

Capturing the Invisible Beauty: Schlieren Imaging Technology Reveals the Secrets of Gas Flow

Yuhong Li

Singapore American School, Singapore, Singapore

terrenceliyh@gmail.com

Abstract. Schlieren imaging technology is a magical tool that can "see" air and temperature fluctuations. Schlieren imaging technology uses the refraction of light to convert tiny changes in fluid substances into visual images, making invisible physical phenomena intuitive and easy to understand. High-end Schlieren imaging systems offered by companies like Holmarc, are designed for advanced applications and come with sophisticated features. These systems can be quite expensive, often costing several thousand dollars, making them less accessible for educational institutions, hobbyists, or researchers with limited budgets. In this project, we designed and constructed an affordable custom Schlieren imaging system utilizing a concave mirror, a point light source, and a knife-edge filter. The system was used to investigate various thermal and aerodynamic phenomena by introducing different heat sources and airflow disruptions. Experiments using hot water, a hair dryer, and a candle flame produced distinct Schlieren patterns: the candle flame exhibited a well-defined transition from laminar to turbulent flow, the hair dryer demonstrated contrasting temperature fluctuations, and hot water vapor diffusion demonstrated clear turbulent thermal plume dynamics. These experiments highlight the system's capability to resolve complex relationships between airflow velocity and heat transfer. In the hair dryer experiment, the speed and temperature of the airflow were vividly captured in the images, helping us better understand the complex relationship between wind speed and heat conduction. One of the most striking results was the imaging of the candle flame. The Schlieren diagram not only revealed the shape of the flame but also visualized the surrounding heat flow dynamics and temperature gradients, illustrating the transition from laminar to turbulent flow. This project demonstrates the great potential of custom Schlieren imaging technology in thermal and fluid mechanics research, providing us with a new visual language to uncover the physical mysteries behind these seemingly ordinary phenomena by "seeing" temperature and airflow. This research has opened up an unprecedented perspective for dynamic monitoring of heat sources and analysis of air flow, and provides more possibilities for future scientific exploration.

Keywords: Schlieren imaging; Air flow; Visualization.

1. Introduction

Visualizing fluid flow and thermal gradients in transparent media has long posed a challenge in fluid dynamics, gas dynamics, and heat transfer research. Traditional optical imaging techniques often fail to directly capture invisible flow structures such as air currents, temperature fields, and shock waves. Schlieren imaging, a highly sensitive optical method, overcomes these limitations by converting minute refractive index gradients—induced by density variations—into observable light intensity changes. This allows researchers to visualize otherwise invisible phenomena including boundary layer development, thermal plumes, and compressible shock structures [1].

The origin of Schlieren techniques dates back to the 17th century when Robert Hooke first investigated refractive effects in airflow. However, it was not until the 19th century that August Toepler developed the modern Schlieren optical arrangement, laying the foundation for systematic flow visualization in scientific experiments [2]. Since then, Schlieren imaging has been widely applied in aerodynamics, supersonic and hypersonic flow studies, combustion diagnostics, and explosion visualization, becoming a key tool in both fundamental and applied fluid mechanics. The principle behind Schlieren imaging lies in the deflection of collimated light rays caused by spatial



variations in the refractive index of a transparent medium. These deflections, though small, are transformed into intensity contrasts by using a knife edge or aperture in the imaging system. The resulting image corresponds to the spatial derivative of the refractive index field, and hence, to the density gradient of the flow [3]. Compared to other flow visualization techniques such as interferometry or particle image velocimetry (PIV), Schlieren imaging offers several advantages: it is non-intrusive, requires no seeding particles, and can be implemented using relatively simple experimental setups. With recent advancements in high-speed cameras, digital sensors, and computational post-processing, modern Schlieren systems now support high temporal and spatial resolution, enabling detailed visualization of fast transient phenomena [4]. High-end Schlieren imaging systems, such as those offered by companies like Holmarc, are designed for advanced applications and come with sophisticated features. These systems can be quite expensive, often costing several thousand dollars, making them less accessible for educational institutions, hobbyists, or researchers with limited budgets. [5]

In this project, an affordable custom schlieren imaging system was designed and constructed using a concave mirror, a point light source, and a knife-edge filter. The setup enabled the visualization of various thermal and aerodynamic phenomena by introducing localized heat sources and airflow disturbances. The resulting high-contrast images effectively captured real-time interactions between airflows and temperature gradients, demonstrating the system's capability in revealing fundamental fluid dynamic and thermophysical behaviors. This platform holds potential for extended applications, such as evaluating exhaled airflow patterns through face masks—relevant to respiratory health and disease transmission studies.

2. Basic Principles

Schlieren imaging is an optical technique that visualizes refractive index gradients in transparent media, which are typically induced by variations in density or temperature. It converts these invisible gradients into detectable variations in light intensity through optical deflection.

2.1. Refractive index change

In a homogeneous medium, light propagates in straight lines. However, when the medium exhibits spatial variations in density, the corresponding refractive index gradient causes the light to bend. The angular deflection θ of a light ray due to a refractive index gradient $\partial x/\partial n$ can be approximated by Snell's Law:

$$\theta \propto \frac{\partial x}{\partial n} \quad (1)$$

This deflection shifts the light ray's trajectory at the image plane. In a classical Schlieren setup, a knife-edge is positioned at the focal point of a concave mirror or lens system to partially obstruct these deflected rays. Light rays that are strongly deflected are either blocked or diverted, producing contrast in the final image. The resulting brightness distribution is thus directly linked to the gradient of the refractive index in the observed medium.

2.2. Link Between Light and Air Density

Refraction causes light to bend as it travels through mediums of different refractive indices. Using knife-edge filtering, we can effectively block some of the refracted light, creating contrast in the final recorded image, allowing us to visualize the relative refractive indices of different sections of the medium [6]. The refractive index of a medium, n , is based on the density of the medium, as described in the Gladstone-Dale equation:

$$n = 1 + kp \quad (2)$$

Where k is the Gladstone-Dale constant, a material-dependent coefficient. This equation is commonly used in aerodynamics and fluid dynamics to relate variations in air density to optical refraction effects. Density can be calculated using the Ideal Gas Law:

$$p = \frac{P}{R \times T} \quad (3)$$

Where: P is the pressure, T is the temperature, R is the specific gas constant.

The diffraction angle Θ of a beam of light through a refraction index gradient is:

$$\epsilon_x = \frac{1}{n} \int \frac{\partial n}{\partial x} dz \quad \epsilon_y = \frac{1}{n} \int \frac{\partial n}{\partial y} dz \quad (4)$$

Where:

- n : background refractive index
- $\partial x, \partial y, \partial n$: refractive index gradients
- Integration is along the light-path

The relative intensity change, $\frac{\Delta I}{I_0}$, at the detector due to knife-edge filtering is:

$$\frac{\Delta I}{I_0} = a \cdot \epsilon_y \quad (5)$$

Where a is the system sensitivity factor. More generally:

$$\Delta I \propto \int \frac{\partial n}{\partial y} dz \quad (6)$$

Showing that image contrast reflects the integrated refractive index along the light path [6].

3. System design and construction

3.1. Overall light path system design

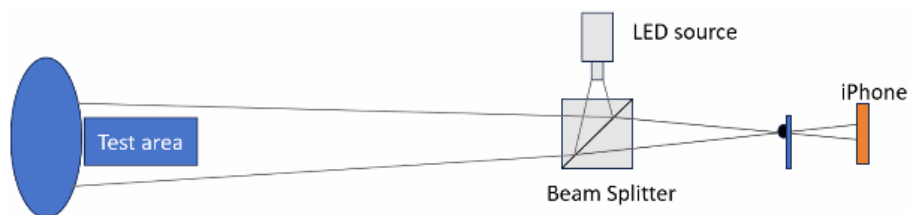


Figure 1. Optical path structure diagram

The Schlieren imaging system adopts a typical coaxial optical path design, which mainly includes components such as a point light source, a beam splitter, a test area, a knife edge and a camera (Fig.1)

[8]. First, the point light source emits a high-brightness, collimated light beam, which is reflected by the beam splitter and irradiated to the test area.

When the light passes through the area, if there is a change in the refractive index caused by temperature or density (such as hot air, airflow, etc.), the light will be slightly deflected. The deflected light passes through the beam splitter again and is guided into the camera lens. A knife edge (or a digital knife edge simulated by software) is set near the focal plane of the camera to partially block the deflected light, so that light with different degrees of deflection shows brightness differences in the image. Finally, the camera records these changes in light intensity to generate a high-contrast Schlieren image reflecting the refractive index gradient distribution, realizing the visual analysis of phenomena such as gas flow, thermal plumes and shock waves. In the Schlieren imaging system, a concave mirror served as the primary optical element, paired with a high-intensity white LED acting as the point light source. A 50:50 beam splitter cube was positioned at a 45° angle between the LED and the mirror to facilitate a single-axis optical path. Light emitted from the LED passed through the beam splitter and was reflected by the concave mirror through the test region. Any refractive index gradients—caused by thermal or airflow disturbances—resulted in angular deflections of the collimated beam. The distorted wavefronts were then reflected back toward the beam splitter, which redirected the returning light laterally toward the knife edge and camera assembly. (Figure 1)

3.2. Hardware selection



Figure 2. Collimated Light Source

The system (Fig. 2) employs a high-brightness white LED point light source as the illumination component. White light offers broad spectral coverage, stable output, and minimal heat generation, making it well-suited for high-contrast Schlieren imaging in the visible range [9]. A collimating lens is used to focus the LED into a near-point source, thereby enhancing the system's sensitivity to minute light deflections caused by refractive index gradients.

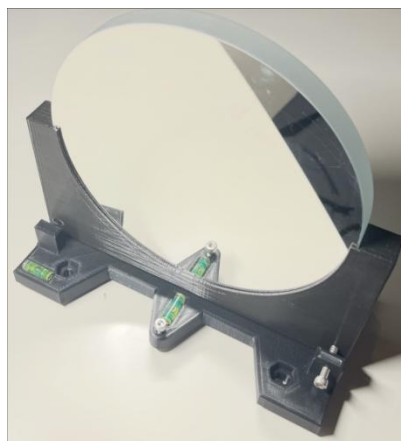


Figure 3. Concave Mirror

A concave mirror (Fig. 3) with a focal length of 750 mm is used as the primary imaging element. The long focal length contributes to improved collimation, greater optical path stability, and higher spatial resolution—allowing the system to detect small variations in air density. Additionally, it increases the size of the measurable test area, making the setup suitable for observing medium-scale flow fields and thermal gradients [10]. The mirror is positioned at the terminal end of the optical path, focusing the beam—after interaction with the test region—onto the knife edge for intensity modulation.



Figure 4. Beam Splitter

A 50:50 beam splitter (Fig. 4) directs the collimated light from the source toward the concave mirror and subsequently channels the returned beam to the imaging sensor. This configuration enables a compact, coaxial optical layout that minimizes alignment complexity while maintaining system robustness and precision.



Figure 5. Knife-Edge Assembly

A finely machined blade is positioned at the focal plane of the concave mirror to serve as the knife edge. It selectively blocks deflected light rays, converting refractive index gradients into observable intensity variations. By adjusting the knife-edge (Fig. 5) orientation and position, the system's directional sensitivity can be finely tuned to highlight specific flow features or thermal disturbances.

3.3. Light path construction

The operational mechanism of Schlieren imaging involves several key steps. Initially, a bright, point-like light source is used, and its rays are collimated into parallel beams using a lens or a parabolic mirror. These collimated rays traverse the test area, where any density variations cause them to refract. Upon exiting the test area, the light is focused by another optical component, and a knife-edge or similar cutoff device is positioned at the focal point to partially block the light. The resulting image, formed on a screen or captured by a camera, reveals the density variations as variations in brightness or darkness.



Figure 6. Complete Schlieren system. 2.(a) Vertical View. 2.(b) Horizontal View

4. Experiment

During the experiment, a high-brightness white LED point light source is first passed through a collimator to form an approximate point light. The light beam is reflected by a beam splitter and then irradiated into the test area. Objects to be measured, such as hot water, hair dryers, etc., are placed in the measured area. The deflected light is reflected by a concave mirror and passes through the beam splitter again to be guided to the camera light path. At the same time, a knife edge is set at the focal position to block part of the deflected light to form a light-dark contrast. Finally, the camera records the image to visualize the gas density or temperature gradient. The entire process does not require contact with the measured medium, is easy to operate, and has high imaging sensitivity [11].

4.1. Candle

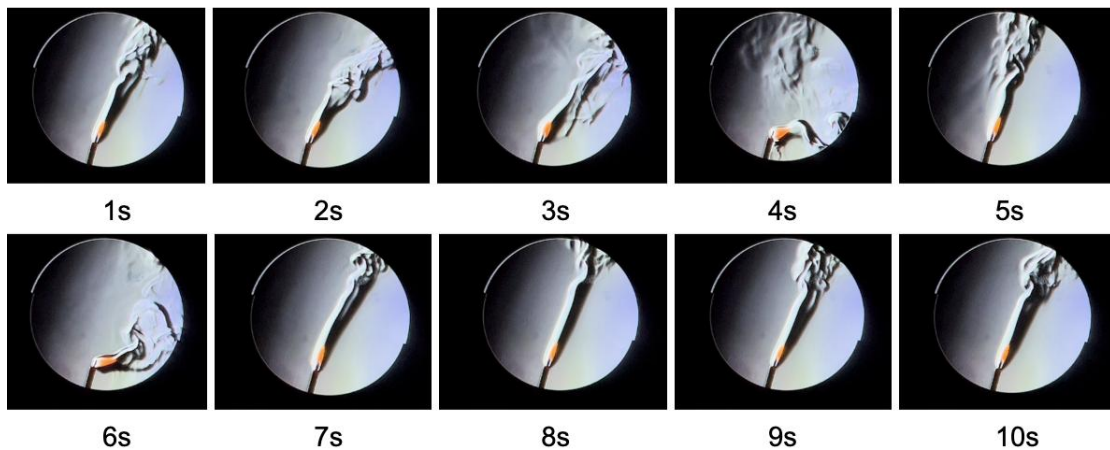


Figure 7. The candle was blown at around 2 seconds, causing the plume of hot air to bend to the right. At the seventh second, the blowing ceased, and we can see the plume return to its original shape. Undisturbed, the schlieren system captured the characteristics of the flow of the flame: a laminar-turbulent transitional flow

The candle flame exhibited a well-defined transition from laminar to turbulent flow (see Figure 7). One of the most remarkable results is the imaging of the candle flame. We can not only see the shape of the flame, but also reveal the heat flow dynamics and temperature changes around the flame through the schlieren diagram.

4.2. Hot Water

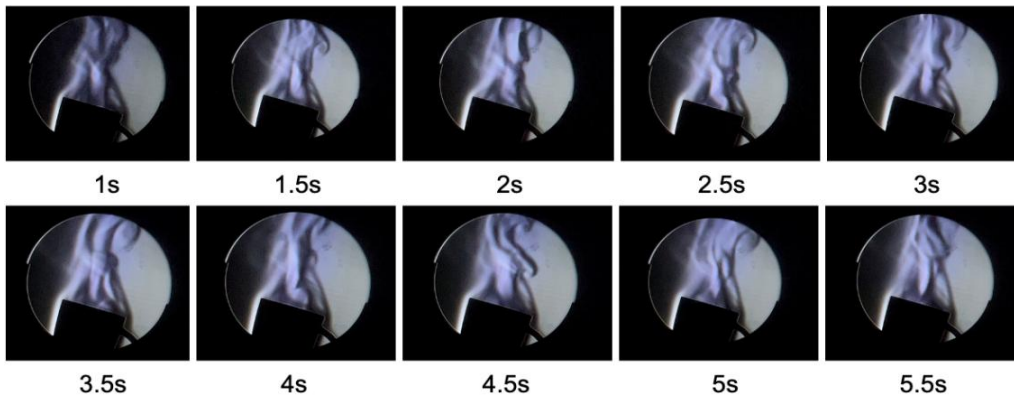
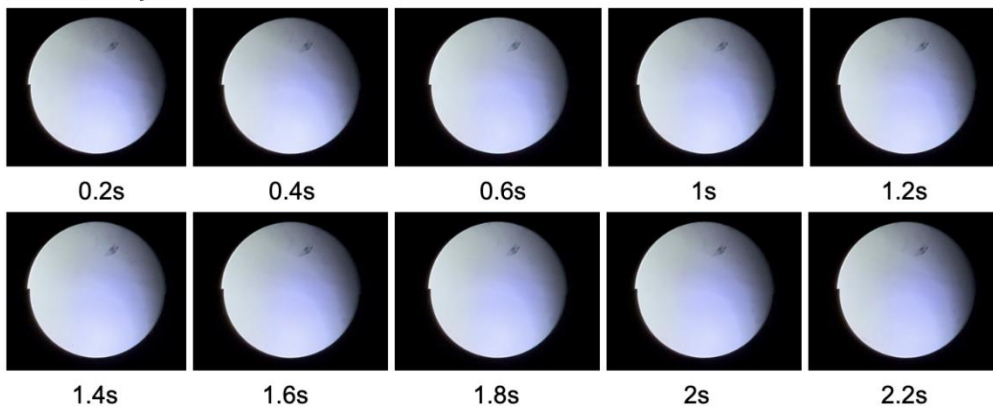


Figure 8. The evaporation of the water from the mug forms a turbulent plume of hot water vapour directly above the surface of the water. The hot plume slowly diffuses and loses its buoyancy due to entrainment by the cold air in its surroundings

Hot water vapor diffusion demonstrated clear turbulent thermal plume dynamics. From Figure 8 we can see that the hot plume slowly diffuses and loses its buoyancy due to entrainment by the cold air in its surroundings.

4.3. Cool Hair Dryer and Hot Hair Dryer

Cool Hair Dryer



Hot Hair Dryer

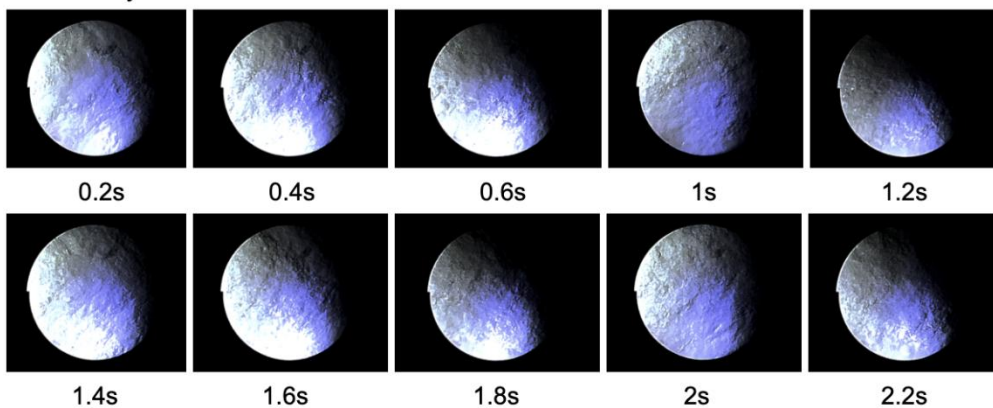


Figure 9. The cold hair dryer had little to no effect on the schlieren image, whereas fluctuations of the hot air dryer can be seen clearly. This illustrates the impact of temperature on the sensitivity of Schlieren systems

In the hair experiment (see Fig 9), the speed and temperature of the airflow are vividly presented in the image, the cold hair dryer had little to no effect on the Schlieren image, whereas fluctuations of

the hot air dryer can be seen clearly, helping us to deeply understand the complex relationship between wind speed and heat conduction.

5. Conclusion

In this project, a custom Schlieren imaging system was designed and constructed using a concave mirror, a point light source, and a knife-edge filter. The assembled system was utilized to visualize thermal and aerodynamic phenomena by introducing various heat sources and airflow disruptions into the test region.

Controlled experiments were conducted with heat sources including hot water, a hair dryer, and a candle flame. Each source produced distinct Schlieren patterns. The candle flame revealed clearly defined convection currents, while the hair dryer generated turbulent flow structures. The diffusion of hot water vapor was also prominently visualized, effectively illustrating the interaction between localized temperature variations and ambient airflow.

In addition to thermal sources, the system was employed to observe airflow behavior during blowing. These tests revealed complex flow structures such as vortices, wake formations, and boundary layer development. These findings demonstrate the capability of the Schlieren setup to capture real-time variations in air density and visualize the dynamic nature of fluid interactions with exceptional clarity.

The successful execution of these experiments affirms the effectiveness of Schlieren imaging for exploring fundamental principles in fluid dynamics and thermophysics. Potential future applications of this system include the analysis of exhaled airflow through face masks—relevant for respiratory health and disease transmission studies—as well as investigations into the aerodynamic performance of sports equipment, airflow in ventilation systems, and thermal management in electronic devices. Moreover, the integration of high-speed imaging, digital processing techniques, and computational fluid dynamics (CFD) has the potential to significantly enhance the analytical capabilities of Schlieren systems. These advancements could allow for more precise characterization of transient and high-speed flow phenomena.

Overall, this project demonstrates the utility of Schlieren imaging as a powerful and versatile tool for visualizing invisible flow and thermal interactions. By providing qualitative and potentially quantitative insight into fluid behavior, this technique offers valuable contributions to both scientific research and engineering development. The outcomes of this study lay the groundwork for expanded experimentation and future interdisciplinary investigations.

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