MCEN 4151 | Flow Visualization | Team Second

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Introduction

The purpose of the Team Second assignment is to explore fluid phenomena using smoke as the visualization technique. For the image captured in this report, laminar flow, turbulent flow, and the Kelvin-Helmholtz instability are the observed phenomena. Incense is burnt to produce the smoke, and the flow is visualized using a fluorescent light and a black backdrop.

Apparatus Setup

As shown in Figure 1, the setup requires a light source underneath the subject, a black backdrop to remove distracting background features, incense, and a lighter (not pictured). The incense is held at a downward angle by hand. Having an assistant hold the incense would be ideal, but is not necessary. The camera is positioned on a tripod and set to the desired focus, and images are captured by using Canon's EOS Utility Software on a laptop that is connected to the camera body. Using this method, there is a lot of freedom to move the incense around while still having the capability of taking shots. The camera is positioned approximately 24 inches away from the incense and 0˚ from the horizontal. The light source is positioned 24 inches below the backdrop opening.

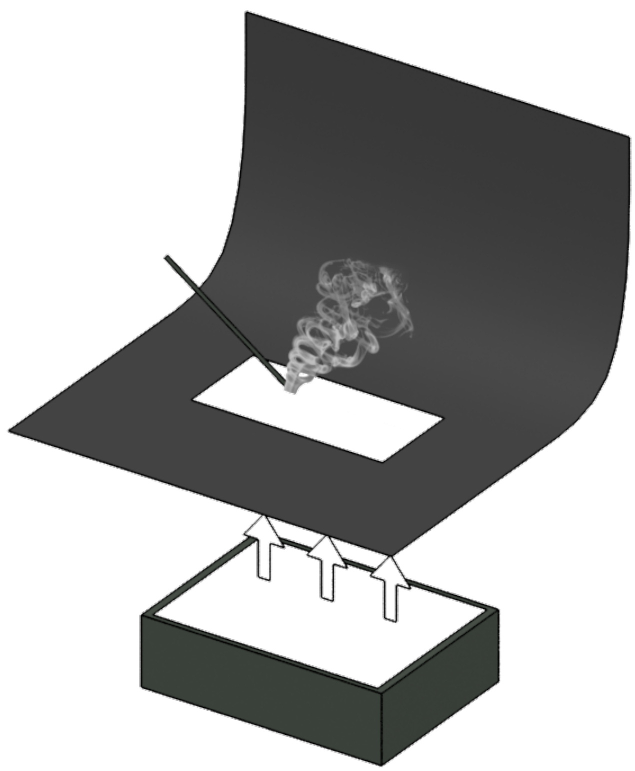

Figure 1: Apparatus setup where light is projected from underneath a black backdrop and the incense is held at a downwards angle above the opening.

Fluid Dynamics

Laminar Flow to Turbulent Flow

The flow of smoke is driven by the differences in density between two fluids. When the incense is ignited, the smoke, or the burnt incense (carbon particles), has a higher temperature than its surroundings. The fine incense particle, with a lower density than the surrounding air, rises, and the cooler air with a higher density sinks. The rate at which the smoke rises is an indication of the magnitude of the temperature difference between the smoke and air. The faster the smoke rises, the larger the temperature difference. The Reynolds number can be used to calculate the upward velocity of the smoke particles where U is the velocity (m/s), L is the characteristic length (m), and ν is the kinematic viscosity (m^2/s).

$$Re = \frac{UL}{\nu}$$

For air slightly above room temperature at 300K, the kinematic viscosity is 1.568 x 10^{-5} m^2/s [1]. The length of the laminar region was approximately 9 inches (0.2286 m) before turning turbulent. Before turbulent flow occurs, the Reynolds number is 2300 [2]. Using this Reynolds number, then the velocity is:

$$U = \frac{\nu Re}{L} = \frac{1.568\ x\ 10^{-5}\frac{m^2}{s} \cdot 2300}{0.2286\ m} = 0.1578\frac{m}{s}$$

If the smoke velocity exceeds 0.1578 m/s, the flow becomes turbulent.

Kelvin-Helmholtz Instability

The vortex sheets seen from the captured image can be explained by the Kelvin-Helmholtz instability. Consider the diagram in Figure 2 from the National Polytechnic Institute of Toulouse visualizing the evolution of a vortex sheet. Initially at a), the stream velocity at the top of the fluid layer is moving faster than the stream velocity below it. This difference in velocity causes the smoke layer to shear and form a trough and crest as shown in c). Soon after, the phenomenon is observed where the smoke layer begins to roll up and form a uniform vortex.

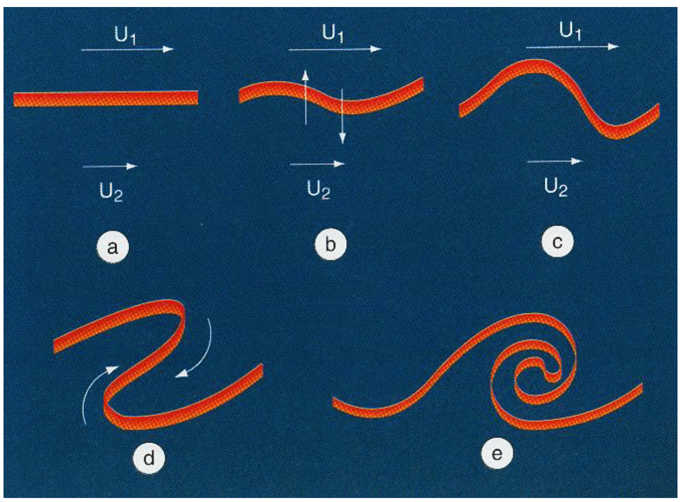

Figure 2: Evolution of a fluid layer experiencing a vortex sheet [3]

In Figure 3 below, the yellow path indicates the Kelvin-Helmholtz instability. The larger arrow represents the smoke layer moving faster than the air around it.

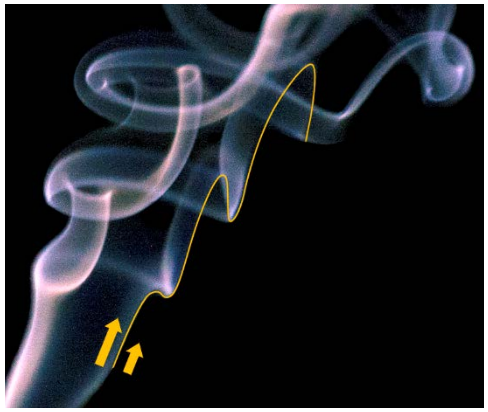

Figure 3: Fluid layer shearing due to higher stream velocity than the surrounding air.

Visualization Technique

The visualization technique used comes from the smoke emitted by burning incense. The interaction between the smoke and the air is the fluid dynamics being visualized. The required materials for visualization is a black backdrop, a light source, incense sticks for multiple trials, and a lighter to light the incense. Light an incense stick until it burns, and then blow out the flame. The incense will continue to burn and smoke for several minutes. The surrounding air is held at room temperature, and the flow of air in the room is circulating at typical conditions. The incense was held at a downward angle because it produced more interesting flow patterns. Having the incense in a vertical position produced some interesting patterns, but the turbulent flow did not happen until much later, which was out of the field of view.

The light source used to illuminate the smoke is a small construction lamp in a pitch black environment. A single lamp pointed towards the ceiling was considered because it creates a dramatic backlit effect on the smoke. Using too many light sources from different angles would lessen the contrast and make the smoke appear flat. A pitch black environment was chosen to further minimize distracting features in the background of the image. No flash was used for the image.

Photographic Technique

The specifications for the photograph are shown below in Table 1. A high ISO of 1600 was chosen to increase the sensitivity of the sensor to the light. By increasing the ISO, the shutter speed could be decreased, which in turn reduces the motion blur of the flow. A slower shutter speed at the same ISO resulted in too much motion blur and decreased brightness. The aperture was set to f/2 to allow for a brighter features in the image.

Table 1: Image Specifications

Camera	Canon EOS Rebel XS
Lens	Helios 44-2 58/2
Aperture	f/2
Shutter Speed (s)	1/125

ISO	1600
Focal Length	58 mm
RAW Image Dimension	3888x2592
Final Image Dimension	3914x3913

Field of View and Distance from Object to Lens

The scale of the smoke is approximately 9 inches in width and 6 inches in height. Within the image, the incense stick is 6 inches in length, but only 3 inches of it is actually shown. The distance from the camera lens to the smoke is approximately 24 inches.

Post-Processing

As shown in the figure below, the left figure is the original image, and the right figure is the final image. The black background of the original image was edited to remove noise and any other distracting features. The curves were edited to bring out more contrast in the smoke, and additional color corrections were made to provide a cool and warm color palette. The post-processing enhanced the important information about the flow by bringing out the darker colors.

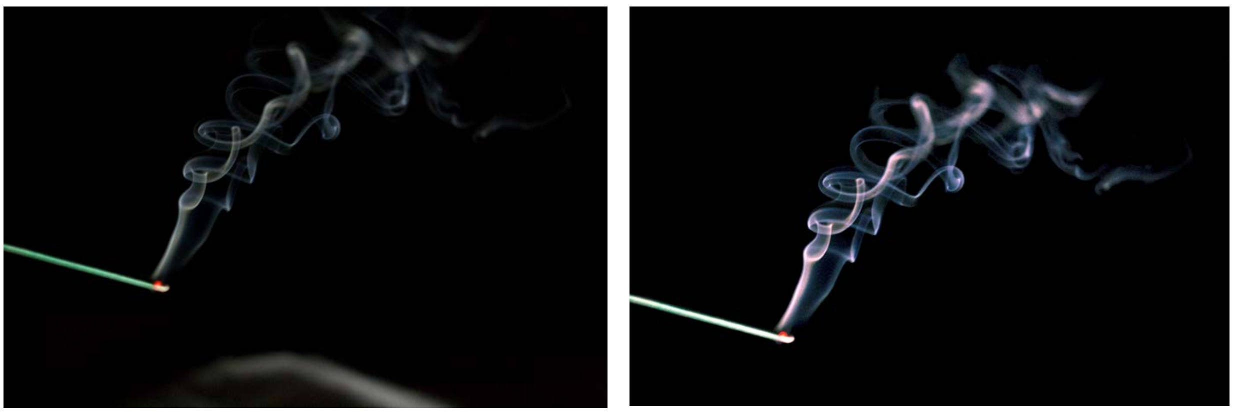

Figure 4: Original image on the left and the post-processed image on the right.

Conclusion

The image reveals the Kelvin-Helmholtz instability on the beginning of the incense stick, where it first begins as a sheet of laminar flow. The flow eventually becomes turbulent and loses its shape. I like the contrast and color range of this image. The fluid dynamics of the flow is complex and happens around us every day. What I dislike about the image is the amount of noise. There is too much noise when zooming in, and a different lighting setup could have been used. I am unsure of how the spirals in the smoke form. They do not appear to be of a Kelvin-Helmholtz nature because the vortices are generated along an axis parallel to the direction of the flow, whereas Kelvin-Helmholtz vortices are generated about an axis perpendicular to the flow direction. I fulfilled my intent of visualizing the smoke flow as it is perturbed by the surrounding, cooler air. It is both artistic and scientific in the way the image is composed and because of how the lighting is set up to create drama. It reveals the underlying physics clearly while still being aesthetically pleasing. To develop this idea further, the incense should be used as a visualization technique to look at flow around a cylinder or airfoil.

References

[1] "The Engineering ToolBox," [Online]. Available: http://www.engineeringtoolbox.com/dry-air-properties-d_973.html. [Accessed 11 November 2015].

[2] "The Engineering ToolBox," [Online]. Available: http://www.engineeringtoolbox.com/laminar-transitional-turbulent-flow-d_577.html. [Accessed 11 November 2015].

[3] "Kelvin-Helmhotz instability," [Online]. Available: http://hmf.enseeiht.fr/travaux/CD0001/travaux/optmfn/hi/01pa/hyb72/kh/kh_theo.htm. [Accessed 11 November 2015].