Group Project #1 Report

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Flow Visualization: The Physics and Art of Fluid Flow

Students were given the opportunity to work with teams in order to observe a phenomenon that may not be easily captured by a single person. A few members of Team Zeta decided to work together to capture the phenomenon of combustion. In order to properly display and view combustion, the team used a high speed camera and chose to produce a video instead of a single image. The following report discusses the physics and art of the combustion of gas phase butane through a rubber balloon.

To properly ignite the balloon, a few different attempts were used. For my video, a knife was covered in gasoline, and lit on fire with a lighter. The knife was then used to pour the flaming gasoline onto the balloon, which burned through the rubber surface, initiating the combustion. The knife was held at about 1 inch above the balloon, and tilted to allow the gasoline to drip onto the balloon. The experiment was conducted on plywood with a black wood backdrop. One person held the flaming knife with a fire resistant glove, while the other person operated the camera. The balloon was an approximate 3 inches across and 5 inches long.

Although gasoline was used to ignite the butane filled balloon, the amount used limited its effect in the explosion. The relative volume of butane was significantly higher than that of the gasoline, so the gasoline was able to burn off almost completely before the explosion occurred. The rubber balloon exploded off, but did not ignite until after complete combustion of the butane. Therefore, the explosion analysis will be simplified by dealing with only butane, oxygen, and the byproducts of that combination. Equation 1, seen below, shows the complete combustion of butane, C_4H_{10}, with oxygen, O_2.

$$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O \qquad (1)$$

This formula assumes that plenty of oxygen is available in the environment. Since the experiment was conducted outside, this assumption is made for the experiment as well. The combustion byproducts are carbon dioxide, CO_2, in addition to water. Weighing the balloon before and after filling it with butane indicated that the butane weighed about .1 g. The volume was an estimated 33 in^3, so the density is then calculated as .003g/in^3.

The balloon combustion was an extremely captivating phenomenon. The gasoline burns through the balloon surface, and leaves the butane exposed to the atmosphere. The butane slowly expands, creeping up to the gasoline on the knife, initiating the explosion. The flames then travel in all directions outward from the center.

The flames also assume a variety of different shapes and sizes. These correspond to different concentrations of the butane gas. At a higher concentration, the flames appear brighter. Following a bright region, one is able to note specific fluid flow patterns that occur in the gas dispersion. The active forces that occur on these sections of fluid are the force of gravity, pulling the plumes toward the earth, and the buoyancy force, equal to the weight of the displaced fluid, which in this case is air. The force of gravity is equal to the multiplication of the gravitational constant, 32.2 ft/sec^2 times the mass of the fluid. The equation for the buoyancy force is seen below in equation 2, where g is gravity, m is the mass of the fluid, ρ_f is the density of the surrounding fluid which is air, and V, which is the volume of displaced fluid [1].

$$F_{Buoy} = \frac{2gm\rho_f V}{m+\rho_f V} \qquad (2)$$

Although it is difficult to calculate the buoyancy force accurately due to the unknown size of fluid pockets, it is easy to estimate the relative sizes of each force in comparison to the other active forces. If the fluid moves upward, the buoyancy force is greater than the force of gravity, and vice versa. If the fluid remains stationary, the buoyancy force is relatively equal to the force of gravity. With these two forces known, it becomes possible to draw a free body diagram of a packet of combusting fluid, seen as Figure 1, right.

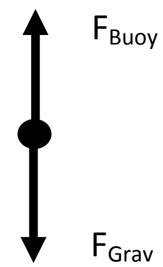

Figure 1: Free Body Diagram of Butane Parcel

Looking at this diagram, one might wonder how the parcels of butane were able to accelerate in the horizontal directions as well. This acceleration is due to the force of the pressure gradient. Gases will always move from a high pressure area to a low pressure area until equilibrium is reached. Since the gas trapped inside the balloon had a higher pressure than the ambient environment, the butane gas expanded in all directions after the rubber was popped. These two forces, along with their interaction with the pressure gradient, can explain all fluid phenomenons seen in the video. Another effect that plays a role in the physics of the flow is shearing, which occurs between the boundary layer of the butane and the ambient air. This causes asymmetric movement as the boundary layer only acts on the outer edges of the fluid pockets.

The camera used to film this phenomenon in slow motion was the Olympus i-SPEED 2. The movie was shot at 1000 frames per second (fps), and played back at 40 fps until the start of the explosion when it is slowed down to 20 fps, and then finally ending at 40 fps after the majority of the explosion occurs. The fluid appears to move about 4 inches in 2 seconds of regular playback. Since this rate is 20 fps, it moves 4 inches in 40 frames, which corresponds to an average regular speed of 8 ft per second. This incredibly fast speed gives an idea of how the physics are impossible to see without a high speed camera.

The i-SPEED 2 does not allow any change on the typical camera settings such as aperture, shutter speed, or ISO. The only things the team was able to adjust were the frame rate and manual focus of the lens. The team chose to focus the lens on one end of the balloon, allowing some flow to be visible in front of the focus plane, and some flow to fall behind it. This created an interesting point of view with such a small depth of field, and a total field of view of only about 2 feet. According to the specification sheet, the global shutter speed was 5µs, and the pixel size was 14 microns across [2]. However, Microsoft Movie Maker was the only available software to edit the movie, and severely degraded the quality. The only post processing was the speed control discussed above, and credits added at the end.

Overall, I thought the video showed a very captivating fluid flow, and it was fascinating to watch it in slow motion. However, I was disappointed with the low quality of the video shot at 1000 fps.

If I were to go through with this experiment again, I would certainly sacrifice capturing some of the minute movements of the flames for a higher quality video at a much lower frame rate per second.

Sources

1. White, Frank M. *Fluid Mechanics*. New York: McGraw-Hill, 1986. Print.
2. "High Speed Video Cameras." *I-SPEED 2 / Olympus*. Web. 20 Mar. 2012. <http://www.olympus-ims.com/en/hsv-products/i-speed-2-new-features/>.