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Flow Visualization
Professor Hertzberg
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Team Image 1 Report

For the first team assignment in Flow Visualization: A Course in the Physics and Art of Fluid Flow, my team decided to explore the capabilities of high-speed cameras. The idea originated because one of our group members builds and launches large model rockets as a hobby and he wanted to photograph a rocket engine igniting and burning using a high-speed camera. Based on this original idea we made a list of flow phenomenon that could only be fully revealed using a high-speed camera. In addition to the rocket engine, we wanted to film a row of matches igniting, water boiling in a beaker, an electric mixer mixing pancake batter, and an egg cracking and dropping into a hot pan. We were originally planning to use the high-speed camera available in the Durning Lab but instead we were able to use the Phantom v710 high-speed camera demoed by Vision Research. Because time was limited on the day of the demo we were only able to film the ignition and burn of the rocket engine and a row of matches igniting. However, using the Phantom v710 allowed us to capture much more detail than the Durning Lab camera would have provided. I ended up submitting a high-speed video of the row of matches igniting. Two of my teammates utilized the match video in different ways while the other two submitted a still image and a high-speed video of the rocket engine igniting and burning.

To capture the high-speed footage we machined a small aluminum block with holes drilled in one side to position the matches. A Solidworks model of the aluminum block can be seen below in Figure 1. To give a sense of scale each match in the image is about 1/8" in diameter. The flow apparatus of the setup is somewhat hard to define. It could be defined as either the head of the match itself or the atmosphere of the room in which the matches are burning. However, both contribute to the physics of the flow so I will call the system composed of the match head and the surrounding atmosphere the flow apparatus.

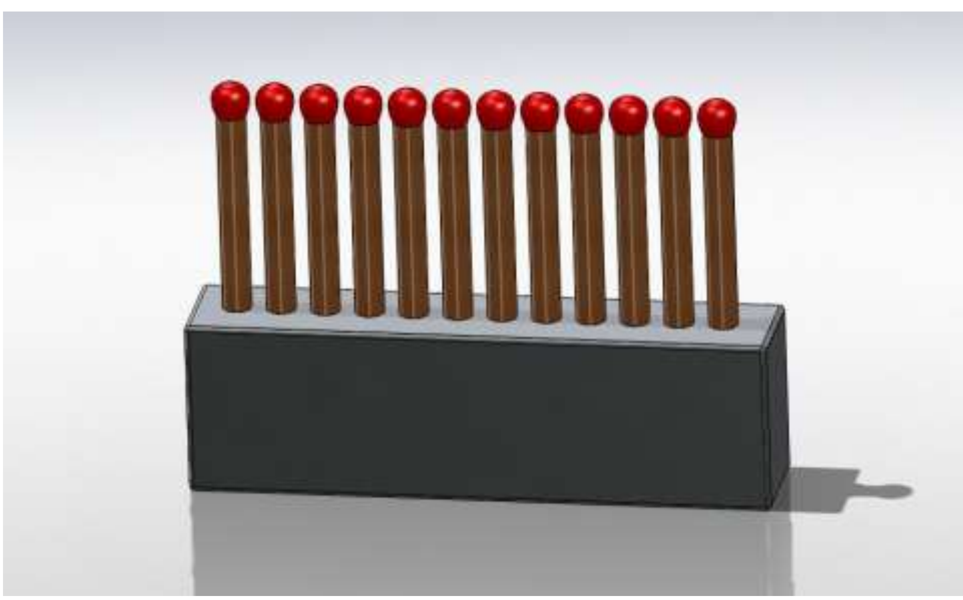

Figure 1

Now that we have defined the flow apparatus we can discuss the flow itself. It is important to note that the flow itself is not the flame. The flame is just the flow visualization technique. The flow itself is simply heated air that is being forced upward by buoyant forces because it is much less dense than the cooler air around it. Because we know the frame rate of the video and the approximate size of the match heads in the video we can get an estimate of the speed of the flowing air within the flames. This value can then be used to estimate the Reynolds number of the air. Reynolds number gives the ratio of inertial forces to viscous forces acting on a fluid. It is defined as:

$$Re = \frac{UD}{v}$$

Where U = mean fluid velocity, D = hydraulic diameter, and v = kinematic viscosity. The kinematic viscosity of air at 1300 K (about the temperature of the flames) is 182.1×10^{-6} m^2/s. Using the physical size of the image and the match heads we can estimate the hydraulic diameter for the flow to be about 1 inch or 0.0254 m. Using the frame rate of the video and the size of the match heads I estimate the mean fluid velocity to be about 1 m/s. Plugging in the numbers we get the Reynolds number for the flow above the match heads to be approximately 140. Such a low Reynolds number indicates the flow should be laminar. However, the video clearly shows turbulent flow. I believe this discrepancy comes from the fact that the only good way to measure the fluid velocity is by tracking and timing the movement of small particles that are launched off the match head. These particles may be traveling much slower than the surrounding air and therefore the Reynolds number value could have been much too low.[1]

I believe the most interesting phenomenon revealed by the high-speed camera may be the way in which the flame and flowing air billow and rotate. This can be explained by thinking about the forces acting in the fluid. The fluid rotates and billows because there are unbalanced forces acting on parcels of air within the flow. Hot and less dense air rushes upward through the center of the flow while colder air away from the center of the flow is not moving as fast and pushes downward on the other side of the air parcel. This is illustrated in Figure 2. These unbalanced forces push the parcels of air upward while at the same time producing a moment on the air parcel causing it to rotate.[2]

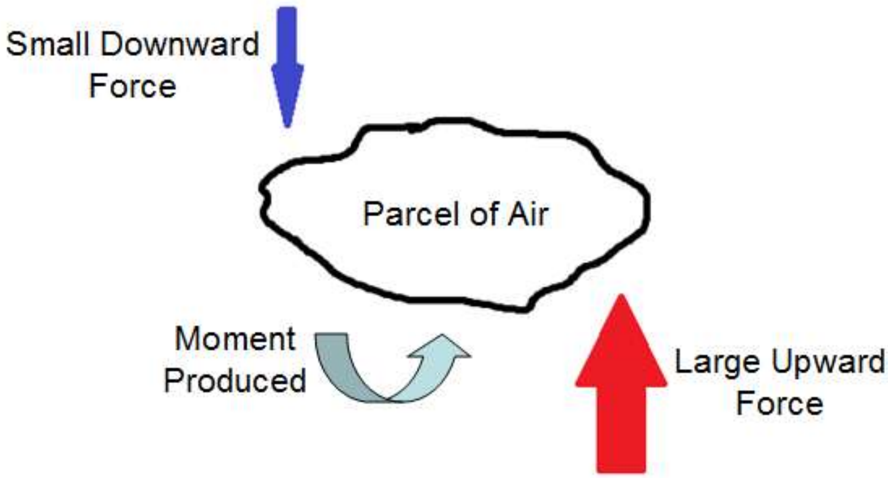

Figure 2

As discussed above, the visualization technique used to photograph the flow is simply the flame itself. No external lighting was required because the light emitted by the flames can best be captured by the high-speed camera when the rest of the room is completely dark. We were careful to use strike anywhere camping matches because we felt that they would emit more light than matches from a matchbook.

Six still images from my final 36-second video can be seen below in Figure 3. Each capture represents about a five second jump in the video starting from a playtime of five seconds and ending at thirty seconds. These six still images fairly accurately illustrate was it happening in the actual video. The size of the field of view in the video is about 6 inches wide and 4 inches tall. The distance from the lens of the high-speed camera to the matches was about 3 feet. The high-speed camera used to capture the high-speed video was a Vision Research Phantom v710. This is an extremely powerful high-speed camera. It is capable of taking up to 1,400,000 pictures-per-second at its lowest resolution and 7,530 fps at a high-definition resolution of 1280 by 800 pixels. Because the camera was demoed by Vision Research and was only on campus for several hours I was unable to obtain the exposure specifications of the camera. I do know that we were shooting at 5000 fps. This frame rate seemed adequate to capture all of the flames movements. Because of the proprietary format that the high-speed video was encoded in and the large file sizes generated by high-speed video, my team had difficulty editing our videos. I have not made any modifications to my submitted video but I may do that before the semester ends.

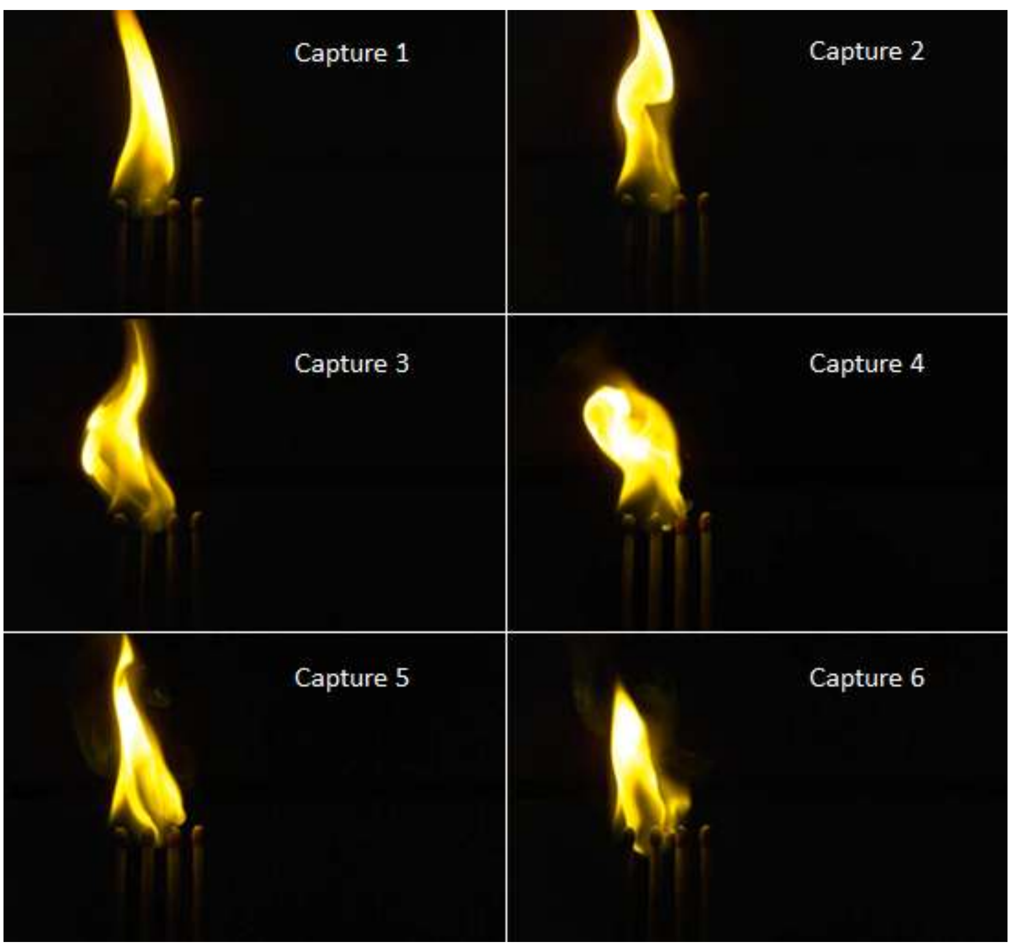

Figure 3

The video reveals in great detail the flow and flame patterns above a burning match head. The physics of the initial match head ignition can be seen in great detail along with the movement of the flames themselves. I like the fact that the high-speed camera allowed us to see details within the flame that could not have been seen otherwise. Because of the high-speed camera the fluid physics are shown extremely well. If time had allowed on the day of shooting I would have liked to further adjust the settings on the high-speed camera to try and capture the blue flame below the match heads. I also wish I could have edited the video. To develop this idea further I would like to burn other substances in front of the high-speed camera; things with more vigorous flame activity or perhaps chemicals that burn in different colors. I'm sure the high-speed camera would reveal things that couldn't be seen otherwise.

Works Cited

[1] "Flame." *Wikipedia, the Free Encyclopedia*. Wikimedia Foundation, Inc., 10 Apr. 2011. Web. 15 Apr. 2011. <http://en.wikipedia.org/wiki/Flame>.

[2] "Reynolds Number." *Wikipedia*. Wikimedia Foundation, Inc., 26 Jan. 2011. Web. 09 Feb. 2011. <http://en.wikipedia.org/wiki/Reynolds_number>.