Lighter Flame Background Oriented Schlieren

MCEN 5151 Flow Visualization - Team Second Report

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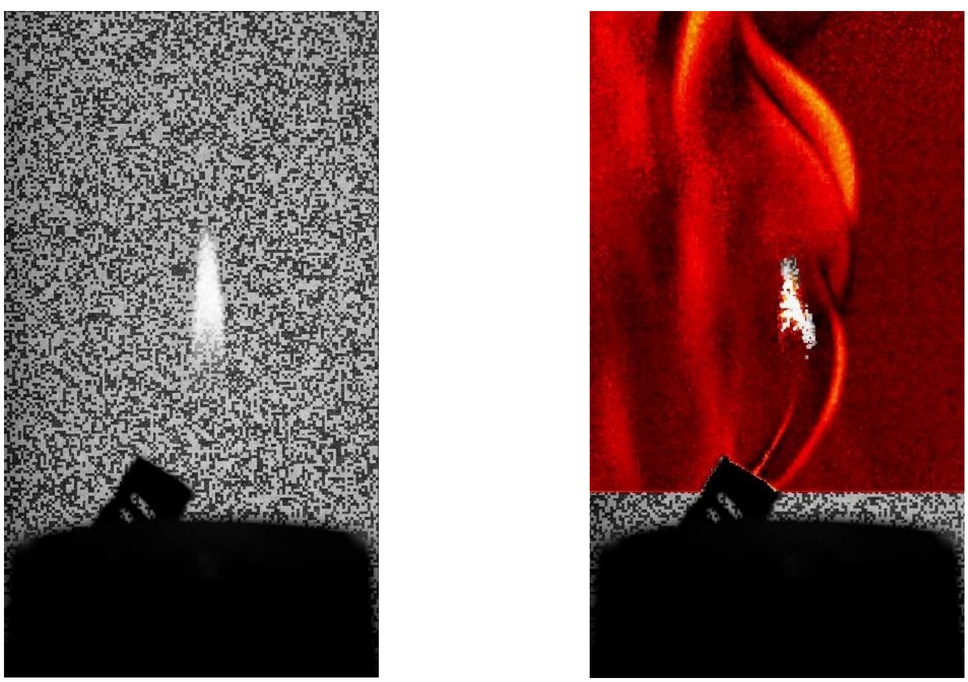
November 3, 2025

Special thanks to Xeen Meighan and Alana Martinez who helped with the imaging process.

Statement of Meaning Figure 1 was created for the second team flow visualization assignment and shows a butane lighter flame burning in front of a schlieren background. This setup attempted to illustrate the density differences in the air surrounding the lighter flame using background oriented schlieren (BOS) processing methods. To better highlight the density gradients in the air created by the lighter, a video was recorded, split into individual frames for processing, processed, and assembled again into a video. A red color scheme was chosen for the BOS processing to artistically mimic the appearance of a flame. The processed video reveals flame flickering and the movements in the surrounding air due to these oscillations. Laminar flames (like this one) can be characterized with the help of dimensionless number (reduced frequency, Grashof) calculations.



(A) Compressed Black and White (8-bit) Photo

(B) Processed Photo

Figure 1: Background oriented schlieren image of a butane lighter flame.

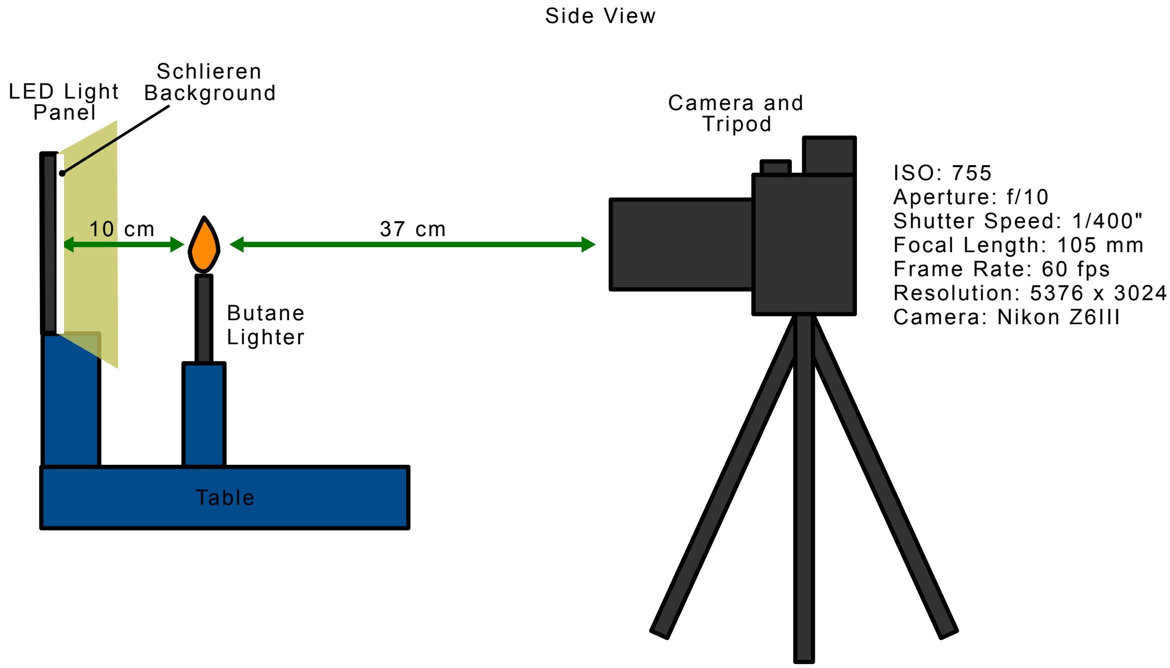


Figure 2: Side view of visualization setup

Setup and Flow Description This flow was created in the ambient air with a butane lighter, a randomly generated noise schlieren background, an LED panel, and a mirrorless camera. The butane lighter was held stationary so the flame was centered in the image. A 10 W, 4500 K color temperature LED panel lamp served as a backlight behind the schlieren background. The schlieren background was taped to the LED panel lamp and was sourced from a tv noise image found on the Wikimedia Commons.[1] Multiple ten second videos were recorded of the flame at 60 frames per second and then analyzed in post processing.

As shown in Figure 2, a Nikon Z6III camera with a 105 mm f/2.8 Nikkor macro lens was used to record the butane lighter flame from 37 cm away, keeping the flame at a large size within the image frame while capturing a sufficient background area behind the flame to support post processing BOS analysis. The flame was positioned 10 cm in front of the LED panel and schlieren background. A tripod was used to stabilize the camera during the video recording process.

The video of the burning flame was taken at 60 frames per second with a resolution of 5376×3024 pixels. This frame rate and resolution was chosen because it balanced the high resolution capabilities of this camera with a faster frame rate that would minimize motion blur.

When the butane from the lighter combusts, it heats the surrounding air which rises with the combusted products due to buoyancy effects. The hot air rises, making more room for cooler air near it to take its place — a process known as unforced convection. In the case of the lighter flame, the fastest moving air starts by the side of the base of the flame and moves toward the center axis as it rises.[2] Not surprisingly, the hottest temperatures at these elevations also are at or very close to these locations.[2] Dimensionless numbers such as the Grashof number (comparison of buoyant and viscous forces) can be used to characterize this unforced convection. If the buoyant forces are very strong compared to the viscous forces, the less buoyant fluid will rise very quickly without being inhibited by the surrounding fluid. Conversely, if the viscous forces are very strong compared to the buoyant forces, then the buoyant fluid will rise more slowly and may have difficulty pushing the surrounding fluid out of the way as it rises. A large buoyant to viscous force ratio could be correlated with a flow containing more turbulence, whereas a smaller ratio could be correlated with a laminar flow. Calculating the Grashof number requires some measured values and some values estimated using previous experimental measurements. The equation for the Grashof number can be seen in Equation 1.[3]

Another dimensionless quantity that could be used to characterize this flow is a reduced frequency. The reduced frequency can be used in models that predict a flame's behavior when exposed to an external acoustic field, or when variables such as the fuel-air mixture, flow rate, or fuel type are changed.[4] Undisturbed flames, such as those from a protected lighter or a candle, tend to oscillate back and forth when they burn. These oscillations can be caused by the disturbances in the fuel-air mixture ratio and flow rate,[4] though they could also be caused by parts of the natural convection cycle. In this experiment, the flames oscillated at about 10 hz, which is similar to rates found in previous experiments.[5] Calculating the reduced frequency of the flames requires some measured values and some estimated values (see Table 1). The equation for reduced frequency is shown in Equation 2.[6]

Constant	Description	Value
L	height of flame	30×10^{-3} m
R	radius of flame	5×10^{-3} m
S_L	laminar burn velocity of butane	$0.4\,\mathrm{m\,s^{-1}}$ [7]
ν	kinematic viscosity of air	$15.06 \times 10^{-6}\,\mathrm{m^2/s}$ [8]
α	half cone angle of flame	18°
ω	flicker frequency	188.5 rad/s
β	coefficient of volume expansion	5.1×10^{-4}
g	gravitational acceleration	$9.81\,\mathrm{m/s^2}$
T_s	temperature of flame	1970 [9]
T_∞	ambient temperature	20

Table 1: Constants and measurements. Some measurements (angle and frequency) were measured using Fiji.[10]

$$\mathrm{Gr} = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2} = \frac{(9.81)(5.1 \times 10^{-4})(1970 - 20)(30 \times 10^{-3})^3}{(15.06 \times 10^{-6})^2} = 1.16 \times 10^6 \tag{1}$$

$$\text{Reduced Frequency} = \frac{\omega R}{S_L \cos\alpha} = \frac{(188.5)(5 \times 10^{-3})}{(0.4)\cos 18} = 2.48 \tag{2}$$

The reduced frequency found in Equation 2 is 2.48, which is of order 1. This means that heat of reaction, flame speed, and flame area all likely play equal roles in flame oscillations.[4] The Grashof number is relatively high, indicating that the flame is likely turbulent.[3] However, the recorded flame appeared to burn slowly and take an organized shape, which would be indicative of laminar convection. This discrepancy could be due to an improperly estimated flame temperature or coefficient of volume expansion number.

Visualization Technique Background oriented schlieren was used to image the air density variations surrounding the flame. This technique compares image backgrounds between two image frames. Areas where a lot of background change (distortion) occured are then highlighted with an image overlay mask. In this experiment, the background image was distorted by the temperature driven density changes created by the flame. More details about BOS techniques can be found in the document written by JoshTheEngineer.[11] A clear background with a distinctive pattern needs to be used when imaging with BOS techniques. If the background is too homogeneous, the background comparison will fail to find many visual distortions. Proper lighting and contrast also helps, which is why a 10 W LED panel was used to illuminate the background.

Photographic Technique 29 cm is the minimum focus distance of the Nikkor 105 mm f/2.8 macro lens that was used to record the videos.[12] As shown in Figure 2, a Nikon Z6III with an f/10 aperture, a 1/400 second shutter speed, and a 755 ISO setting were used to capture the image. The Z6III digitally recorded videos at 60 fps with dimensions of 5376×3024 pixels and a view angle of $23.167 \times 15.333°$.[12]

To create the BOS background comparison with the Matlab script created by JoshTheEngineer,[11] I used a comparison box size of 12 pixels and a search box of 16 pixels. I also used an interpolation factor of 5 to smooth out the color map. To create the videos with these settings, I modified the Matlab script.

After cropping and editing, the final video had dimensions of 1920×1080 pixels and was played at 3 fps. The video playback was slowed down to allow the viewer to see the background changes calculated by the BOS processing. Video compilation was done with KdenLive.

Analysis and Reflection As mentioned previously, the image shows the density variations in the air surrounding a butane lighter flame. These density variations are caused by temperature gradients created by the lighter flame. I'm relatively pleased with the background modifications created by Matlab script, though I do wonder how the image would have looked if different "difference finding" algorithms were used. I also wonder if the background that I used helped or hindered the background comparison process. The background I used has a lot of noise and detail, but it is at the same scale. Perhaps the background difference detection would have been better if I had chosen a background designed specifically for BOS.

Regarding the image layout, I could have cropped out the bottom third of the image, since it was mostly black and there weren't any useful details there. I could have also held the butane lighter vertically rather than at an angle. This could have made the flame more symmetric.

The videos taken were spatially resolved enough for the BOS processing to be done. However, they might have benefitted from a higher frame rate. When reviewing the individual video frames, I found that the flame moved more than I wanted it to from frame to frame. Video frame rate is often inversely proportional to the resolution, so if I increased the frame rate, I might not have had a desirable resolution.

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