Team Project 2[1]

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The propagation and behavior of spray flames was examined by using a 35mm camera to capture images of the flames generated when a small spray of alcohol droplets was ignited. The spray was generated with an ordinary handheld spray bottled commonly used to wet the leaves and flowers of houseplants. The alcohol in the bottle was sprayed into the flame of a small candle and the resulting "puff" of flame was recorded.

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The images were created in order to observe the fluid physics that are occurring when a spray flame is created. In this instance, the transient nature of the flames photographed made capturing decent images quite difficult because not only did one have to deal with the inherent difficulty of photographing flames but also there was only a short instant during which the flame existed. Thus, quite a few images consisted only of the small candle flame used as an igniter, the spray flame having already passed.

The setup for these images was generally simple, with most of the focus upon safety rather than the generation of the spray flame itself. Generating a spray flame is quite easy; one merely needs to spray flammable liquids into an extant flame to create a large, somewhat dangerous "flame thrower". Spray flames of this sort are commonly associated with pressurized fluids in metal spray cans (i.e. hairspray or spray paint); unfortunately, this type of flame can heat the liquid contents of the can, causing them to vaporize and exert tremendous pressures on the walls. This can result in a catastrophic explosion when the can ruptures and the vapors ignite. Obviously, it is in the photographer's best interest to avoid such a situation. Thus, a small spray bottle, like those commonly used to mist water onto houseplants, was used to generate small puffs of flammable vapor. This ensured that the flame existed only for only a second or two, thereby preventing any heating of the bottle's contents and allowing time between flames for the contents to cool in the unlikely event that any such heating did occur. The second benefit of the hand spray bottle is that the bottle itself is made of plastic; this prevents the bottle from acting as a strong pressure vessel that results in the explosion seen with spray cans as well as eliminates the possibility of metal shrapnel that can occur with spray can explosions. Also, any significant heating of the hand spray bottle would cause it to melt, a phenomenon which can be observed be the experimenter before an accident can occur.

To add a final element of safety to the setup, the ignition flame was provided by a candle and the trigger of the spray bottle attached to a string, allowing the experimenter to pull the string and create small puffs of flame while the remaining safely distant from the flame apparatus. The spray bottle was filled with one of the “flaming spirits”, 190 proof Everclear alcohol, and was placed approximately 2 inches from the candle flame in order to ensure combustion occurred before the spray of alcohol had dissipated too much.

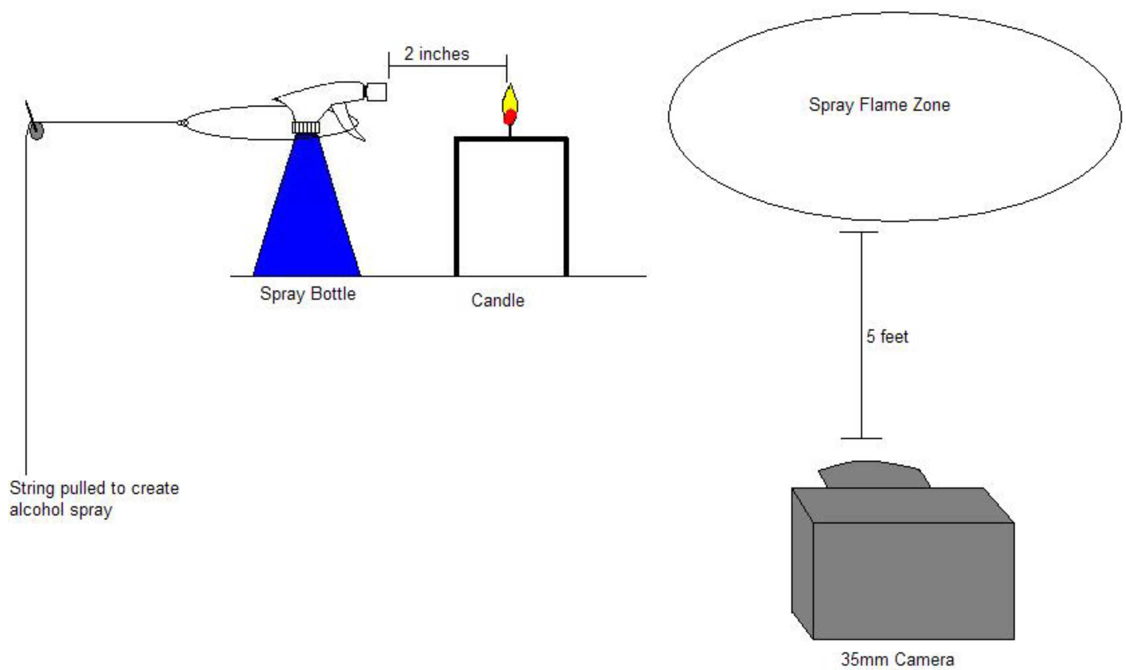

Figure 1: Spray flame "generator" setup and camera positioning.

The size of the generated flame was relatively small, limited by the amount of fuel released when the trigger of the spray bottle was pulled. The resulting flames existed for about one second and traveled approximately two feet in that time due to the fuel droplet velocity imparted by the action of the spray bottle. Also, some slight upward drift of the flame was observed due to the heating of the air. The actual shape of the flame itself consisted of balls of flame approximately one foot in diameter although the photographs generated show numerous shapes that changed too quickly for the eye to process yet were stable enough to be imaged effectively.

The physics of the spray flame combustion are quite complicated, as Lemaire et al. stated "Multi-phase turbulent flames typically involve a large set of coupled phenomena such as atomization, dispersion, vaporization, molecular, and turbulent mixing, and chemical reactions." Our spray flame clearly falls into the area of turbulent flows because we can quite readily observe a vortex ring the submitted image. First, however, it is important to understand how a spray flame combusts, the specific chemical interactions extant in the combustion are interesting but are not necessary to understand the basic physics of how the burning occurs.

In order for our spray of fuel to combust, the fuel must reach that high temperature at which combustion may occur. The small candle flame was used to catalyze the combustion reaction by raising the temperature of the droplets that passed near the flame. Once these droplets were heated and began to combust, the heat from their reactions in turn heated the "shell" of droplets surrounding them, thereby initiating the combustion of the next layer of droplets. This process occurs extremely quickly so that the entire spray of fuel combusts in a matter of moments. The existence of turbulence in the spray of fuel droplets helps encourage mixing, thereby exposing more droplets to combustion initializing heat in a shorter period of time. This is why the design of spray nozzles for diesel engines aims to increase in-cylinder flame swirl and turbulence; the adding mixing effects help speed combustion and result in a desirable faster overall fuel burning time.

The main evidence of turbulence in the generated image is the mushroom cloud shape of the flame; this shape exists due to a vortex generated by the turbulent flow of the fuel droplets. Lemaire et al notes "Vortex/flame interactions are often considered to typify elementary processes of turbulent combustion." As the droplets are sprayed out of the bottle, the spray expands radially and slows due to drag forces from the still air into which it was sprayed. If the trigger of the bottle is pulled slowly, the initial spray will expand radiallly and slow while more spray continues to travel forward and fill the area left behind by the droplets that expanded outward. As this flow continues, the slowed outward droplets will be pulled back towards the central shaft of droplet flow as other air is entrained in the flow of that central shaft. The slight upward motion of the flame that is observed in the photograph is simply due to the rising of the air heated by the flames.

Another very interesting aspect of the spray flame is the behavior of the droplets themselves. The droplets do not simply burst into flame and disappear; rather there remains a droplet of liquid fuel that is suspended inside of a shell of vaporized fuel. It is upon this shell of fuel vapor that the combustion reaction feeds; the heat from the reaction slowly vaporizes the sphere of liquid fuel and feeds it to the flame. This behavior helps explain the colors observed in the flame, the blue color occurs near the beginning of the flame when oxygen is plentiful and the combustion reaction can occur stoichiometrically, generating the most heat and radiating in a blue color. The yellow color of the remainder of the flame occurs because of the phenomenon known as pyrolysis; as the fuel droplet burns, the droplet of liquid fuel is shielded from the air by the shell of vapor and flame and once all of the combustible fuel has been evaporated and burned some carbonized soot remains behind. These soot particles are heated by the flames and radiate yellow light, thereby giving the flame its' characteristic yellowish color.

The visualization technique used is a combination of boundary marking and particle seeding. The burning fuel droplets and pyrolized particles act as markers to help define the boundary of the flames. Because the boundary markers are radiating particles, the layers of flame are opaque, allowing one to see into the different layers of the ball of flame. The only lighting for these photos came from the flame itself; the photographs were taken at night in an area shielded from ambient light. While this did make setup and initial focusing difficult, it allows the attention of the image to be on the flame itself without any distracting elements.

The camera used was a Pentax ZX-5N with a 28mm to 200mm lens set at about 50mm and the shutter speed was set at 1/250th of a second with an aperture of f/5.6 and the film used was 400speed Fuji Superia X-tra. The camera was hand held with the subject approximately five feet away resulting in a field of view of about four feet by three feet. A minimal amount of editing was done with Adobe Photoshop in order to crop the photo to its' current dimensions and the Sharpen filter was used to enhance the definition of the flame edges.

The final image is more impressive than I had hoped, photographing such a transient subject in low-light conditions is very difficult, I was not sure when I took the photos that it was possible to have a fast enough shutter speed to eliminate motion blur while also allowing sufficient light to create the image. Obviously the black background of the photo is washed out due to the photo processing attempting to brighten the photo but I believe this could be eliminated by someone with more skill in Photoshop or possible by having the photo redeveloped. Overall, however, I am happy with the image because the vortex swirl is quite evident and the photo is devoid of too much motion blur.

References:

Lemaire et al. Unsteady Effects on Flame Extinction Limits During Gaseous and Two-Phase Flame/Vortex Interactions. *Proceedings of the Combustion Institute*, v 30, n 1, January, 2005, p 475-483