted from teammate John Goblirsch's Procedure):

The materials in Table 1 were acquired and used for this experiment.

Table 1

1	Methanol (HEET Gas Line Antifreeze)
2	Glass for mixing
3	Table salt
4	Safety goggles
5	Safety gloves
6	Matches

All of which are labeled and displayed in the Figure 1:

Figure 1: Experimental Materials

The images were shot outside, at night, on a closed driveway. Methanol was poured into a small glass and varying amounts of salt were added and stirred. The mixture was then poured in a controlled size and shape onto the concrete. Once the camera was set-up and initialized, the solution was ignited using a match, creating the beautiful orange flames seen in the images. There was a slight but steady wind from the west, which generated a lot of interesting flame motion. It is important to note that methanol (or methyl alcohol) is poisonous, and any skin or eye contact should be avoided, so protective gloves and goggles should be worn at all times during this experiment. Safety, of course, was our number one priority, and it is important to always read the safety labels when dealing with hazardous chemicals and follow laboratory safety guidelines where they apply.

Camera Settings:

Table 2

Camera Model	**Canon Powershot G12**
Lens	**28-80 mm**
F-Stop	**f/5.6**
Exposure	**1/500 sec**
ISO Setting	**ISO-3200**
Exposure Bias	**0 step**
Focal Length	**21 mm**
Aperture (Max)	**4**
Subject Distance	**Roughly 12 in ≈ 300 mm**

For the original photographs, a high ISO setting was chosen in order to resolve more of the flow in the low-light set-up. The added grain was acceptable because of the amount of detail that was preserved. The focus was set manually, and the photograph was taken from a short distance away (about 12 in). A 5-shot burst was used to capture the movement of the flow. The field-of-view of the final is approximately twice that of each of the originals, which ends up being about two feet at the site of the fire. The motion of the fluid flow was resolved nicely, which maintains the experimental context that was desired for the final image.

Image Post-Processing:

Figure 2

Figure 3

Final Image Settings	Original Image Settings
Width - 5243 px	Width - 3468 px
Height - 1939 px	Height - 2736 px
Resolution - 72 dpi	Resolution - 180 dpi
Color Space - sRGB	Color Space - sRGB

The final image, Figure 2, was post-processed in the open-source program the GIMP (GNU Image Manipulation Program). It was cropped to the above dimensions in order to accommodate crops from the three images that compose it. Since the original images (Figure 3 is one example) are a little bit dark and lacking in contrast, the levels were adjusted channel-by-channel: first red, then blue, then green, then red once again to return the background to a darker black tone, while largely retaining the color of the flame. The overall levels were raised, which increased the intensity of the flames. These were the only changes made, and the photograph aspect ratios were retained (no image "stretching" was done).

Discussion:

The intricate and seemingly random geometry of the flames is a very complex interaction between many factors. The ones that will be considered in this paper are: geometry and temperature profile (which is important for the geometry due to density).

Combustion, such as a lit match, causes atmospheric oxygen to get consumed, and other gases (including carbon dioxide) to be produced. In addition, energy is liberated in the form of heat and light. The produced gases are hotter than the environment due to the generated energy, and they expand, as heated gases often do. Then, because their density is lower than the surrounding atmosphere, the heated gas rises. While it is moving up, it carries energy with it, thus the flame ends up pointing upwards. Also, because the products of combustion move upwards, they make more oxygen available to make the flame continue to burn [5]. In our case, the flame takes on various shapes because the surrounding air was not static. In fact, random gusts of wind that were estimated to be at 25 miles per hour entered the testing environment at random intervals, all of which were at lower temperatures and varying densities from the flame and surrounding ambient air. This led to the uncanny shapes of flame seen in the final image [5]. Given standard temperature and pressure, the Reynolds number of the incoming external air flow is roughly described by Equation 1 [1]:

Equation 1

$$\mathrm{Re} = \frac{\rho \mathrm{V} L}{\mu}$$

where:

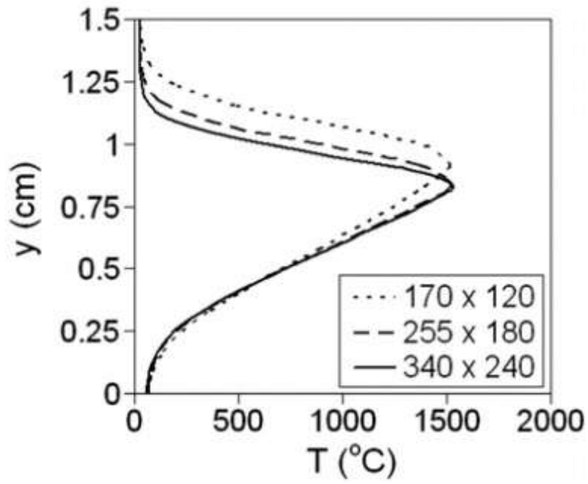
- V is the mean velocity of the object relative to the fluid (m/s)
- L is a characteristic linear dimension, (travelled length of the fluid) (m)
- μ is the dynamic viscosity of the fluid (Pa*s)
- ρ is the density of the fluid (kg/m³)

An example calculation shows what the Reynolds number of the incoming flow might have been:

$$Re = \frac{1.275\frac{kg}{m^3} * 11.18\frac{m}{s} * 5m\ (estimated)}{1.845\ x\ 10^{-6}\ Pa * s} = \mathbf{3.9\ x\ 10^6} => Turbulent\ Flow$$

This makes sense, given the almost chaotic look of the flames' geometry. As the turbulent flow interacts with the flames, they take on the turbulent characteristics as well.

The flames themselves were ignited on a fairly static pool of methanol and salt mixture. An experiment with a similar set-up was performed at the Indian Institute of Technology, Madras, more tightly controlling the dimensions of the pool (or "layer"), also using methanol [2]. Figure 4 is a plot of the results obtained from that experiment.



Results from grid independence study.

Figure 4 - Temperature Profile for Pool Surface [2]

The temperature can be evaluated when a couple assumptions are made; if the oxidation of fuel is assumed to be irreversible and infinitely fast, thermal enthalpy and species concentrations are represented by linear functions of $\mathcal{E}$, and the reaction occurs for $\mathcal{E}$ = *Yo,d (Yo,*$\mathcal{E}$*+ ckYv.w)* [see 3 for detailed variable definitions]. Temperature is obtained by inserting specific values for enthalpy, species concentrations, and specific heats [3].

The important part of this to note is that the temperature profile peaks at around y = 0.75cm, which is nearby the center of the fuel layer. While we did not perform measurements of the flame temperature, it is likely that it was hottest in the center as this theory suggests.

Conclusion:

In order to adequately describe the flow of the fluid, it would be important to take into account much more of the temperature effects of the ambient air mixing with the external (outdoor) air flow. The turbulence induced by the gusts of wind also complicates the system, which makes a mathematical model somewhat impractical. The basic geometry of the fire, however, with most of the flames being largest near the fuel source, and extending upwards while thinning agrees with the standard model that one might observe when lighting a match or lighter.

Suggestions:

Set up a digital timer circuit to take the photographs rather than trying to time it by hand, because it took nearly 100 photos to get the final photo that was used. Not all of the photos were poor (in fact, many were very good, albeit showcasing different flames and flows each time), but it would have been nice to have more uniform photography and fluid flow. Finding a more sensitive digital camera could also be helpful in reducing noise due to the dark background. Also, finding a precise way to limit the incoming air streams could eliminate some of the variability inherent in the system. Finally, paying more careful attention to the parameters of the flow (velocity, etc.) as well as the temperature profile of the flow would allow for a more advanced analysis than what can be seen here.

References

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