Visualizing Air Density Gradients Using a Schlieren Imaging System

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Abstract

Small variations in air density caused by temperature differences or fluid motion change the refractive index of air and bend light rays in ways that are normally invisible to the human eye. Schlieren imaging is an optical technique that converts these small angular deflections into measurable intensity variations, allowing refractive index gradients to be visualized directly. In this project, we built and aligned a mirror-based Schlieren imaging system using a concave mirror, a point light source, and a knife-edge filter positioned at the focal plane. Heat sources such as a lighter generated refractive-index gradients that deflected light rays traveling through the test region. The knife-edge partially blocked the focused light, converting these deflections into brightness variations that were captured with a smartphone camera. The resulting images revealed rising convection plumes and time-varying flow structures above the heat source. These observations were consistent with the expected behavior of a Schlieren system and with the theoretical prediction that image intensity is sensitive to spatial gradients of refractive index rather than absolute density. This project demonstrates how ray optics and Fourier optics combine to transform small phase variations in light propagation into visible intensity contrast using a relatively simple experimental setup.

1 Background and Introduction

Many important fluid and thermal phenomena are governed by spatial variations in density, temperature, and pressure. In gases, these variations are often invisible to the naked eye even though they strongly affect flow behavior. Examples include the rising plume above a candle or lighter, heat transfer from hot surfaces, combustion, aerodynamic flow around objects, and shock waves in compressible flow. A major challenge in experimental optics and fluid visualization is therefore to make these transparent disturbances visible without significantly perturbing the system itself.

Schlieren imaging addresses this challenge by converting small refractive-index gradients into intensity contrast. Because the refractive index of air depends on density, changes in temperature or pressure create small optical inhomogeneities that slightly deflect passing light rays. These deflections are too small to observe directly, but they can be amplified optically using a focusing element and a spatial filter. The technique was developed by August Toepler in the nineteenth century and remains a foundational tool in aerodynamics, combustion research, heat transfer studies, and optical diagnostics [1, 2].

The physical basis of the method is that refractive index is linked to density through the Gladstone–Dale relation,

$$n - 1 = k\rho, \tag{1}$$

where n is refractive index, ρ is density, and k is the Gladstone–Dale constant for the medium. A spatial gradient in density therefore creates a spatial gradient in refractive index, which bends light rays as they propagate through the disturbed region. In a Schlieren system, these bent rays are focused to a plane where a knife-edge partially blocks them. Rays deflected in one direction are blocked more strongly and appear darker, while rays deflected in the opposite direction are blocked less and appear brighter. The final image therefore encodes the spatial derivative of refractive index rather than the refractive index itself.

Modern Schlieren imaging systems range from high-end laboratory instruments with precision parabolic mirrors, laser illumination, and high-speed cameras to more accessible systems built with LEDs and consumer imaging devices. Advanced systems can visualize shock structures, supersonic flow, and rapidly evolving combustion events with excellent spatial and temporal resolution [1]. Related techniques such as background-oriented Schlieren (BOS) extend the method to larger fields of view and more quantitative analysis. However, a persistent challenge is achieving sufficient sensitivity and contrast while keeping the setup simple, affordable, and reproducible. High-performance systems usually require careful alignment, stable illumination, and high-quality optics.

The goal of this project was to build a simpler mirror-based Schlieren system that could still resolve meaningful refractive-index gradients in air. Using a concave mirror, a point light source, a knife-edge filter, and a smartphone camera, we sought to visualize convection plumes generated by a lighter and connect the observed image contrast to the underlying physics of ray deflection and spatial filtering.

2 Methods

2.1 System Design

We constructed a single-mirror Schlieren imaging system because it offers a simpler optical path and lower component count than a multi-lens or $4f$ arrangement. The system consisted of a concave mirror with focal length

$$f = 37 \text{ cm} = 0.37 \text{ m},$$

a point light source formed using an LED and small aperture, a ball lens to concentrate the source, a razor blade used as the knife-edge, and an iPhone camera for image capture.

In the single-mirror geometry, light from the point source reflects from the concave mirror and is refocused to the focal plane after traversing the test region. Any refractive-index gradient in the test region causes a small angular deflection of the rays. The knife-edge placed at the focal plane partially blocks the returning beam so that these angular deflections are converted into measurable brightness differences.

2.2 Optical Principle

If the refractive index varies across the test region, rays experience a small angular deflection ϵ approximately given by

$$\epsilon \approx \frac{1}{n} \int \frac{\partial n}{\partial x} \, dz, \tag{2}$$

where $\partial n/\partial x$ is the refractive-index gradient transverse to the optical axis and z is the propagation direction. The focusing optic maps this angular deflection into a displacement at the focal plane:

$$\Delta x = f\epsilon. \tag{3}$$

Thus, a longer focal length increases sensitivity by producing a larger focal-plane shift for a given angular deflection. In our setup, the 37 cm focal length provided sufficient sensitivity to visualize convection plumes from a lighter while keeping the overall setup compact.

From a Fourier optics perspective, the knife-edge acts as a spatial filter at the Fourier plane. Uniform illumination corresponds primarily to low spatial frequencies, while phase gradients introduced by the disturbed medium produce higher spatial-frequency components. Partial blockage at the focal plane converts these phase variations into observable intensity contrast in the final image.

2.3 Alignment and Experimental Procedure

The setup was assembled on an optical table. The point light source, knife-edge, and camera were positioned near the focal region of the concave mirror and adjusted iteratively so that the reflected light returned to the focal plane along a common optical axis. A small aperture, approximately 1–2 mm in diameter, was used to approximate a point source. A ball lens was placed in front of the LED to help concentrate the light and improve source quality.

Initial alignment was performed by locating the brightest returned spot from the mirror and adjusting the source position until a clean image formed at the focal plane. The razor blade was then inserted at the focal plane and translated laterally in small increments until roughly half of the focused beam was blocked. This approximately 50% cutoff condition was chosen because it provides a strong balance between sensitivity and brightness.

Once alignment was complete, a lighter was placed in the test region so that its heated air plume passed through the beam path. Images were recorded with an iPhone camera positioned adjacent to the source. Automatic camera exposure was used, and ambient room lighting was kept as low and as stable as practical to improve contrast. Several trials were taken while fine-tuning the knife-edge position and heat-source location.

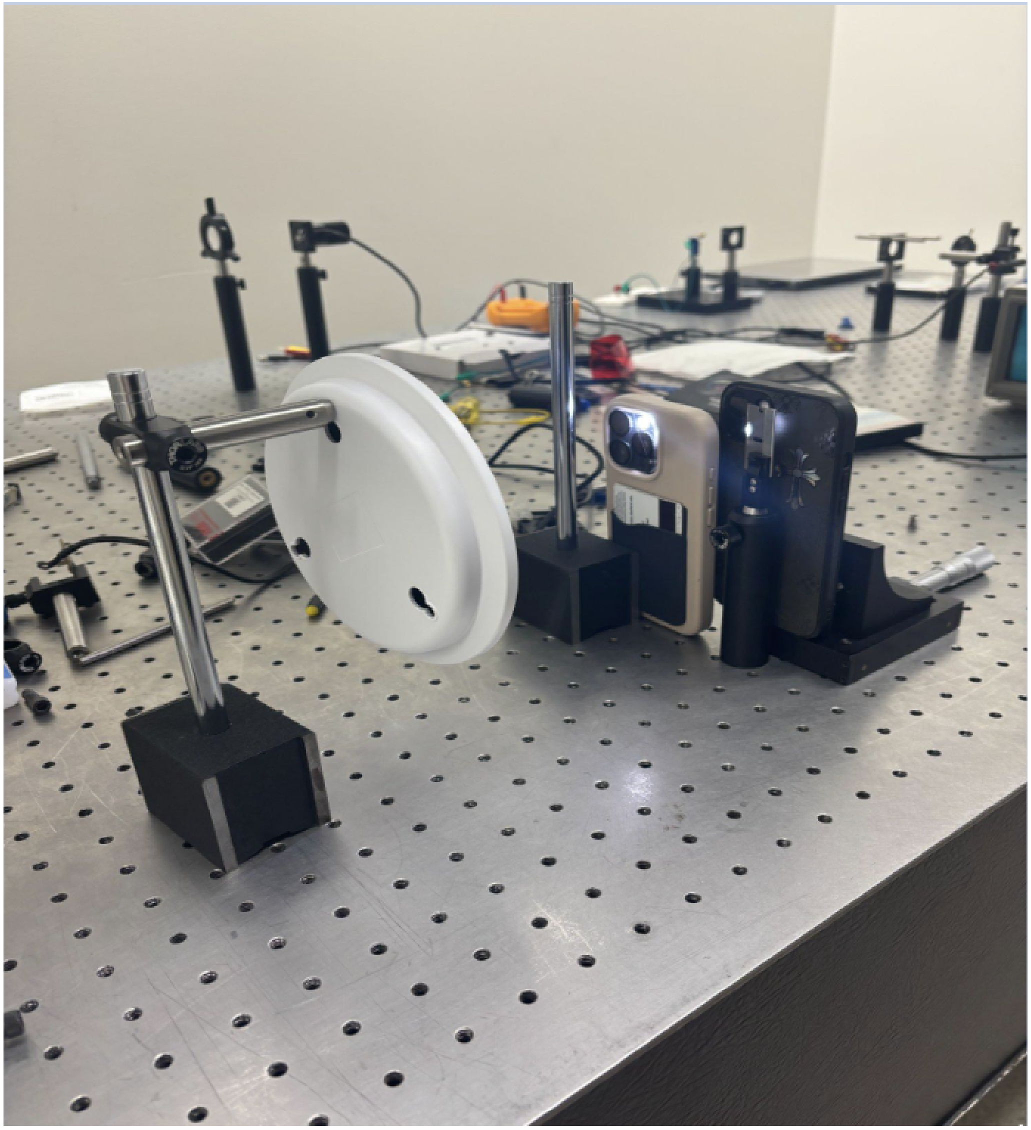
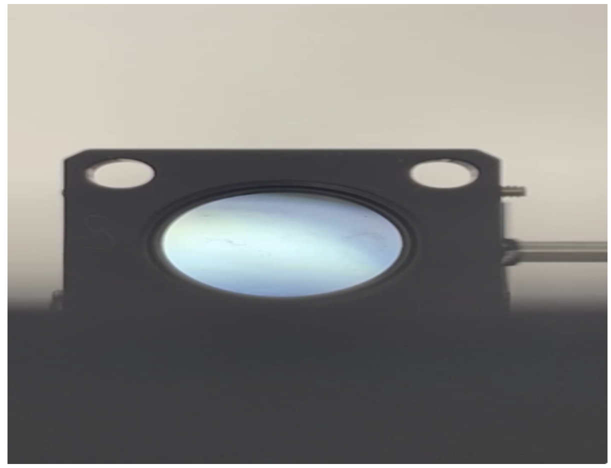


Figure 1: Full experimental setup of the mirror-based Schlieren system on the optical table. The figure shows the aligned source, mirror, and imaging path used to visualize refractive-index gradients generated by a heat source.

(a) Concave mirror used in the system ($f = 37$ cm).



(b) Knife-edge positioned at the focal plane.

Figure 2: Key optical components of the Schlieren system. The concave mirror provides focusing and sensitivity to angular deflection, while the knife-edge converts small focal-plane shifts into measurable intensity variations.

3 Results

The completed system successfully visualized refractive-index gradients produced by heated air and lighter vapor. When the lighter was introduced into the test region, the recorded image showed vertically rising bright and dark streaks above the source. These structures were not visible under ordinary viewing conditions and only became apparent once the Schlieren system was aligned and the knife-edge was tuned properly.

Figure 3: Schlieren visualization of lighter-induced convection. The observed bright and dark streaks correspond to spatial gradients in refractive index, revealing upward-moving thermal plumes and turbulent flow structures above the lighter.

The strongest contrast appeared directly above the lighter, where the thermal gradient was largest. The image also showed that the plume was not static: the dark and bright bands moved and evolved over time, indicating a dynamic convection process rather than a fixed optical artifact. When the heat source was removed, the visual distortion and contrast largely disappeared, and the image returned toward a more uniform background. This provided a simple physical check that the observed signal was caused by the heat-induced refractive-index gradient.

To assess the observed image structure, we qualitatively examined intensity transitions across the plume. Regions containing stronger refractive-index gradients produced sharper bright-to-dark boundaries, whereas regions away from the plume were comparatively uniform. The width and shape of the visible plume were consistent with expected thermal convection in room air, with the strongest signal concentrated near the lighter and diffusing as the heated air rose. These results support the theoretical prediction that Schlieren imaging responds to spatial derivatives of refractive index rather than to absolute density.

4 Discussion

The experiment demonstrated that a relatively simple and low-cost optical system can produce clear Schlieren images of thermal flow in air. This is important because many high-performance Schlieren systems rely on expensive optics, precision alignment hardware, and specialized cameras. Our results show that a compact mirror-based system using a consumer camera can still reveal meaningful optical signatures of convection.

The observed contrast is consistent with the expected operation of a Schlieren system. Uniform regions of air do not appreciably deflect light and therefore appear nearly uniform in brightness. By contrast, the steep refractive-index gradients near the lighter bend rays enough to shift their focal-plane position relative to the knife-edge. Depending on the direction of that shift, rays are either more strongly blocked or less strongly blocked, producing alternating dark and bright bands.

Knife-edge placement was one of the most sensitive experimental parameters. If the knife-edge blocked too little of the beam, the image lacked contrast. If it blocked too much, the image became too dim and noisy. The best results were obtained near the half-blocked condition, which agrees with standard Schlieren practice and with the expected tradeoff between sensitivity and dynamic range.

Although the experiment was mainly qualitative, it suggests several paths toward more quantitative analysis. With a calibrated intensity response, image processing could be used to extract line profiles across the plume and compare them to theoretical or numerical models of thermal gradients. A higher-speed or higher-dynamic-range camera could improve temporal resolution and allow more detailed observation of turbulent fluctuations. More stable mounting and controlled illumination would also improve reproducibility.

One limitation of the present setup is that the image quality was constrained by alignment sensitivity, ambient conditions, and the use of a smartphone camera with automatic settings. In addition, the lighter plume is a convenient but somewhat uncontrolled source of refractive-index variation. Even so, the system produced a clear and physically meaningful demonstration of Schlieren imaging.

5 Conclusion

In this project, we designed, built, and tested a single-mirror Schlieren imaging system for visualizing refractive-index gradients in air. Using a concave mirror with focal length 37 cm, a point light source, a knife-edge filter, and an iPhone camera, we were able to observe convection plumes generated by a lighter. The resulting images revealed bright and dark flow structures that were consistent with heat-driven density gradients and dynamic turbulent motion.

These results confirm the central idea of Schlieren imaging: small phase changes caused by refractive-index gradients can be transformed into visible intensity patterns through optical focusing and spatial filtering. The experiment also showed that this effect can be achieved with a relatively accessible system rather than only with large, high-end laboratory equipment.

Future work could extend this system in several directions, including intensity-profile analysis for more quantitative interpretation, background-oriented Schlieren for larger-scale flow visualization, and higher-speed imaging for faster transient phenomena such as combustion instabilities or shock structures. Overall, the project successfully connected ray optics, Fourier optics, and real physical flow phenomena in a clear experimental demonstration.

References

References

[1] G. S. Settles, *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media*. Springer, 2001.

[2] W. Merzkirch, *Flow Visualization*, 2nd ed. Academic Press, 1987.

[3] M. Born and E. Wolf, *Principles of Optics*, 7th ed. Cambridge University Press, 1999.

[4] Harvard Natural Sciences Lecture Demonstrations, "Schlieren Optics." Available: `https://demonstrations.fas.harvard.edu`

[5] NASA, "Schlieren Image Showing Shockwaves Between Two T-38 Aircraft." Available: `https://www.nasa.gov/gallery/schlieren`