Playing With Fire

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Flow Visualization

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Objectives

Fire has always been a source of fascination for humans. It deserves great respect for its destructive potential. It also deserves great reverence for its mysterious beauty. I wanted to capture the beauty in the movement and flow of fire.

Set up

To create the fluid flow, the fire-breather held lamp oil in his mouth and spit it out to create a fine mist, mixing the fuel with air to create the right ratio for combustion. The fire breather spit this jet of air and fuel over a lit torch. When the fuel air mixture passed the torch, it caught fire. The torch was held at arm's length from the fire-breather's body.

A wet towel and fire extinguisher were present on the site for safety. Also for safety reasons, the fire-breathing was performed outside in a large parking lot. The outside location presented a problem as it was a very windy night. The wind carried the flames away very quickly, so only short bursts of fire were possible.

Physical Analysis

In the flow of flame, there is a combination of natural convection and forced convection. Both the still frames and the videos show that the fire flies off the torch almost horizontally, indicating that forced convection dominates. The effects of heat transfer due to natural convection are negligible if the ratio of Grashof number to the square of Reynolds number is much less than 1, $\frac{Gr}{Re^2} \ll 1$ (Cengel and Ghajar, 2007). To test the assumption that forced convection dominates, Grashof and Reynolds numbers were calculated for the flow using Equations 1 and 2 (Cengel and Ghajar, 2007) respectively.

$$\boldsymbol{Gr = \frac{g\, \beta\, (T_s - T_\infty)\, L_c^3}{\nu^2}} \qquad (1)$$

g : gravitational acceleration = 9.81 $\frac{m}{s^2}$

T_s: surface temperature (K)

T_∞: ambient air temperature (K)

β : thermal expansion coefficient (K^{-1})

L_c: characteristic length (m)

ν: kinematic viscosity ($m\ s^{-2}$)

The adiabatic flame temperature (AFT) for lamp oil was used to approximate T_s. AFT assumes complete combustion which is not a bad estimate as the flame was heavily oxygenated by the high winds. An AFT value for lamp oil specifically was not available, so it was estimated by the AFT for n-heptane, one of the main components of lamp oil (Howard, 2010). AFT for n-heptane is 2200℃ (Lohninger, 2011). The ambient air temperature, T_{∞}, was about 16℃ at the time of shooting (Weather Underground). By making the simplifying assumption that the burning air and fuel mixture is an ideal gas, the thermal expansion coefficient β can be approximated by $\frac{2}{(T_s+T_{\infty})}$, the inverse of the average temperature between the surface and the surroundings (where temperatures are in Kelvin). The L_c for the natural convection system was the diameter of the torch, which was approximately 6 cm. Because the fuel air mixture was dilute, the kinematic viscosity of air at the average temperature (1108K) was used. This dynamic viscosity is $1.40*10^{-4}$ m^2/s (Engineering Toolbox).

$$Gr = \frac{9.81\,\frac{m}{s^2}\left(\frac{2}{289\,K+2473\,K}\right)(2473\,K-289\,K)\,(0.06m)^3}{\left(1.40*10^{-4}\,\frac{m^2}{s}\right)^2}$$

Using these parameters, Gr was estimated to be $1.7*10^5$.

$$Re = \frac{V\,L}{\nu} \qquad (2)$$

V: free stream velocity (m s^{-1})

L: characteristic length (m)

ν: kinematic viscosity (m s^{-2})

The forced convection comes from the fire breather's breath and from the wind. The frame rate was 15 frames per second or 0.067 seconds between frames. By looking at still frames, it was determined that a fireball traveled about 3 meters in 8 frames. This gives a velocity of the fireball of about $\frac{3\,m}{8 frames} * \frac{15\,frames}{1\,second}$ = 5.6 m/s. The wind speed at the approximate location and time of shooting in South Boulder on 3/21/11 at about 8:30 pm the wind was reaching gust speeds of about 10 km/hr or 0.28 m/s (Weather Underground, 2011). This means that the free stream velocity was dominated by the fire-breather's jet of breath. This meant that the characteristic length of the system should be taken to be the initial jet diameter of about 1 cm. The same dynamic viscosity of air was used as in the calculation of Gr.

$$Re = \frac{5.6\,\frac{m}{s}*\,0.01\,m}{1.40*10^{-4}\,\frac{m^2}{s}}$$

Using these parameters, Reynolds number was estimated to be about 400.

$$\frac{Gr}{Re^2} \approx \frac{170000}{400^2} \approx 1$$

In order to ignore natural convection, $\frac{Gr}{Re^2}$ must be much less than 1 (Cengel and Ghajar, 2007), however it was estimated to be equal to approximately 1. This indicates that natural convection and forced convection are both important to the flow. Because so many generalizations and assumptions were made, the estimated value of $\frac{Gr}{Re^2}$ = 1 is not associated with a high level of confidence. It is still quite possible that the actual value of $\frac{Gr}{Re^2}$ is less than 1. It is likely that the actual value of Gr is *somewhat* smaller than Re^2; therefore, forced convection is more important though natural convection may not be ignored.

Flow Visualization Techniques

The flow visualization technique employed was simple boundary seeding. The boundary between the flame and the air was visible because the not yet combusted hydrocarbon particles are at such high temperatures that they emit blackbody radiation, some of which we feel as heat and some of which we see as light. Although some light in the video came from nearby streetlights and apartments, the main source of light in the video was the blackbody radiation from the flame.

The video is not very well temporally resolved. Within each frame there is motion blur as each shutter speed was not fast enough to freeze the flow. In addition, for each jet of fire, only 8-10 frames were captured. The spatial resolution in each still is also a problem. The details in the flame cannot be made out because the light is so bright that the entire area of the flame is blown out and white. In order to have good resolution for this flow, a high speed camera would be necessary. At about 600 to 1000 frames per second there would be sufficient time resolution. The shutter speed would be fast enough to freeze the flow and there would be enough frames for the duration of each fire blast that the movement of the flames could be captured. The spatial resolution problem would also be solved because the high frame rate for high speed cameras mandates a small aperture. This would allow for better delineation of the shape of the flames.

Photographic information

The video was filmed with an Olympus FE-340 8.0 megapixel digital camera; however the quality was less for the movie than it is for the images. Each frame was 320 by 240 pixels. It was shot at 15 frames per second. These were the only options the particular camera offered in the video setting. The still photos of the torch alone shown at the beginning and end of the video were shot with the same camera with a shutter speed of 1/400 seconds, an aperture of 5.6, and an ISO of 1600. These settings were chosen to let in a very small amount of light and reduce motion blur. The original still photos were 2048 by 1536 pixels. The ISO was likely even higher for the images shot in video mode, which would explain the grainy appearance. The camera was located about 3 meters from the fire.

The video was edited in iMovie. Each video clip was adjusted to have higher brightness and contrast and fading transitions were added. All sound from the original video was cut out. To create the slow motion effect, the stills were extracted and lined up to show for about 0.3 seconds each, with fading transitions between frames. The contrast of the stills of the torch at the beginning and end of the video were elevates with Photoshop's "Curves" tool. The levels of red were also increased with this tool. The first and last stills were then inverted.

Discussion

The idea has great potential. Unfortunately for safety reasons due to the high wind speeds, we were not able to try the process multiple times to get the best footage. However, I would really like to repeat this set up with a high speed camera. I would like to see better definition in the jet of flames and much better temporal resolution. I do not feel the video captures how beautiful fire is, so much as how *cool* it is (no pun intended). I feel that better quality footage and slower playback speeds would better show the detailed physics of the flame as well as its beauty.

Works Cited

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