

Toaster Inferno

During our first meeting as a team, we didn't struggle to come up with ideas. We landed on experimenting with a one-mirror schlieren imaging setup—Jay had used this technique for his Get Wet assignment and wanted to improve on his results. Both Anton and I were fascinated at his work and were on board with the idea, excited to learn more about the technique in practice. We prepared our setup and decided to test multiple sources of flow, generating videos that we both found interesting and would clearly visualize the flow physics/development.

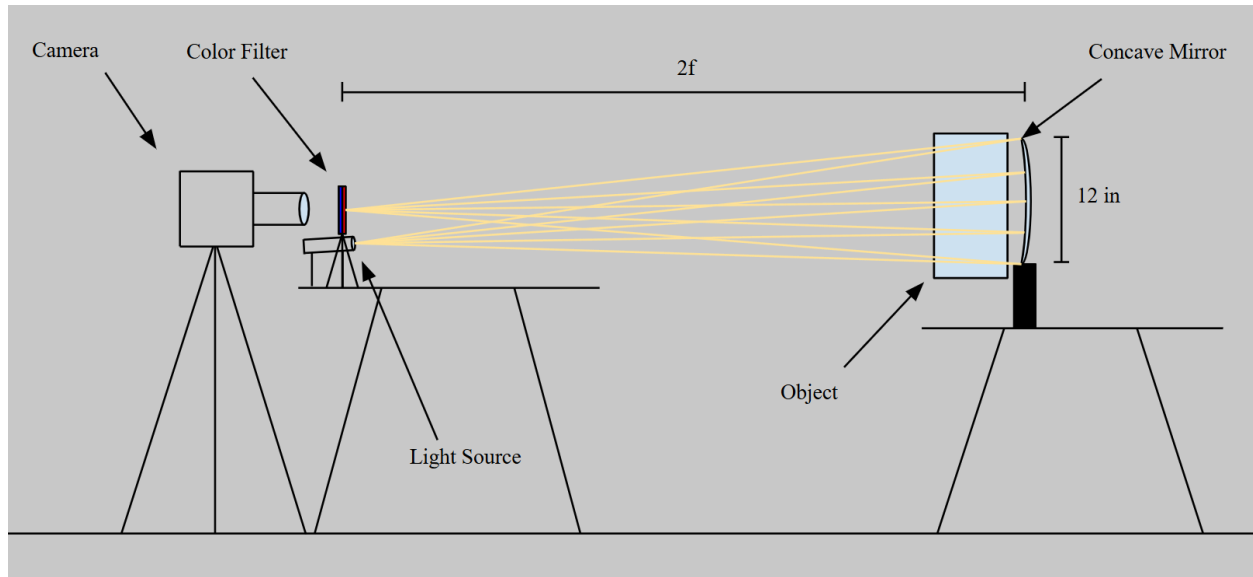


Figure 1. Experimental Setup

The team rented a high speed camera and concave mirror to aid with the setup. We provided ourselves with a light source, a color filter, and the sources of flow of our own choosing. Referencing Figure 1, the diameter of the concave mirror is 12 inches. An important part of schlieren imaging is placing the color filter precisely at the focal point of the light returning from the concave mirror (generally, where the light source is). To find this point, we used the Gaussian mirror equation:

$$\frac{1}{f} = \frac{1}{d_0} + \frac{1}{d_i}; \quad d_0 = d_i \quad \therefore \quad d = 2f.$$

With the mirror having a focal length of about 8 ft, the distance between the color filter and the mirror is about 16 ft. The objects are placed as close to the mirror as possible to reduce mirroring of the object itself in the camera (making it seem like there are two objects), an effect that comes with only using one mirror.

The flow that I decided to visualize is the thermal plume rising from a toaster placed directly in front of and below the mirror. The buoyant plume is represented in Figure 2—the heat from the toaster causes the air inside to increase in temperature, and therefore decrease in density according to the ideal gas law. The lower density air rises due to a buoyancy force caused by density differences between the hot air and surrounding air. The distinction between buoyancy forces compared to viscous forces can be characterized by the Grashof number (*ScienceDirect Topics*):

$$Gr_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2},$$

where L is the characteristic flow, $T_s - T_\infty$ is the temperature difference previously mentioned, g is gravity, β is the thermal expansion coefficient, and ν is the kinematic viscosity. It can be seen that larger viscosities mean that larger stresses are needed to produce a given rate of deformation, so convection is opposed by larger viscosity, ν (MIT OpenCourseWare, 2008). It is possible to estimate the Rayleigh number for this scenario. Taking:

$$\begin{array}{ll} g = 9.81 \text{ [m/s}^2\text{]} & \beta = 3\text{E-}3 \text{ [1/K]} \\ T_\infty = 298 \text{ [K]} & L = 0.15 \text{ [m]} \\ T_s = 373 \text{ [K]} & \nu = 1.9\text{E-}5 \text{ [m}^2\text{/s]} \end{array}$$

$$Gr_L = \frac{9.81 \frac{\text{m}}{\text{s}^2} \cdot 3\text{E-}3 \frac{1}{\text{K}} (373\text{K} - 298\text{K}) (0.15\text{m})^3}{(1.9\text{E-}5)^2 \frac{\text{m}^2}{\text{s}}} = 2.1\text{E}7.$$

The Grashof number is on the order of 10^7 , indicating the dominance of the buoyancy driven effects relative to viscous forces for the toaster. This is consistent with Figure 2, as the viscous forces are clearly not sufficient enough to stop the motion generating the massive plume.

The Grashof number, however, does not take into account the thermal diffusion of the plume. The temperature gradient between the rising plume and the surrounding air introduces the need for thermal diffusion estimation for accurate modeling. The the ratio of momentum diffusivity to thermal diffusivity in a fluid can then be introduced with Prandtl number:

$$Pr = \frac{\nu}{\alpha},$$

where α is the thermal diffusivity of air. Using $\alpha = 2.7E-5$ [m²/s], and combining the Prandtl number with the Grashof number, the final result is the Rayleigh number. This non-dimensional number combines the effects of buoyancy, viscosity, and thermal diffusion to lead to the following:

$$Ra_L = Gr_L Pr = \frac{g\beta(T_s - T_\infty)L^3}{\alpha\nu}.$$

Plugging in the estimated numbers,

$$Ra_L = \frac{9.81 \frac{m}{s^2} \cdot 3E-3 \frac{1}{K} (398K - 298K)(0.15m)^3}{1.9E-5 \frac{m^2}{s} \cdot 2.7E-5 \frac{m^2}{s}} = 1.5E7$$

The final Rayleigh number is also on the order of 10^7 , indicating the dominance of the buoyancy driven convection relative to viscous and thermal diffusion. The similarities in the two non-dimensional numbers show that rather than the thermal energy diffusing into the surrounding air, the heated air is mostly transported upwards from the strong buoyant forces (Lienhard & Lienhard, 2024).

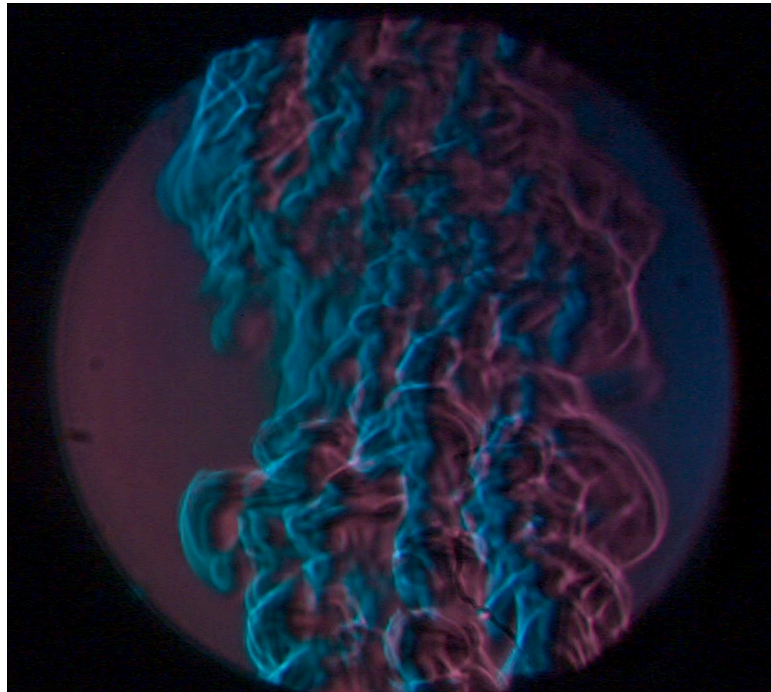


Figure 2. Experimental Results

The concave mirror and high-speed camera were rented from the engineering department at the University of Colorado Boulder. We built the color filter out of thin colored plastic taped onto a frame of popsicle sticks. These materials were provided free by the engineering department. The

toaster was my own. The video was taken in a dark room to provide a controlled environment for the provided light source—a dc-powered 140 lumen flashlight, the front covered with aluminum foil with a small hole for a point light source. The light was placed next to the camera because that allows for the focal point to line up for both, getting optimal light for schlieren imaging. We chose schlieren imaging for this visualization because it can turn refractive-index gradients into intensity differences that make the heat visible on the camera. (Settles, G. S., 2001).

We used a Chronos 1.4 high-speed camera with 800x600 pixels shot at 2873 fps. The edited video turned out to be 1440x1080 pixels. The shutter speed of our camera was 348 μ s. The final video was sped up 4x in ClipChamp to produce a better visualization of the flow, resulting in 2873/4 $\cong$ 718 fps. The aperture was set to f/1.2 and the focal distance was set to around 16 ft. Edited video was cropped to highlight flow of interest.

The image is a beautiful encapsulation of turbulent flow with the artistic addition of color gradients that add shadow and flow distinction. I really appreciate how the red highlighted flow is supported by the blue background, and the blue highlighted flow is supported by the red background. Next time, I would like to invest more time into image editing. There are specs on the video, presumably from the interior of the lens, which could be removed with a software like DaVinci Resolve. The fluid physics are depicted clearly and the artistic intent that I was trying to accomplish is completely shown. Overall I am happy with the results, and I now am comfortable around the concept of schlieren flow, how it works, and how to set it up for a physical experiment.

References:

Grashof Number - an Overview | Sciencedirect Topics,
www.sciencedirect.com/topics/chemistry/grashof-number. Accessed 6 Oct. 2026.

Lienhard, J. H. V, and Lienhard, J. H. IV. *A Heat Transfer Textbook*. 6th ed., Version 6.00, Phlogiston Press, Cambridge, MA, 2024.

“Physics and Chemistry of the Terrestrial Planets: Earth, Atmospheric, and Planetary Sciences.” *MIT OpenCourseWare*, MIT OpenCourseWare,
ocw.mit.edu/courses/12-002-physics-and-chemistry-of-the-terrestrial-planets-fall-2008/. Accessed 5 Oct. 2026.

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

Settles, G. S. (2001). *Schlieren and shadowgraph techniques visualizing phenomena in Transparent Media*. Springer Berlin Heidelberg. Page 27.W