Jet Diffusion Flame

The purpose of this image is to photograph the complex phenomena of a turbulent jet flame. An aerosol can of WD-40 was used as the fuel for the jet diffusion flame. The source of oxidizer for this combustion process is just the oxygen contained in the ambient air. The flame is impinging on a wall as seen below in Figure 1. The fuel jet was shot through a match to ignite the fuel and begin combustion. The only source of light for this image is the small amount of moonlight coming in through the open garage door. The very dark garage enhances the image because of the drastic contrast. For safety reasons, the flame is impinging on a cool cement wall in the garage. Furthermore, the image was taken at night so the garage door could be open to allow for proper ventilation.

Figure 1. Jet Diffusion Flame, Re = 8323.

The general flow set up is shown below in Figure 2. This is a top view of the experimental set-up. The WD-40 aerosol can was approximately two and a half to three feet away from the wall. Initially, the fuel jet was shot through a match to initiate combustion, after which the flame was stabilized near the wall. The camera was approximately two and a half feet away from the flame, next to the wall, as seen in Figure 2. Since WD-40 is proprietary, there is little to no chemical or physical properties that are published. The Material Safety Data Sheet lists two of the constituents in WD-40 as 2-Butoxyethanol and Liquefied Petroleum Gas [1]. The MSDS states that 2-Butoxyethanol and Liquefied Petroleum Gas make up approximately 25% and 10% of the weight of WD-40 respectively. Since the fuel is mainly composed of 2-Butoxyethanol, and its chemical and physical properties are published, the fuel will now be assumed to be composed completely of this chemical. 2-Butoxyethanol is a hydrocarbon that is often in the liquid state, and has the chemical formula $C_8H_{16}O_2$. The viscosity of this fuel was found on the web to be 2.9 cP at 25^{o}C [2]. Likewise, the density was found online to be 0.9019 g/mL [3]. The velocity for this flow was found experimentally. The velocity was approximately 2.3 ft/s. Similarly, the diameter of the jet, seen in Figure 1, is approximated to be 1.5 inches. Using these parameters, and the proper unit conversions, the Reynold's number turns out to be 8323. The equation for Reynold's number, and the converted parameter values are below in Equation 1.

$$\mathrm{Re} = \frac{\rho \cdot v \cdot D}{\mu}$$

Equation 1. Reynold's Number

Where ρ is the density, and after a unit conversion the value for the density of 2-Butoxyethanol is 901.9 kg/m^3. Similarly, after unit conversion, the value for velocity v, characteristic dimension D, and the viscosity μ come out to be 0.703 m/s, 0.0381 m, and 0.0029 kg/m*s respectively.

The turbulent jet diffusion flame in Figure 1 was able to be stabilized against a cement wall. Flame stabilization is a very important parameter in combustion, and the design of a combustor. Some examples of common everyday devices that rely on flame stabilization include a furnace, natural gas stove, and a jet aircraft engine. Furthermore, flame stabilization is paramount in the new NASA SCRAMJET engine that traveled at nearly Mach 9.8. Basically, "the attachment of a diffusion flame to a solid or liquid surface is of both fundamental and practical importance because of their relation to flame holding by bodies in combustion chambers" [4]. Flame stabilization, or attachment is theorized to occur when the local velocity of the fluid flow is less than the flame speed. A common feature in flames is a flame base, or edge flame, which attaches to a surface and displays a small dark space in between the flame and the surface. Takahashi et al found that the highest reactivity spot, called the reaction kernel, is formed in a relatively low (<1600K), fuel lean zone of the flame base [4]. Furthermore, the geometric irregularity of the flame base allows for the back-diffusion of radical species, like OH, against the incoming oxidizing stream. The photograph in Figure 1 is not of sufficient quality to show the details of the flame base. But, the stationary reaction kernel located in the flame base "provides a continuous ignition source and sustained stable combustion fast enough to consume the incoming reactants" [4]. Thus, flame stabilization displays a flame base that contains a reaction kernel, and although Figure 1 does not contain sufficient detail to highlight the flame base or reaction kernel, one must exist for flame stabilization.

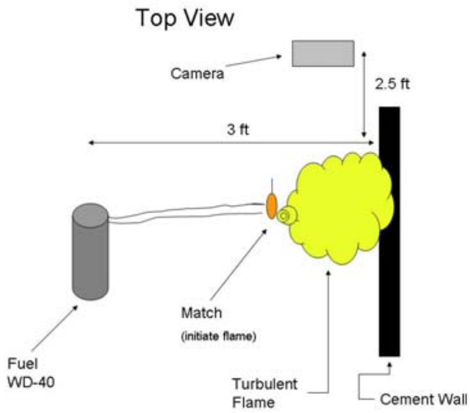

Figure 2. Experimental Set-up

Below is a list of some parameters that give a little more insight into the photograph.

- Size of field of view
    - Approximately ≈ 2.2 ft by 3.6 ft (height by width respectively)
- Distance from lens to object
    - ≈ 2.5 ft
- Lens focal length and other lens specs.

    - Focal length - f = 8.0mm
    - Lens Specs
        - Focal length – 8 to 24 mm
        - Max Aperture – 1: 2.8 to 4.9
- Camera Type
    - Nikon Coolpix 4300 Digital Camera
    - Effective 4 Megapixel Resolution
- Exposure Specifications
    - Aperture – F7.6
    - Shutter Speed – 1/706 sec
    - Focus – Auto Focus
    - Sensitivity – Auto (manual say auto is usually ISO 100)
- Photoshop Processing
    - Original Image Provided
    - Final Image
        - Cropped Image
        - Shadow/Highlight – increase Shadows by 50%
        - Rotate the image about the vertical axis
        - Add Gradient map
        - Paste the images together
        - Included Inverted image
    - Image Sizes
        - Original Image – 2272 by 1704 pixels ≈ 11.5MB
        - Photoshop Image – 1896 by 2640 pixels ≈ 26 MB (including inverted image)

This image reveals the complex nature of jet diffusion flames. Furthermore, the image highlights the mechanism of flame stabilization, in which a flame attaches to a solid or liquid surface. What I like about the image, artistically, is the flow of the flame through the frame. The original image actually mirrors the image in Figure 1. Photoshop was used to rotate the image to another point of view using the rotate about the vertical axis command. The original image shows the flame traveling from right to left. I believe that since I'm so use to following things from left to right, like reading, the image bothered me at first. As such, I rotated the image. Even though the turbulent flame is rather rough and violent, as seen in the picture, the course of the flame through the frame is rather soothing to me. Furthermore, I would like to know if there is a way to image the flame base revealing the stabilization of the flame against the wall. I really appreciate the scientific complexity, yet simple beauty of the turbulent flame. Unfortunately, there is a little motion blur in flame. To improve on this picture, I would really like to capture the flame base, or the zone of stabilization for the flame.

References

[1] Material Safety Data Sheet http://www.wd40.com/Brands/pdfs/msds-spotshot_stain.us.pdf, 12/7/04.

[2] Viscosity http://www.arb.ca.gov/db/solvents/solvent_pages/Glycol_Ethers-HTML/2-butoxyethanol.htm, 12/7/04.

[3] Density http://www.atsdr.cdc.gov/toxprofiles/tp118-c3.pdf, 12/7/04.

[4] Takahashi, F., Schmoll J. W., et al. **"Attachment Mechanisms of Diffusion Flames"**, 27th Symposium on Combustion, Vol. 1, pp 675-684, 1998.