MCEN 5151 – Flow Visualization Matt Phee

Team Project 1 Report

This image is my submission to the Team Project 1 assignment. Conception of this experimental setup began when our team was made aware of an upcoming high-speed camera demonstration by Vision Research Inc. Desiring to make use of the impressive Phantom v710 camera, we resolved to choose flows that would most benefit from high-speed capture. That is, we chose flows that happen on very small time-scales. My flow, shown in Figure 1, consists of a line of matches lighting in series. The images that constitute this time-lapse span only 5 milliseconds (ms) as the final match head ignites. The specific phenomenon I wanted to capture is the interferential behavior of the transient, buoyant plume from the newly ignited match head with the buoyant gas from the steadily burning matchsticks.

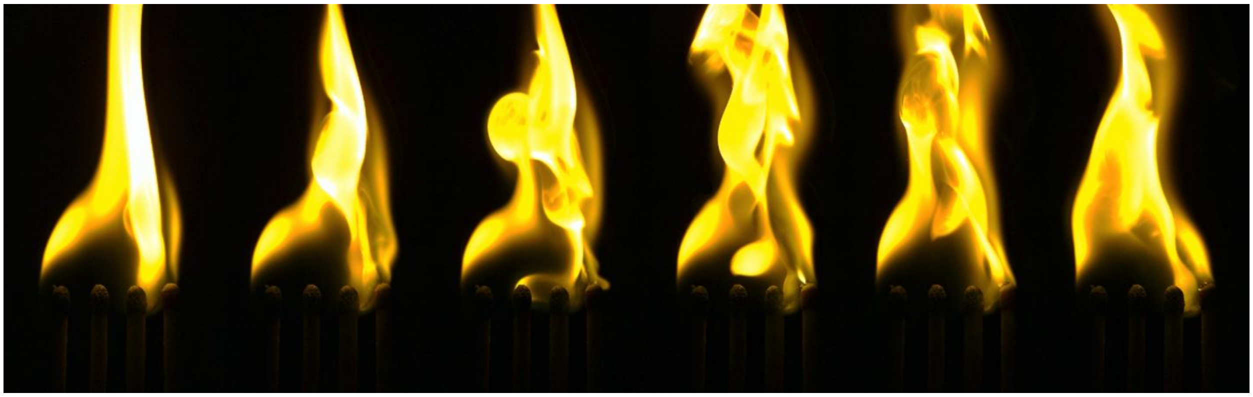

Figure 1: Time lapse compilation of strike-anywhere match ignition and interferential buoyant plumes over ~5 ms

The only novel component used for this experiment was a small aluminum block, approximately 2 x ½ x ¼ inches in size. Ten holes of 1.5 mm diameter were drilled 1 cm into the block at 1.5 mm intervals using a drill press. For this experimental run, four strike-anywhere matches were inserted into four adjacent holes. The assembly was placed in front of a black backdrop. Finally, the Vision Research Phantom v710 high-speed camera was positioned with its lens approximately two feet from the assembly. Frame size, focusing, and exposure settings were specified by the Vision Research technicians using proprietary software. The experimental apparatus is shown in Figure 2. At this point, the procedure for achieving the depicted flow was extremely simple. An additional match was used to carefully ignite the leftmost match in the assembly. Ignition proceeded down the row of matches at approximately one match per second, a rate dictated by the degree of gas expansion, ignition temperature of the match head chemical mixture, and spacing between matches. All lights were turned off in the room allowing for the best achievable flame visualization.

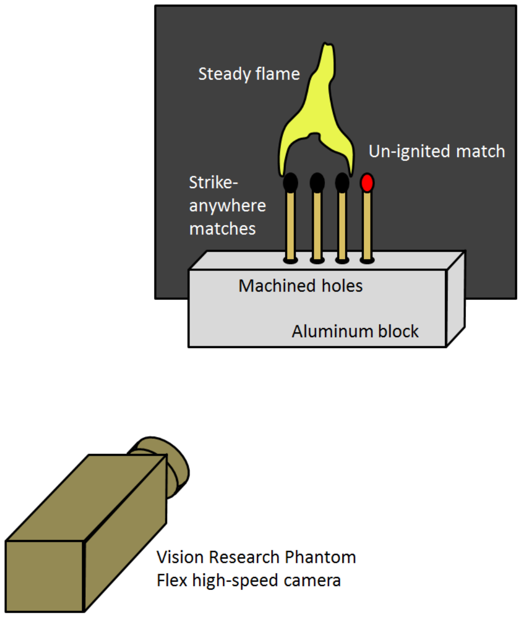

Figure 2: Diagram of experimental apparatus

The primary fluid phenomenon under scrutiny here is interferential behavior of buoyant plumes rising from the point of combustion. This phenomenon is actually a combination of three thermodynamic fluid processes: 1.) combustion of match head chemicals, 2.) rapid adiabatic expansion of hot product gases, and 3.) buoyant rising of gas parcels. Combustion is simply "a chemical reaction during which fuel is oxidized and a large quantity of energy is released" [1]. The chemical makeup of a strike anywhere match head is primarily composed of phosphorus sesquisulfide P_4S_3 and potassium chlorate $KClO_3$ [2]. In this case, P_4S_3 is the fuel and $KClO_3$ provides oxygen. Products of combustion include potassium chloride, sulfur dioxide, and phosphorus pentoxide. Because $KClO_3$ provides all necessary oxygen, air is not needed for the initial combustion to occur. This of course changes when the flame proceeds to burn the matchstick which is nothing more than wood coated with a thin layer of paraffin wax. The match head combustion reaction is represented by the species-balanced equation (1).

$$3P_4S_3 + 16KClO_3 \rightarrow 16KCl + 9SO_2 + 6P_2O_5 \tag{1}$$

The heat released from combustion raises the temperature of product gases very quickly. If the system is considered to be only those substances that are either reactants or products of combustion and assuming no net heat transfer occurs with the surrounding air, this is considered an adiabatic process, and the final temperature is called the adiabatic flame temperature [1].

Now, of course, the assumption that combustion is adiabatic is not a reasonable one here. The hot exhaust gases will actually begin transferring heat immediately to the surrounding air. Thus, the actual temperature T of the flame is considerably lower than the theoretical T_{af}. Using a digital thermometer, our team measured a steady flame temperature of roughly 900 K. Nonetheless, as pressure constraints have not been placed, the high temperature gases will undergo rapid adiabatic expansion. This can be represented ideally by the ideal gas law (2). Real gases will not behave precisely according to this equation, but it allows for a quick qualitative understanding of what is going on.

$$PV = nRT \tag{2}$$

As (2) shows, when the temperature T of a gas is raised at constant pressure P, the volume of the gas V must increase proportionally. Now that it has been expanded, the gas is far less dense than the surrounding air. We are all familiar with the concept that "hot air rises". The reason for this is a net upwards force that is felt by a hot parcel of air. Let's first consider a force balance for an arbitrary volume of air in air of uniform temperature. Based on hydrostatic pressure laws, the net force on the volume from pressure alone will be upwards as air below the volume is at a slightly higher pressure. When the gravitational force on the volume of air is considered, the net overall force acting on the volume is zero. If however the density of the volume of air is reduced, the gravitational force per volume of air will decrease allowing the net upward force to accelerate the parcel up. This is essentially what happens during buoyant rising [3]. A simpler way to think about this is to define the upward buoyant force $F_{buoyancy}$ exerted by a fluid on a body as the product of the fluid density ρ_{fluid}, gravitational acceleration g, and volume of the gas parcel V_{parcel} (3).

$$F_{buoyancy} = \rho_{fluid} g V_{parcel} \tag{3}$$

The only force countering $F_{buoyancy}$ is the downward gravitational force [4]. The resultant net upwards force on a parcel of expanded hot gas can be reasoned either of two ways. First, know that a constant mass of gas will feel a constant gravitational force regardless of its density, but $F_{buoyancy}$ acting on it will increase as ρ_{parcel}decreases and V_{parcel} increases. Alternatively, if we consider a constant volume of gas, we recognize that V_{parcel} and $F_{buoyancy}$ will remain constant, but the gravitational force exerted on a less dense volume of gas will decrease. Ultimately, the result is a net upwards force on, and therefore an upwards acceleration of, the hot gas parcel. Because product gases that reach such high temperatures emit electromagnetic radiation with wavelengths in the visible spectrum we observe the rising gas as a flame.

In this experiment, once all the fuel on the match head has been combusted, the flame becomes relatively stable as the wooden matchstick is slowly burned. My image shows more than a simple, stable flame. It shows that, as the fourth match head ignites over the course of 5 ms, a plume of exhaust gas rises more rapidly than the steady flame gas, overtaking and disturbing it. The most reasonable explanation for this is the fact that the chemical constituents of the match head burn at a higher temperature than the wood sticks. As the chemicals ignite, the parcels of gas produced are relatively hotter than the steady flame gas. Still governed by equations (2) and (3) respectively, adiabatic expansion and buoyant lifting for this parcel both happen at an increased rate. Additionally, the dynamic viscosity of a fluid increases with temperature. The apparent difference in viscosity between steady flame gas and plume gas may contribute to how cleanly the plume is able to punch through the existing flow without mixing.

Despite the high temperature and quick velocity of the gas, this is a laminar flow. I have approximated its Reynolds number. For simplicity, I assume the product gases are air and that their viscosity at atmospheric pressure and 900 K is $\mu = 4.04x10^{-5}\ kg/m \cdot s$ [5]. The density of air at these conditions is approximately $\rho = 0.392\ kg/m^3$ [5]. For this flow, I estimate the velocity and characteristic diameter of the stream to have been $V = 2.268\ m/s$ and $D = 1.5\ mm$ respectively. Calculation of the Re is shown in (4).

$$Re = \frac{inertial\ forces}{viscous\ forces} = \frac{\rho V D}{\mu} = \frac{(0.392\frac{kg}{m^3})(2.268\frac{m}{s})(0.0015\ m)}{4.04x10^{-5}\ kg/m\cdot s} \approx 33 \qquad (4)$$

$Re = 33$ is a reasonably low Reynolds number. It is not low enough to consider a flow within Stokes regime, but it is still well within the confines of laminar flow. Even though the image appears to be chaotic, the clear and traceable flow lines of the plume and flame provide visual confirmation that the flow is quite laminar.

Some fluids, like water and air, lack sufficient pigmentation to make flow visualization images apparent. Flows involving these fluids are often seeded with particles or dyed with fluids to make their physics more clear. The hot expanding gas that results from combustion requires no such seeding. The combustion reaction produces new chemical species as wells as heat. The heat rapidly increases the temperature of exhaust gases and causes them to emit electromagnetic radiation with wavelengths in the visible light spectrum. This is what we call a flame, the color of which is dictated by the gas species produced. Flames produce light and so do not need to be externally illuminated. Moreover, flames are easier to see in the dark. In cases of combustion flow like this, it is not the flow that must be altered but the surroundings. Light sources must be snuffed and the surroundings made dark so that emitting flows can be seen. We removed all perceivable light from the experimental surroundings by moving to a room with no windows and turning off all lights. The flame provided the sole source of light giving us fantastic contrast with the black background and surroundings. Such clear visualization (both spatially and temporally resolved) in low light conditions was only possible due to the fantastic properties of the Phantom v710 camera.

The primary photographic technique was high-definition, high-speed video photography. My group and I made use of the remarkable Vision Research Phantom v710 camera to capture our flow with exceptional clarity. The field of view was 4in x 2.5in and the depth of field extended roughly 1 in behind the subject, though the backdrop was not visible. The camera lens was positioned about two feet from the subject. The original video was captured at 5000 frames per second and 1 Megapixel (1280 x 800 pixels) resolution. Exposure time of each frame was 189.54μs. Other camera settings like aperture and sensitivity were not specified. The video was recorded as a .cine file, the proprietary format used by Vision Research products. Using the corresponding proprietary Cine Viewer 675 program, I carefully located the frames I wanted and exported them as 1280 x 800 pixel .tiff images. Cine Viewer 675's image processing options are limited, but I was able to adjust the hue of the images before exporting to make the subtleties of the flames more apparent. Using Adobe Photoshop Elements 8©, I cropped each of 6 stills and assembled them into a single .tiff file of 2183 x 680 pixels. Finally, I increased contrast very slightly. Figure 3 shows a side-by-side comparison of an original .tiff capture as exported from Cine Viewer 675 and the final photo compilation I submitted.

Figure 3: Before and after comparison of image post-processing

Overall, I am pleased with my work. From an experimental standpoint, I am glad we chose a simple flow as using a new photographic technology proved quite time consuming for our group. I am thrilled with the performance of the camera at extremely low light conditions. I recognize that ignition captures as clear and deliberate as these would not be possible without high-end technology. I believe I effectively captured my target flow – the ignition of a match and the resulting perturbations in a previously steady flame. I stand by my choice to export high-speed video capture as still frame images. I enjoy images that are able to take a fast action and freeze it in time, and to this end I believe I was successful. In the future, I would like to work more with the .cine footage I have and produce a complementary video for this flow.

References

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[5] Wolfram Alpha™ Computational Knowledge Engine. 2011. http://www.wolframalpha.com/.