

As a student, stress can easily find its way into my life. A day where I wake up feeling on top of things can quickly turn into a late night scramble. To reduce the magnitude of stress that I experience, I try to take a little bit of control over my environment by setting the mood. I'll use lamps instead of overhead lighting, play music, light candles, get into comfy clothes—but one of my favorite methods for relaxation is lighting incense, the inspiration for my Get Wet project.

Although I had never touched a camera, apart from the one mounted to my phone, I decided to use my new (yet used) camera. I was determined to capture a high quality photo because I knew that the smoke from an incense stick would create a fascinating shot. My parents live close by—after telling Mom my idea, she was instantly on board and excited to enable my photo. She helped me clear out a space in the house and create an optimal environment for the photo to be taken. We initially tried smaller sticks of incense, but weren't happy with the quality of the flow. We then tried lighting a large bundle of sage, which worked incredibly well in producing an appropriate amount of smoke to clearly display the smoke's evolution. We continued forward with the sage, adjusting lighting, camera settings, and airflow to find conditions that communicated the flow phenomenon adequately. We worked together as a team, with my mom holding the light source and me taking the picture.

The sage bundle itself was about the size of my thumb, with the pieces of sage being bound together by two strings of rope. We placed the bundle on the table; I set the camera up so I could see the top of the bundle, but leaving room in the camera FOV to see enough of the smoke development. The exact setup with dimensions can be seen in Figure 1, showing how each component necessary for the photo was configured.

We lit the sage using a standard lighter, heating up the top for about 20-30 seconds until it was hot enough to produce smoke and burn on its own. The heat created by the lighter breaks down the organic material—decomposition products are released into the air, creating the mixture that we know as smoke. The smoke mixture is hotter than the surrounding air, and the resulting density decrease (from temperature increase) causes an upward buoyant force on the smoke, producing the rising plume that can be seen in the photo. Looking closely, the streaklines are apparent in the smoke, especially when the smoke is initially released and can be characterized as a laminar flow. It is interesting to follow these lines as the smoke rises and watch the flow become more turbulent as the hot buoyant air experiences shear from the surrounding atmosphere. I lightly blew air at the smoke to create turbulence, increasing the inertial forces on the fluid that drive the Reynolds number up and creating the eddies that can be seen at the top of the photo.

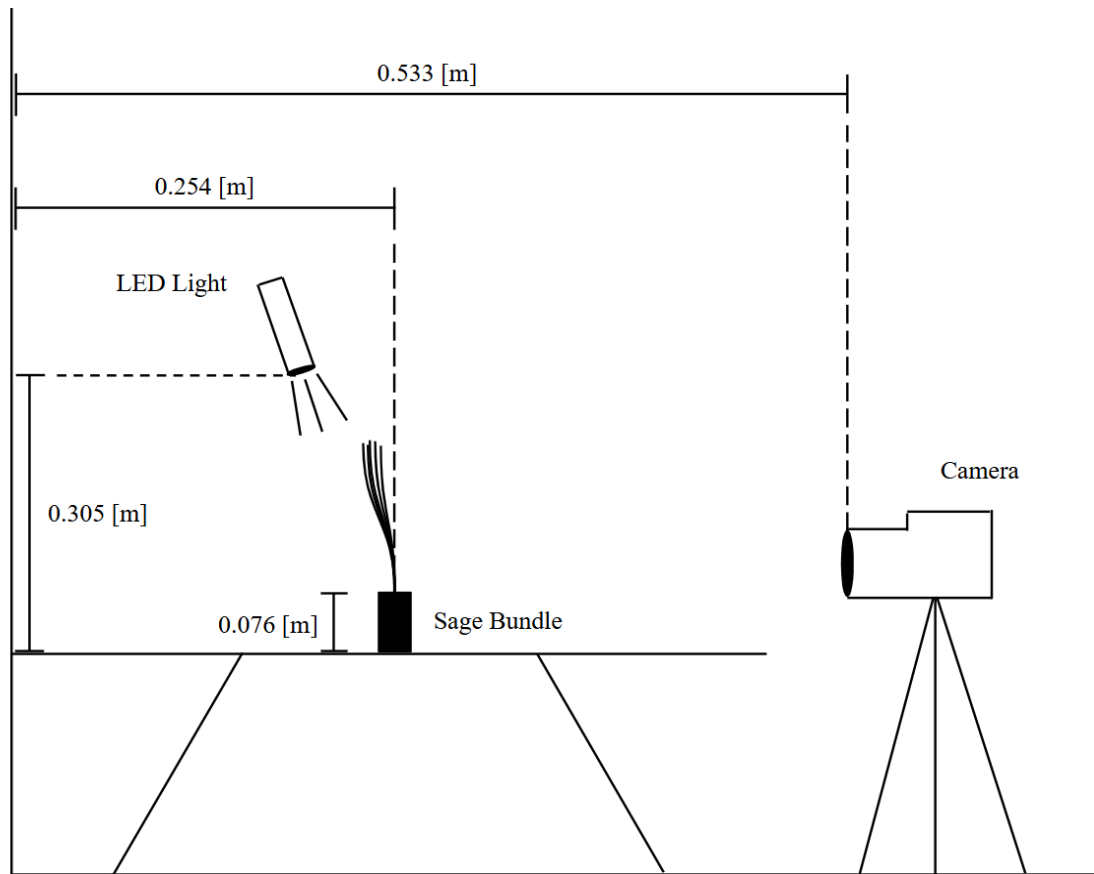


Figure 1. Photo Setup

We lit the sage using a standard lighter, heating up the top for about 20-30 seconds until it was hot enough to produce smoke and burn on its own. The heat created by the lighter breaks down the organic material—decomposition products are released into the air, creating the mixture that we know as smoke. The smoke mixture is hotter than the surrounding air, and the resulting density decrease (from temperature increase) causes an upward buoyant force on the smoke, producing the rising plume that can be seen in the photo. Looking closely, the streaklines are apparent in the smoke, especially when the smoke is initially released and can be characterized as a laminar flow. It is interesting to follow these lines as the smoke rises and watch the flow become more turbulent as the hot buoyant air experiences shear from the surrounding atmosphere. I lightly blew air at the smoke to create turbulence, increasing the inertial forces on the fluid that drive the Reynolds number up and creating the eddies that can be seen at the top of the photo.

An incredibly interesting phenomenon I noticed is that even though the entire top of the bundle was heated, the smoke emerged only from the center. This is likely because there is a greater amount of thermal retention in the center of the bundle, where reduced exposure to the ambient air limits convective heat losses, unlike the outside of the bundle where there is direct exposure and it cools down immediately. Once the smoke exited the bundle, the rising plume developed and

entrained surrounding air, causing the plume to widen and its temperature difference with the surrounding air to decrease. The theoretical model developed by Morton et al. (1956) relates the rate of entrainment to the vertical velocity of the plume, explaining how the surrounding air is incorporated into the rising buoyant smoke mixture. The relationship is expressed by Julien et al. (1999) as:

$$v_e = \alpha W,$$

where v_e is the entrainment velocity, α is the entrainment constant, and W is the vertical velocity. The entrainment constant α characterizes the rate at which surrounding air is incorporated into the plume. Estimating $W = 0.7$ [m/s] and $v_e = 0.07$ [m/s], this yields $\alpha = 0.1$, meaning that the velocity of the air entering the plume is 10% of the vertical velocity (COMSOL Multiphysics). Estimating this coefficient is beneficial to see how entrainment contributes to the expansion of the plume. This is a relevant parameter to look at before the smoke reaches the external turbulent air.

Another non-dimensional number that can be used to characterize this flow is the Reynolds number (Re). I want to analyze the Reynolds number to investigate the development of the smoke plume from smooth to complex structures. The generic equation for Reynolds number is as follows:

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

where U = velocity, L = characteristic length, and ν = kinematic viscosity. The kinematic viscosity of air is assumed to be $1.51E-5$ [m²/s]. Two Reynolds numbers are being estimated at different locations: at the base of the smoke and then farther downstream into a more complex structure. The diameter of the sage bundle is about 2.54 [cm], and the smoke appears to initially be about a tenth of that, so the characteristic length of the first Reynolds number is 0.254 [cm]. In conjunction, the velocity at the start of the smoke is about 0.7 m/s (COMSOL Multiphysics). Then, at the turbulent point that I am defining, the smoke is about the exact width of the sage bundle, so the characteristic length is 2.54 [cm]. At the time this photo was taken, I was softly blowing air at the smoke to create a turbulent effect, estimated to be 5 m/s (Geoghegan et al., 2017). The following are calculated:

$$Re_L = \frac{0.7 \text{ [m/s]} * 0.00254 \text{ [m]}}{1.51E-5 \text{ [m}^2\text{/s]}} = 117.7 \qquad Re_T = \frac{5 \text{ [m/s]} * 0.0254 \text{ [m]}}{1.51E-5 \text{ [m}^2\text{/s]}} = 8410.6$$

The substantial increase in Reynolds number shows that the inertial forces become more significant than the viscous forces as the smoke rises. With the lower Reynolds number, the smoke is laminar, visualized by the streaklines until about halfway up the photo. At that point, the smoke has entered the high velocity flow and has increased greatly in characteristic length. More complicated vortical structures are introduced near the top of the photo from the external airflow creating shear-driven instability.

The room that my mom and I set up was as dark as possible to allow us to focus the light on the smoke particles. I used a black velvet background (purchased from Michaels), choosing velvet because it absorbs light better than something like a wall or piece of paper, which are more reflective. My mom pointed an LED directly at the smoke, lighting it from the back/side. It proved to be an effective way to highlight the flow without creating distraction in the photo.

The diameter of the sage bundle can be used to estimate the FOV. Assuming that the diameter is 2.54 [cm], I estimate that the width is 8 [cm] and the height is 15 [cm]. Referencing Figure 1, it can be deduced that the distance from the sage bundle to the lens was approximately 0.279 [m]. The original image dimensions were 2912 x 5184, and the final image dimensions were 900 x 900. The image was taken with a digital Canon EOS Rebel T5i. I did a lot of adjusting with the ISO, settling on a value of 200. A low iso kept the picture clear, and was able to be used because of the bright LED. The aperture used was f/5.6, the focal length was 32 mm, and the shutter speed was 1/125 sec. In postprocessing, there were grains of color on the image, I assume from small grains of dust on the lens. I used the “retouch” feature in darktable to remove these. No other editing was done for the final result as it did not feel necessary.

I took many images of the smoke, but this specific image was my favorite. I love the contrast between the completely black left side of the photo vs. the bright swirling smoke on the right, seemingly alive. This photo displays the laminar characterization of a flow, but then also captures an intense transition to turbulence with vortices and channels. I achieved more than I imagined, as I initially expected to use a small stick of incense but ended up with a much greater source for the flow. Next time, I would like to fix my light source to create consistency between photos, perhaps adding colored tint to adjust the contrast. Overall, I am very happy with this result.

References:

COMSOL Multiphysics. *Smoke from an Incense Stick - Visualizing the Laminar to Turbulent Transition in Natural Convection*, www.comsol.com/model/smoke-from-an-incense-stick-visualizing-the-laminar-to-turbulent-transition-in-natural-convection-97501.

Geoghegan, et al. “Pubmed.Ncbi.Nlm.Nih.Gov.” *National Center for Biotechnology Information*, U.S. National Library of Medicine, 2017, pubmed.ncbi.nlm.nih.gov/28154922/.

Julien et al. “Plumes in Rotating Convection. Part 1. Ensemble statistics and dynamical balances”, 1999, www.colorado.edu/amath/sites/default/files/attached-files/plume1.pdf.

Morton et al. “Turbulent Gravitational Convection from Maintained and Instantaneous Sources | Proceedings A | the Royal Society.” University of Cambridge, 1956, royalsocietypublishing.org/rspa/article/234/1196/1/9730/Turbulent-gravitational-convection-from-maintained.