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Effect of Gas Temperature on Refractive Index Gradients and Schlieren Visualization of Shielding Gas Flows

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EFFECT OF GAS TEMPERATURE ON REFRACTIVE INDEX GRADIENTS AND SCHLIEREN VISUALIZATION OF SHIELDING GAS FLOWS

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Abstract:
Gas shielding plays a fundamental role in arc welding processes. A wide range of shielding gas compositions can be employed, whose primary functions are to protect the molten weld pool and the electrode from interaction with the surrounding atmosphere, while also providing stable conditions for the electrical arc. Investigating the behavior of shielding gas as it flows through the nozzle is an effective approach to improving welding torch designs and enhancing the understanding of gas flow. Among the various experimental techniques, Schlieren photography is a versatile optical method for visualizing gas flows, based on the deflection of light rays caused by refractive index gradients. Since different gases possess distinct physical properties, some provide significantly better visualization than others under identical conditions. Argon (Ar), one of the most widely used shielding gases in welding, exhibits low optical contrast at room temperature, making its flow difficult to visualize. Carbon dioxide (CO_2), on the other hand, can be clearly visualized under the same conditions. This study evaluates the influence of gas temperature on Schlieren visualization of argon (Ar), carbon dioxide (CO_2), and atmospheric air. Using a GTAW torch, these gases were tested at different temperatures with ambient air as the surrounding medium, resulting in changes in refractive index gradients and image contrast. Theoretical and experimental analyses demonstrate that increasing the temperature of argon and air enhances Schlieren image contrast, whereas carbon dioxide exhibits a progressive reduction in contrast with increasing temperature. These findings indicate that controlled gas heating represents a simple and effective approach to improving Schlieren image quality in gas flow studies.

Keywords Schlieren visualization; Argon and CO_2 Shielding Gas, Thermal effects on refractive index; Gas flow in welding torches.

1 INTRODUCTION

Shielding gas flow plays a critical role in arc welding processes, directly affecting arc stability and weld quality [2, 8, 11, 12]. Several experimental techniques have been proposed to characterize this flow, as reviewed by Barancelli Schwedersky *et al.* [2] and Dreher *et al.* [14]. Among these techniques, particle-based methods such as Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) can be employed to experimentally determine shielding gas flow profiles. Another approach consists of using a refrigerated copper base with a small-diameter hole to collect shielding gas samples and direct them to an oxygen sensor. By varying the position of the sampling hole relative to the torch through a displacement system, it becomes possible to obtain a two-dimensional mapping of the oxygen concentration over the workpiece surface. However, many of these methods require complex setups and involve high operational costs. In this context, Schlieren emerges as a relatively simple and cost-effective alternative for visualizing gas flow fields. Its effectiveness, however, strongly depends on refractive index gradients between the flowing gas and the surrounding atmosphere, which directly influence image contrast and resolution [2, 7, 8 14].

Schlieren is an optical technique that enables the visualization of transparent media by detecting light deflections caused by density gradients. These gradients arise from variations in temperature, pressure, and gas composition, which modify the refractive index of the medium and, consequently, the propagation of light [12]. In welding applications, this technique allows the analysis of shielding gas flow behavior and the assessment of shielding effectiveness. Inadequate flow conditions may promote air entrainment into the arc and molten pool, leading to porosity, oxidation, and arc instability. Furthermore, such analyses support the optimization of torch and nozzle designs, contributing to improved gas coverage and reduced operational costs [2].

The suitability of shielding gases for Schlieren visualization depends strongly on their optical properties. Among others, Argon (Ar), can be viewed as the most important shielding gas for arc welding, since it is by far the most used gas for GTAW (Gas Tungsten Arc Welding) for all different metals, and also the most used gas for GMAW (Gas Metal Arc Welding) with pure Argon being used for aluminum alloys and Argon rich mixtures (containing small quantities of O_2 or CO_2) used for steel welding. One limitation of the Schlieren technique is that argon presents a refractive index very close to that of atmospheric air, making its flow difficult to visualize under ambient conditions [2, 5, 11]. In contrast, gases such as helium and carbon dioxide (CO_2) produce Schlieren images with significantly higher contrast due to their larger refractive index differences relative to air. This difference in visualization quality is illustrated in Fig. 1, where helium and CO_2 flows exhibit significantly greater contrast than argon.

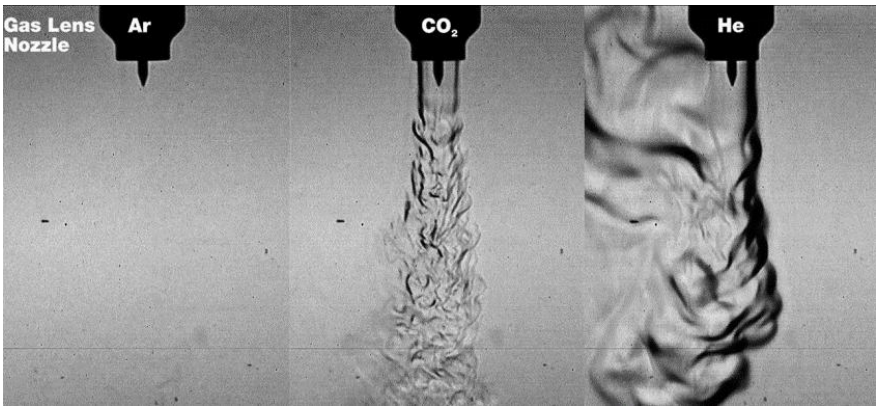


Fig. 1 Schlieren Visualization of Gas flow using (Ar, CO_2, He) in Air [2]

Previous studies have consistently reported this behavior. Barancelli Schwedersky *et al.* [2] and Bitharas *et al.* [5] demonstrated that argon produces low-contrast images even under different flow conditions, while helium provides significantly improved visualization. Additional studies on GMAW shielding efficiency [6] and laser welding applications [7] further confirm the strong influence of gas properties on Schlieren image quality.

Despite these advances, the influence of gas temperature on Schlieren visualization remains insufficiently understood. While thermal effects are known to affect shielding performance, their direct impact on refractive index gradients and image contrast has not been systematically investigated for different gases under comparable conditions.

Previous work by Barancelli Schwedersky *et al.* [2] showed that Schlieren lines can become visible in regions where argon shielding gas is heated by the welding arc. However, in such conditions, the effects of temperature and gas flow cannot be independently distinguished, since the arc simultaneously modifies the thermal and flow fields. Therefore, a controlled investigation of gas temperature is necessary to isolate its specific contribution to Schlieren visualization.

In this context, the present study investigates the effect of gas temperature on Schlieren visualization of argon (Ar), carbon dioxide (CO_2), and atmospheric air using a GTAW torch. The analysis combines theoretical predictions of refractive index and light deflection with experimental observations. This research aims to provide new insights into thermal effects in gas flow visualization and contribute to the optimization of Schlieren-based diagnostics in welding research. By performing the experiments without an electric arc and under controlled gas temperatures, the present approach allows the thermal contribution to Schlieren visualization to be evaluated independently of arc-induced effects. Since the shielding gas flowing around the arc can be heated in some regions, it is important to understand how these temperature variations can affect image visualization.

2 MATERIALS AND METHODS

2.1 Theoretical Background

The Schlieren technique can be implemented using two main optical configurations for gas flow visualization, both based on the Toepler system (Fig. 2). In either configuration, a light source, optical elements (lenses or mirrors), a knife-edge (or cutoff aperture), and an imaging system are employed for data acquisition [11]. Comprehensive reviews of Schlieren systems and recent developments are provided by Settles and Hargather [12], while detailed descriptions of the operating principles can be found in Settles [8].

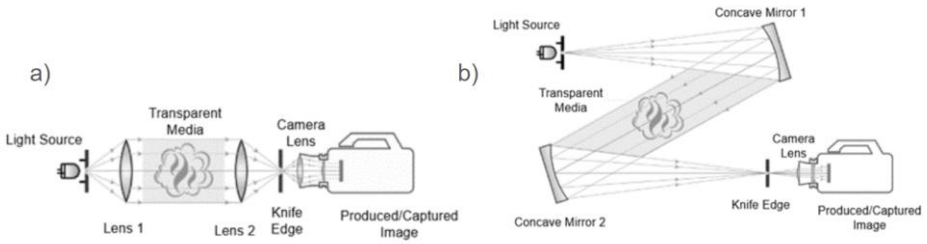


Fig. 2 Schlieren system configurations: (a) Toepler system; (b) Z-type Toepler system [11]

In a typical configuration, light emitted from the source is first collimated and directed parallel to the optical axis before being focused by a second optical element onto its focal plane. At this location, a knife-edge partially blocks light rays deflected by refractive index gradients within the medium. As a result, variations in light intensity are formed at the image plane, enabling flow visualization. The position of the knife-edge is a critical parameter, as it directly affects image contrast and system sensitivity. Misalignment can significantly degrade Schlieren image quality [11].

Another important parameter is the fraction of light blocked by the knife-edge. Lower blockage allows more light to reach the camera, resulting in low-contrast images and potential saturation. Conversely, higher blockage increases contrast but may reduce sensitivity to weak density gradients [8].

To visualize the flow, the light source is first focused by the initial lens or mirror, which collimates the beam and directs it parallel to the optical axis toward the second optical element. This element then reconverges the rays at its focal plane, where the knife-edge is positioned. The knife-edge partially blocks the light rays that are deflected by refractive index gradients in the medium. The resulting light intensity at the image plane depends on the knife-edge position, and its adjustment is essential to ensure proper focal-plane conjugation and to maximize image contrast. Small deviations in this alignment can significantly compromise the sensitivity and overall performance of the Schlieren system [11].

While the optical arrangement defines how light is manipulated within the Schlieren system, the formation of visible flow structures is fundamentally governed by variations in the refractive index of the medium. The refractive index of a gas depends on its molar refractivity, density, pressure, temperature, and other relevant physical properties. For gases, an approximately linear relationship exists between refractive index and density [11], indicating that variations in thermodynamic conditions directly influence light deflection and, consequently, Schlieren image formation.

Considering that, it is expected that the use of a heated gas flow could be a solution to drastically improve the Schlieren visualization capability for pure argon or argon-rich shielding gas mixtures, since it can increase the refractive index difference relative to the surrounding atmospheric air. Although the absolute refractive index of argon decreases with heating, the resulting refractive index gradients within the flow field produce larger light-ray deflections, leading to improved image contrast.

According to Bauchire *et al.* [3], the refractive index of argon varies approximately linearly with temperature over a wide range, with more pronounced variations at temperatures below 2000 K. This behavior allows the refractive index to be estimated at different temperatures based on a known reference value, as illustrated in Fig. 3.

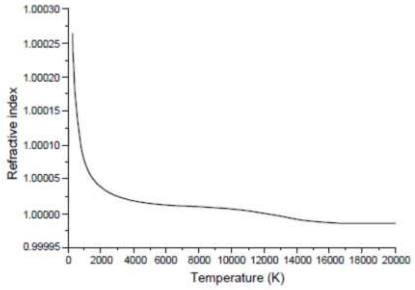


Fig. 3 Refractive index of argon as a function of temperature for λ = 632.8 nm [3]

The absolute refractive index, n, describes the speed of light in the medium and is directly related to gas density ρ [4,8]. Therefore, any change in temperature or pressure that alters density will directly affect the optical response observed in Schlieren imaging.

To quantitatively describe this behavior, the relationship between refractive index, density, and thermodynamic variables can be expressed through the following formulations:

$$n - 1 \propto \rho \tag{1}$$

Where:

$$\lim_{T \to \alpha} n = 1 \tag{2}$$

$$\rho = \alpha \frac{P}{T} \tag{3}$$

Assuming that the atmospheric pressure (P) does not vary with increasing gas temperature, the density of argon becomes inversely proportional to its absolute temperature (T). It therefore follows that:

$$n - 1 \propto \frac{P}{T} \tag{4}$$

The simplified relationship that allows estimation of the refractive index of argon at a new temperature (T), based on a known value at a reference temperature, is directly derived from this proportionality:

$$n_t \approx 1 + \left(n_{298[k]} - 1\right) \times \left(\frac{298[K]}{T}\right) \tag{5}$$

Where n is the refractive index and T is the temperature in Kelvin.

According to Settles [8], the maximum ray deflection angle (ε_{max}) of light between a fluid with refractive index n_t and the surrounding medium n_0 can be used as an indicator of system sensitivity and image contrast in Schlieren visualization. A larger deflection corresponds to stronger light refraction and can be calculated using Equation (6), with the result expressed in arc seconds [8]:

$$\varepsilon_{max} = 2 \times \left(\frac{n_t}{n_0} - 1\right) \times 206265 \tag{6}$$

As indicated by Equation (6), Schlieren image contrast increases with the magnitude of the maximum ray deflection (ε_{max}). Thus, the greater the deflection, whether positive or negative, the stronger the intensity of the brightness variations observed in the image.

For the specific case of CO_2, and according to Marchetti and Simili [10], the refractive index of low-density gases exhibits a linear dependence on density [1, 13]. Under this approach, the refractive index can be determined using the following equations:

$$n = 1 + \alpha_P(T) \times P \tag{7}$$

$$\alpha_P = \frac{\alpha_\rho}{RT} \tag{8}$$

Where n is the refractive index, α_p is the experimentally determined pressure constant that varies with the wavelength of the incident light, R is the universal gas constant, T is the absolute temperature, and P is the atmospheric pressure [10].

Using Equations (7) and (8) and considering $\alpha_p = 9.935 \times 10^{-6}$ m³/mol, $R = 8.314$ J·mol^{-1}·K^{-1} [11], and $P = 0.101$ MPa, the refractive index of CO_2 can be determined as a function of temperature.

2.2 Experimental Setup and Procedure

The experiments described in this study were conducted with shielding gas flowing exclusively through the welding torch, without the presence of an electric arc. The Schlieren optical arrangement followed the "Z-type" configuration originally proposed by Toepler, as illustrated in Figure 4. A high-speed camera (Photron FASTCAM NOVA S9) was used for image acquisition, and the collimated light source was a led.

A more detailed description of the Schlieren system layout and alignment procedures for the Toepler "Z-type" configuration can be found in Okuyama, M. P. *et al.* [11].

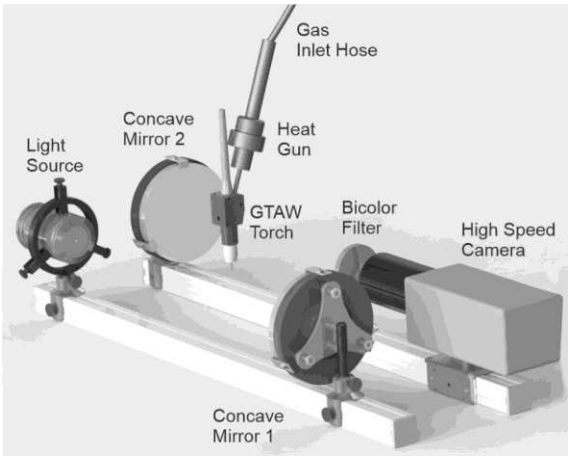


Fig. 4 Experimental Schlieren setup and arrangement of the system components

To investigate the effect of temperature on Schlieren image contrast, an electrically driven heating system was employed to generate controlled thermal gradients in the gas flow. Heating was performed using an analog SMD rework station (model SE-850), equipped with a 250 W hot-air blower and adjustable temperature control.

Gas temperatures of 30 °C, 60 °C, 100 °C, 150 °C, and 180 °C were evaluated, enabling the analysis of refractive index variations and their influence on Schlieren image contrast under different thermal conditions. Temperature measurements were obtained using a portable industrial contact thermometer (S&E Instruments, model 1710-K), with an operating range of − 70 °C to 1250 °C, which was positioned directly above the torch nozzle.

The experiments were conducted using a GTAW torch fitted with a ceramic gas lens cup (53N61 #7). The shielding gases investigated were pure argon, pure carbon dioxide (CO_2), and compressed atmospheric air. The gas flow rate was maintained at 15 ± 1 L/min in all tests to ensure consistent flow conditions across different thermal and gas composition scenarios.

3 RESULTS AND DISCUSSION

The Schlieren images reveal that gas temperature significantly affects optical contrast. For compressed air and argon, increasing the flow temperature enhances image contrast, whereas carbon dioxide (CO_2) exhibits the opposite behavior, with contrast decreasing as temperature increases. Under the 30 °C condition, the gas flow exiting the nozzle is not discernible for air and presents low visual contrast for argon, which is consistent with previous findings reported in the literature [2, 6]. As the temperature increases beyond approximately 50 °C, the flow becomes visible, and between 100 °C and 180 °C the flow structure and its thermal evolution can be clearly identified, allowing a qualitative assessment of the flow behavior and its stability. These trends are illustrated in Figures 5 and 6 (see Supplementary Video S1 and Video S2). As expected, for all the temperatures the argon flow produced a slight better contrast than air, due its physical properties.

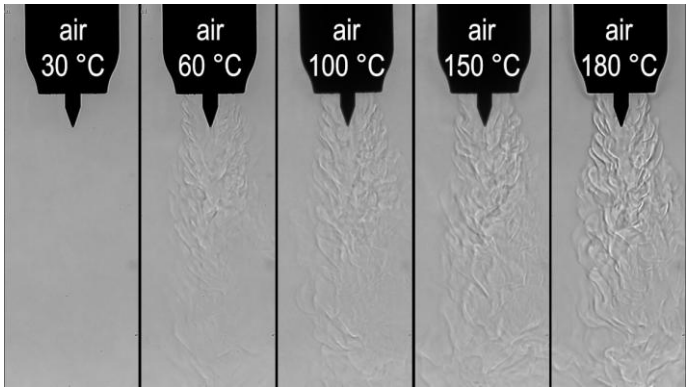


Fig. 5 Schlieren images of compressed air flow at different temperatures

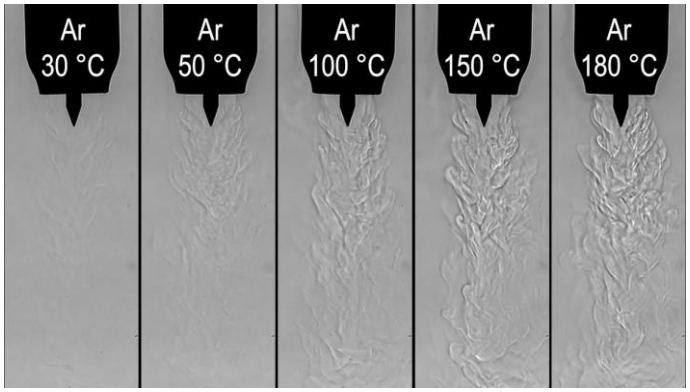


Fig. 6 Schlieren images of argon flow at different temperatures

In contrast, carbon dioxide presents a clearly visible flow at 30 °C, indicating a stronger refractive index gradient at low temperatures. However, at higher temperatures, particularly at 180 °C, a systematic degradation of image contrast was observed, which compromises the definition of the flow path in the Schlieren images, as shown in Figure 7 (see Supplementary Video S3).

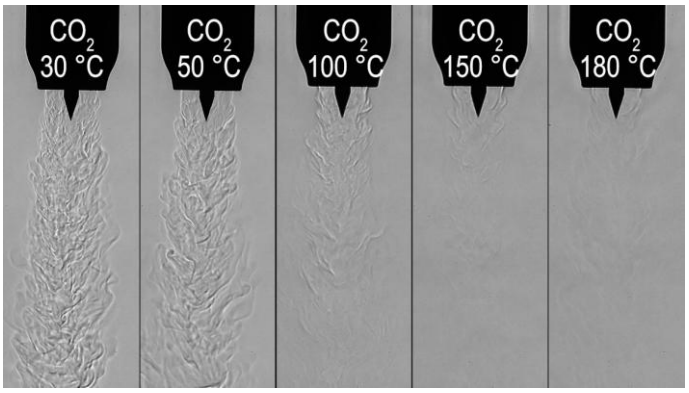


Fig. 7 Schlieren photographs of CO2 flow at different temperatures

To support the experimental observations, the refractive index of carbon dioxide (CO_2) was calculated using Equations (7) and (8). Similarly, Equations (5) were applied to argon and atmospheric air, while Equation (6) was used to determine the maximum angular deviation of the gases relative to air at 27 °C. The values obtained from these equations are presented in Figures 8 and 9.

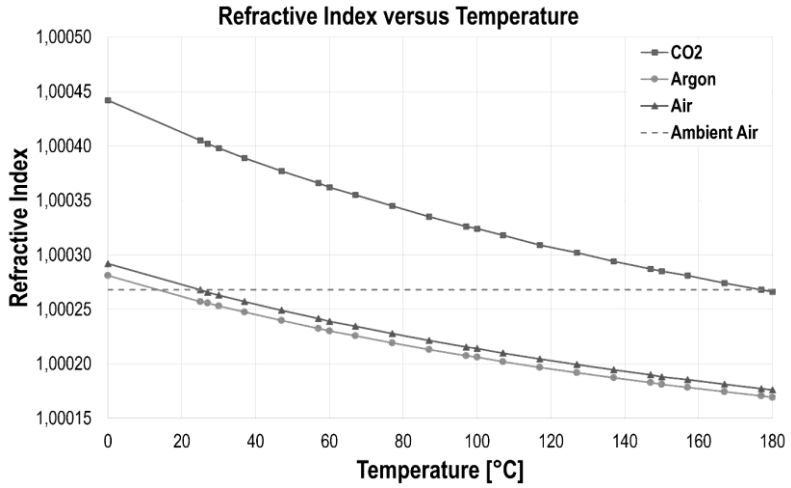


Fig. 8 Refractive index as a function of temperature

The refractive index of all three gases decreases progressively with increasing temperature, as shown in Figure 8. This behavior results from the reduction in gas density due to thermal expansion, which leads to a lower number of particles per unit volume available to interact with light. Classical studies have shown that the refractive index of gases varies with temperature as a consequence of changes in density, as discussed by Lukhovitskii *et al*. [9].

Since the refractive index expresses the ratio between the speed of light in vacuum and its speed in the medium [8], a lower optical density implies a higher light propagation velocity. However, the influence of temperature on Schlieren image contrast does not depend on the absolute value of the refractive index, but rather on the relative refractive index difference between the heated gas and the surrounding medium. Depending on the gas, this relative difference may lead either to an enhancement or to a degradation of image contrast. This explains why gases exhibiting the same qualitative decrease in refractive index with temperature can present opposite trends in Schlieren visibility.

Among the gases evaluated (Figure 8), CO_2 exhibits the highest absolute refractive index at environment temperature, whereas argon presents the lowest value. This difference is directly associated with the molecular properties and specific densities of each gas under identical thermodynamic conditions. As expected, with increasing temperature, the refractive indices of all gases gradually converge toward values

close to unity, corresponding to the refractive index of vacuum [4]. This gradual reduction is clearly observed in Figure 7, confirming the theoretical behavior predicted for ideal gases subjected to heating.
In the case of compressed air and argon, the maximum angular deviation (ε_{max}) at ambient temperature is close to zero. However, as the temperature increases up to 180 °C, the ε_{max} values become progressively more negative. This increase in magnitude, despite the opposite sign, enhances the optical difference relative to the surrounding air and, consequently, the Schlieren image contrast. As a result, a clearer visualization of the gas flow is achieved for these gases at elevated temperatures.
By contrast, CO_2 exhibits the opposite behavior: increasing temperature reduces the magnitude of ε_{max} as the refractive index difference relative to the surrounding air decreases, producing smaller angular deflections of light rays and consequently lower Schlieren image contrast.

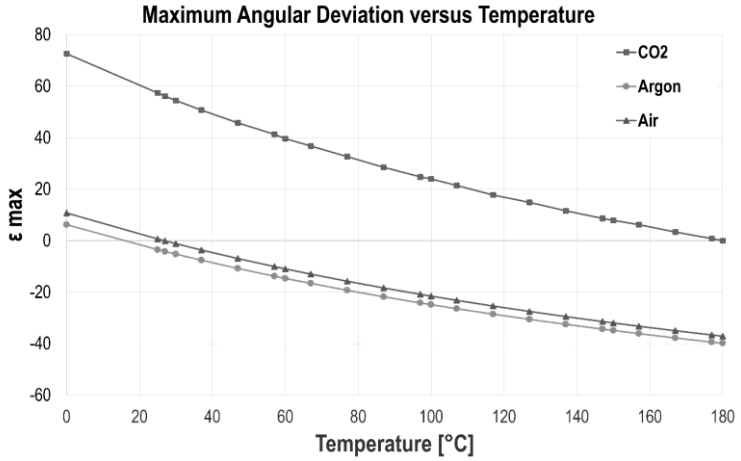


Fig. 9 Maximum Angular Deviation as a function of temperature

The Schlieren image contrast is not governed by the absolute value of the refractive index, but rather by the relative difference between the heated gas and the surrounding medium, and this relationship is quantified by the maximum light-ray deflection, shown in Figure 9. For compressed air and argon, the ε_{max} values at ambient temperature are close to zero, explaining the inherent difficulty in visualizing these flows under cold conditions (23°C), as presented in Figure 1. However, as the temperature increases to 180 °C, the ε_{max} values become progressively more negative. This increase in absolute magnitude enhances the optical gradient relative to the surrounding air, leading to a significantly clearer visualization of the flow.
The magnitude of refractive index variations for the three investigated gases, CO2, Argon, and Air, at temperatures of 30°C, 60°C, 100°C, 150°C, and 180°C are graphically depicted in Figure 10, relative to the ambient conditions of the imaging environment (Air at 25°C).
When CO_2 is heated, its density and refractive index decrease, reducing the refractive index gradient relative to the surrounding air. Consequently, the maximum angular light deflection decreases, indicating weaker refraction and, therefore, reduced Schlieren image contrast. This angular deflection is fundamental to the technique, since image contrast is generated by converting these angular deviations into variations of light intensity at the image plane: the greater the magnitude of ε_{max}, the more pronounced the brightness variation in the corresponding region.
The experimental analysis confirms the theoretical trends. Figure 10 illustrates the magnitude of refractive index variations relative to ambient conditions (Air at 25°C). This data reveals why CO_2 exhibits the opposite behavior compared to the other gases: as it is heated, its density decreases to a point where its refractive index approaches that of the surrounding atmospheric air. Consequently, the magnitude of ε_{max} decreases, leading to a deterioration of contrast and a less distinct flow visualization.

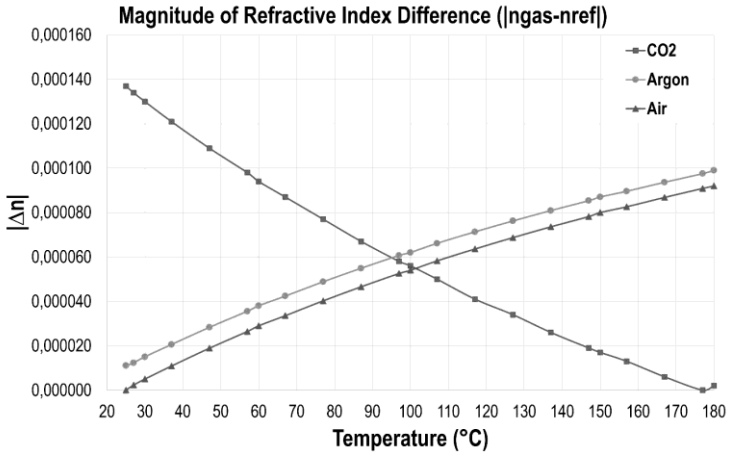


Fig. 10 Magnitude of Refractive Index variations for CO2, Argon, and Air at temperatures of 30°C, 60°C, 100°C, 150°C, and 180°C, relative to the ambient conditions (Air at 25°C)

Physically, the sign of ε_{max} defines the direction of the deviation relative to the optical axis, determining whether the disturbed region will appear brighter or darker than the background in the final image, depending on the knife-edge/color-filter configuration at the focal plane. However, the visibility of the structure depends primarily on the absolute magnitude of ε_{max}. As the refractive index of the gas approaches that of the surrounding medium, the deflection tends to zero. In this limit, no detectable optical variation exists, the contrast vanishes, and the gas becomes effectively invisible to the Schlieren system [8, 12].

When the air is heated, its density decreases locally, generating refractive index gradients relative to the colder ambient air. These gradients produce angular deflections of the light rays, which are converted into intensity variations by the knife edge. As a result, the heated air becomes clearly visible in the Schlieren images. This confirms that temperature-induced density gradients alone are sufficient to generate strong Schlieren contrast, reinforcing the central role of thermal effects in flow visualization using this technique [8, 9].

4 CONCLUSIONS:

The results demonstrate that increasing the temperature of argon significantly improves the contrast of Schlieren images. Although the absolute refractive index of argon decreases with temperature, the relative refractive index difference between heated argon and the surrounding air increases. As a consequence, the absolute value of the maximum light-ray deflection (ε_{max}) increases, intensifying the optical contrast and making the gas flow more clearly visible.

In contrast, CO_2 exhibits the opposite behavior in Schlieren visualization. As temperature increases, its refractive index also decreases; however, within the analyzed range, the magnitude of the maximum ray deflection decreases. This reduction lowers the refractive index gradient relative to the ambient air, causing the gas to become progressively less visible to the Schlieren system.

Therefore, controlled heating of argon represents an efficient strategy to enhance the visualization of gas flows and related phenomena in Schlieren-based experiments, whereas for CO_2, increasing temperature tends to limit the quality of observation.

Finally, the results also provided image examples with the contrast produced by Schlieren-based flow analysis with heated air in different temperatures. This results can be used as temperature reference for diverse Schlieren experiments involving low speed air flow which would not provide results with sufficient contrast without heating the air flow.

5 SUPPLEMENTARY INFORMATION

This article cites the supplementary videos. **Video S1**: Schlieren images of compressed air flow at different temperatures. **Description:** High-speed imaging (Total Frames: 1001; Frame rate: 5000 fps; Shutter Speed: 1/40000 s) The Schlieren images reveal a clear dependence of optical contrast on the gas temperature. Higher flow temperatures for compressed air result in a progressive enhancement of image contrast between the heated gas and the surrounding medium. For compressed air, the gas flow exiting the nozzle is not discernible at 30 °C. As the temperature increases beyond approximately 50 °C, the flow becomes visible, and between 150 °C and 180 °C the flow structure and its thermal evolution can be clearly identified, allowing a qualitative assessment of the flow behavior and its stability. **Video S2:** Schlieren images of argon flow at different temperatures. **Description:** High-speed imaging (Total Frames: 1001; Frame rate: 5000 fps; Shutter Speed: 1/40000 s) The Schlieren images reveal a clear dependence of optical contrast on the gas temperature. Higher flow temperatures for argon result in a progressive enhancement of image contrast between the heated gas and the ambient air. For argon, the gas flow exiting the nozzle is Barely perceptible at 30 °C. As the temperature increases beyond approximately 50 °C, the flow becomes visible. Between 100 °C and 150 °C, the flow structures are well-defined; at 180 °C, the contrast is further enhanced, providing a detailed view of the gas dynamics and stability. **Video S3:** Schlieren images of CO2 flow at different temperatures. **Description:** High-speed imaging (Total Frames: 1001; Frame rate: 5000 fps; Shutter Speed: 1/40000 s) The Schlieren images reveal a clear dependence of optical contrast on the gas temperature. In contrast to air and argon, carbon dioxide (CO_2) exhibits a gradual reduction in image contrast as the temperature rises. At 30 °C, carbon dioxide presents a high-contrast image with a clearly visible flow, indicating a strong refractive index gradient at low temperatures. However, a systematic degradation of optical contrast is observed at higher temperatures, particularly at 180 °C, which compromises the definition of the flow boundaries in the Schlieren images.

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COMPETING INTERESTS
The authors declare that they have no competing financial or non-financial interests that could have influenced the work reported in this article.

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Contributions
All authors contributed to the study conception and design. Each author developed the following activities: Michel Scheffer Durieux: Conceptualization, Methodology, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization and Submission. Joffre Luis Brito Guaricela: Methodology, Validation, Formal analysis, Writing - Original Draft, Writing - Review & Editing. Marcelo Pompermaier Okuyama: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - Review & Editing. Mateus Barancelli Schwedersky: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - Review & Editing, Visualization, Project administration, Supervision. Régis Henrique Gonçalves e Silva: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - Review & Editing, Visualization, Project administration, Supervision.

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