Team Project II: Report

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Introduction

For this project, my objective was to focus on the physics over the artistic aspect of fluid flow and capture a common phenomenon which happens to fast for the human eye to see. I wanted to image an object involving fire and one thing that I have always thought interesting was watching a match ignite, so I decided to use a high-speed camera to film this phenomenon. My intent was to capture the physics behind the phosphorus on the tip of the match igniting, but after viewing the video I realized that I had captured another physical phenomenon, the Kelvin-Helmholtz instability. I took a variety of high-speed videos with different lighting and frame rates and ultimately choose this video because it provided the clearest picture of the flame.

Setup

The setup for this video involved making a wood frame with a hole in the bottom board to hold the match and a swinging arm attached to the top board to strike the match, this is shown in Figure 1. The frame and swinging arm were built from 2x2 inch pine boards with a 2x4 inch pine board base. To get the swinging arm to ignite the match without breaking it, I had to round the end of the arm so that only the center of the arm would hit the match. The type of match used for this video was a safety match and must be struck against a specially coated surface which is usually found on the side of match box. I cut the coated surface from the match box and stapled it to the rounded end of the swinging arm. The frame was 18” tall and 22” wide, I chose to make it this big to ensure that the top and sides of the frame would remain out of the video.

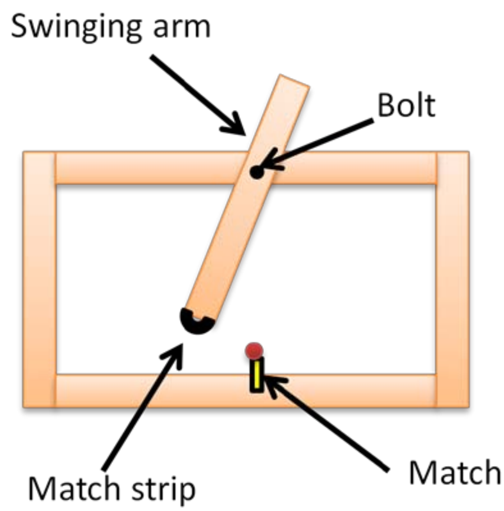

Figure 1: Setup for capturing a high-speed video of a match igniting

Background

Matches consist of a handle made from pine and the lighting end known as the "head." The type of match used in this video is known as a safety match and it achieves its safety from the separation of the reactive ingredients between the match head and the specially coated striking surface. The match strip or striking surface is typically composed of 25% powdered glass, 50% red phosphorus, 5% neutralizer, 4% carbon black, and 16% of a gelatin binder. The match head typically consists of 45-55% potassium chlorate, 20-40% siliceous filler, a neutralizer (ZnO or $CaCO_3$), with a little sulfur and starch, diatomite, and glue. Striking the match causes the phosphorus and chlorate to mix in a small amount which creates a phenomenon similar to the explosive Armstrong's mixture which ignites due to friction between reactive agents. The reactive agents of this type of match are the phosphorus of the striking surface and the potassium chlorate of the match head [1].

Almost immediately after the match is struck, the flame begins to flicker this has been characterized by multiple researchers to have a typical frequency around 10 Hz [2, 3]. The flickering is caused by the Kelvin-Helmholtz instability which is present when there is a sufficient velocity difference across the interface between two fluids [4]. The unstable interface between the high velocity hot product gases in the flame and the cold ambient air causes buoyantly accelerated vortices to form. The vortices are created by the heat released at the flame front which forces the burnt gas to flow predominantly in the radial direction and the pressure field associated with the rotating vortex motion that opposes this flow. The competition between the radial gas flow and the pressure field causes the flame to flicker [2, 3]. The flickering match flame produces a color temperature typically around 1,500 K [5].

Visualization Technique

The image was taken in an indoor environment with an ambient air temperature of 72°F. The match was cut to length of 2" to fit the frame I built for the setup. The high-speed camera was set up directly normal to the frame setup and the lens placed 20.5" away from the match, which was the closest distance I could get to the match while keeping the camera in focus. The match was illuminated with a 500W halogen lamp placed one foot away at a 30° angle from the front of the frame and angled downward at 45° so that the center of the projected light was directed at the match. The flow of the burnt gas is very fast and erratic and takes about 2.3 seconds to consume all the potassium chlorate on the match head.

Photographic Technique

This video was shot using an Olympus i-Speed 2, high-speed video camera, at 1000 fps, an ISO of 400, and a resolution of 800x600 pixels (0.48MP). The lens of the camera was placed 20.5" away from the match and no zoom was used. Using this distance and the scale of the video frame of approximately 4.25" the field of view was calculated with equation 1 as,

$$FOV = \tan^{-1}\frac{Y}{X} * 2 = \tan^{-1}\frac{4.25/2}{20.5} * 2 = 19.2°. \quad (1)$$

The video originally had decent contrast, but artificial artifacts were present in the black background. To fix this, I edited the contrast of the video using Sony Vegas Pro 9.0 to darken the black background, which got rid of almost all the artifacts, and brought out the brightness of the flame. I also cropped the video down to 520x410 pixels to center the match in the video frame and reduce the wood showing from the base of the setup. The video is comprised of three segments all of which contain the slight contrast adjustment and the cropping mentioned previously. I felt that the original video was too long to include multiple segments with different effects, so for the first segment I reduced the length of the video by half by doubling the playback speed. In the second segment I chose to play the video in reverse at four times the original speed. For the third segment I replayed the video at four times the speed with the colors inverted. The last two segments were included to help reveal other physics that might not be seen in the commonly viewed forward playback with no effects added.

I used Handbrake (a video encoder) to reduce the size of the video from 1.8GB down to a more manageable sized file of 2.3MB in a universal mp4 format that is compatible on all computers. After all the editing was done the file was around 12MB, so I used Handbrake again to reduce the file size down to 6.3MB so that it could be easily transferred over the internet. The final video file has a bit rate of 378 kbps and a frame rate of 29.4 frames per second.

Conclusion

This image reveals the Kelvin-Helmholtz instability that is seen in the flicker of a match flame. This effect is seen by the fluttering that occurs on the edges of the flame which is caused by the unstable interface between the high velocity hot product gases in the flame and the cold ambient air. This causes buoyant vortices which result in the flickering of the flame. My favorite aspect of this high-speed video is the detail that is brought out in the interior of the flame where you can see the gas flowing by the waves of light moving through flame. I dislike that I had to provide lighting to get a detailed image of the flame even if the shutter speed was decreased to 500 fps. I feel that the light was required because the camera was too far away from the match for light to adequately get the sensor in the camera. To make this video better, I would choose to use a different high-speed camera or lens that allows me to get closer to the match or can capture light better from 20.5” away. It would also be interesting to record different types of flame setups burning different fuels to compare their differences. I felt that this project accomplished my expectations, I was introduced to a new type technology and I learned how to edit videos for the first time.

References

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