Calibration of a Background Oriented Schlieren (BOS)

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We use two materials with different known refractive indexes to calibrate a Background Oriented Schlieren (BOS) experimental set-up, and to validate the Lorenz-Lorentz equation. BOS is used in our experiments to determine local changes of density in the shock pattern of an axisymmetric supersonic air jet. It is important to validate, in particular, the Gladstone Dale approximation (index of refraction close to one) in our experimental conditions and determine the uncertainty of our density measurements. In some cases, the index of refraction of the material is well known, but in others the density is measured and related to the displacement field.

Introducción:

Background Oriented Schlieren (BOS) is a visualization technique used in transparent media. It is based on Fermat's Principle of the deviation of light due to changes in the index of refraction. The Gladstone- Dale equation (Eq. 1) relates the index of refraction with the density in an ideal gas with n close to 1:

$$G(\lambda, T) = \frac{n-1}{\rho} \quad \text{...Equaton 1}$$

Where $G(\lambda, T)$ is the Gladstone-Dale constant that depends on the temperature and the wavelength that traverses the medium. A dot matrix (Figure 1) is used to observe the apparent displacements due to density variations inside the flow. To quantify these displacements a first photograph of the matrix without the flow is taken, and compared with a photograph taken with the flow. The angle of deviation (Figure 2) can be approximated with Eq. 2.

$$\epsilon = \frac{1}{n_0}\int \frac{\partial n}{\partial r} dz \sim \frac{\partial n}{\partial r} \quad \text{...Equation 2}$$

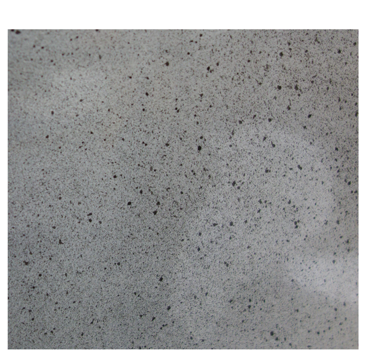

Figure 1 - Background

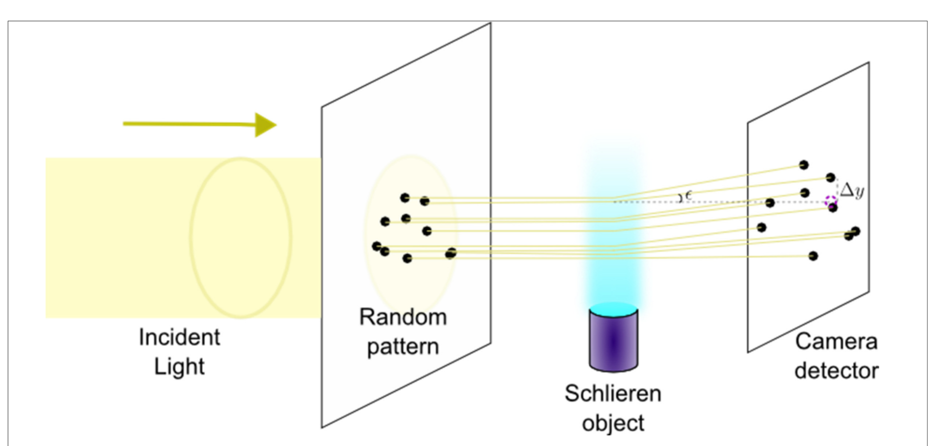

Figure 2 - scheme of the deflected light rays due to the schlieren object.

Through a cross-correlation of both images, a displacement vector is obtained for each interrogation area, and a vector field is generated. This can be associated to the gradient of the refraction index, and the following system of differential equations is obtained:

$$\frac{\partial n}{\partial y} = \frac{n_0}{M Z_D h}\xi_y \qquad \frac{\partial n}{\partial x} = \frac{n_0}{M Z_D h}\xi_x \quad \text{...Equation 3}$$

From the set of first order differential equations 3, a unique Poisson equation (second order differential equation) is obtained:

$$\frac{\partial^2 \rho}{\partial^2 x} + \frac{\partial^2 \rho}{\partial^2 y} = \frac{1}{G(\lambda, T)}\frac{n_0}{M Z_D h}\left[\frac{\partial \xi_x}{\partial x} + \frac{\partial \xi_y}{\partial y}\right] \quad \text{...Equation 4}$$

This equation can be solved through an iterative Gauss-Seidel method with mixed boundary conditions: Dirichlet on the borders parallel to the flow and Neumann in borders perpendicular to the flow.

	Refractive index n	Density [Kg/m^3]	Gladstone-Dale constant [m^3 /Kg]
Air	1.0002921	1.204	-
Carbon dioxide CO_2	1.00046	1.87	2.275x10^{-4}
Acetylene C_2H_2	1.00051		-

A schlieren Z arrangement with parallel beams was mounted as shown in Figure 3. The light source was a 100 Watt LED whose spectrum was obtained with a spectrophotometer (Figure 4). The predominant wavelength was 546 nm (green) so the corresponding value of the Gladstone-Dale constant was used in the equation.

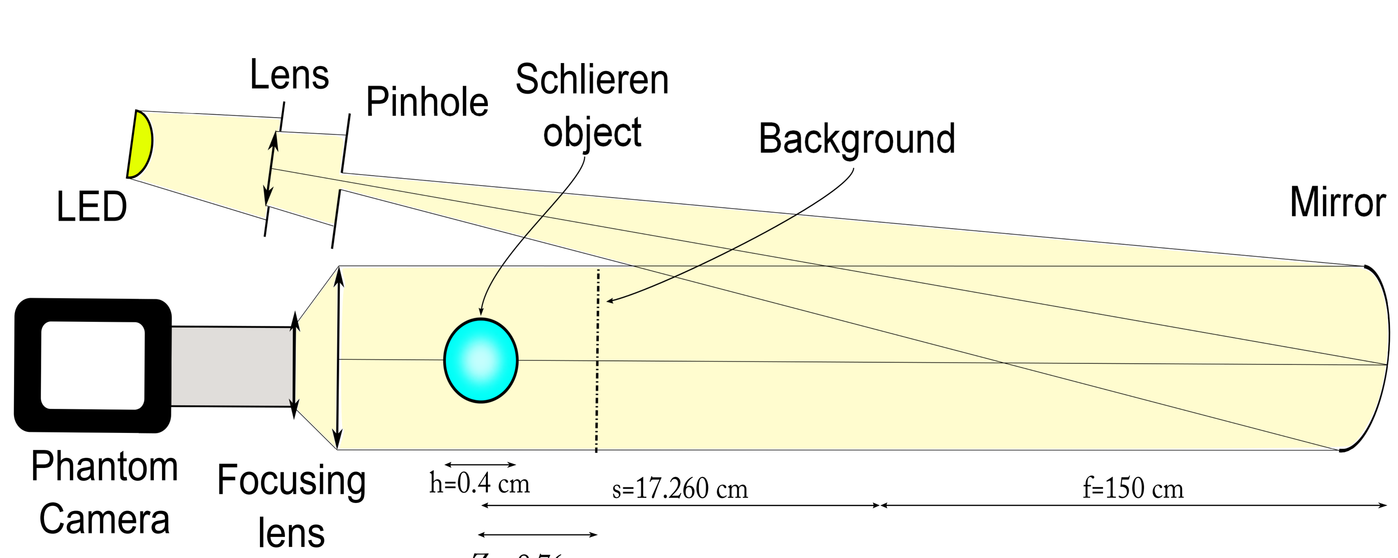

Figure 3 - Experimental setup, parallel ray shadowgraph. In this setup the schlieren object is a free axisymmetric jet of the studied gas.

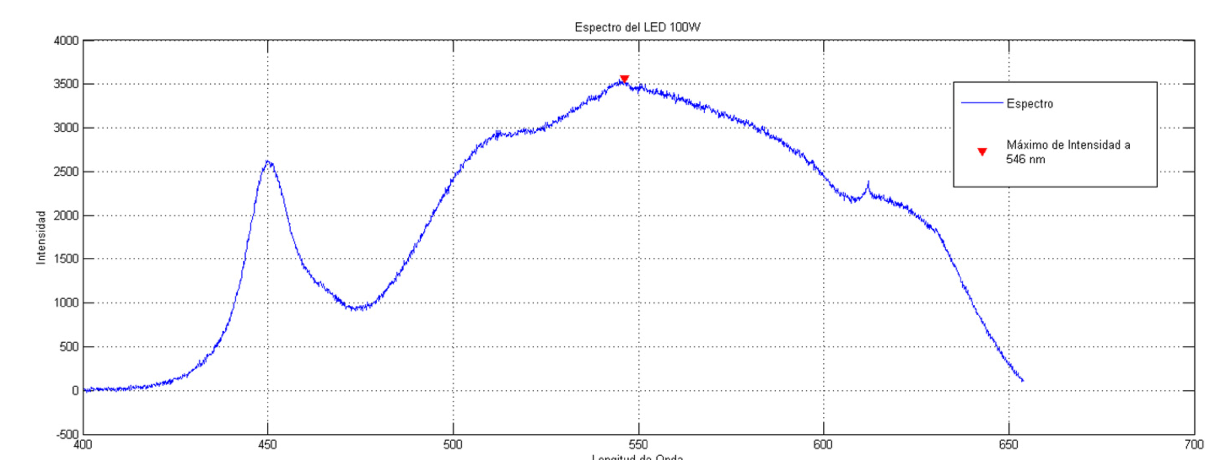

Figure 4 - LED emission spectrum

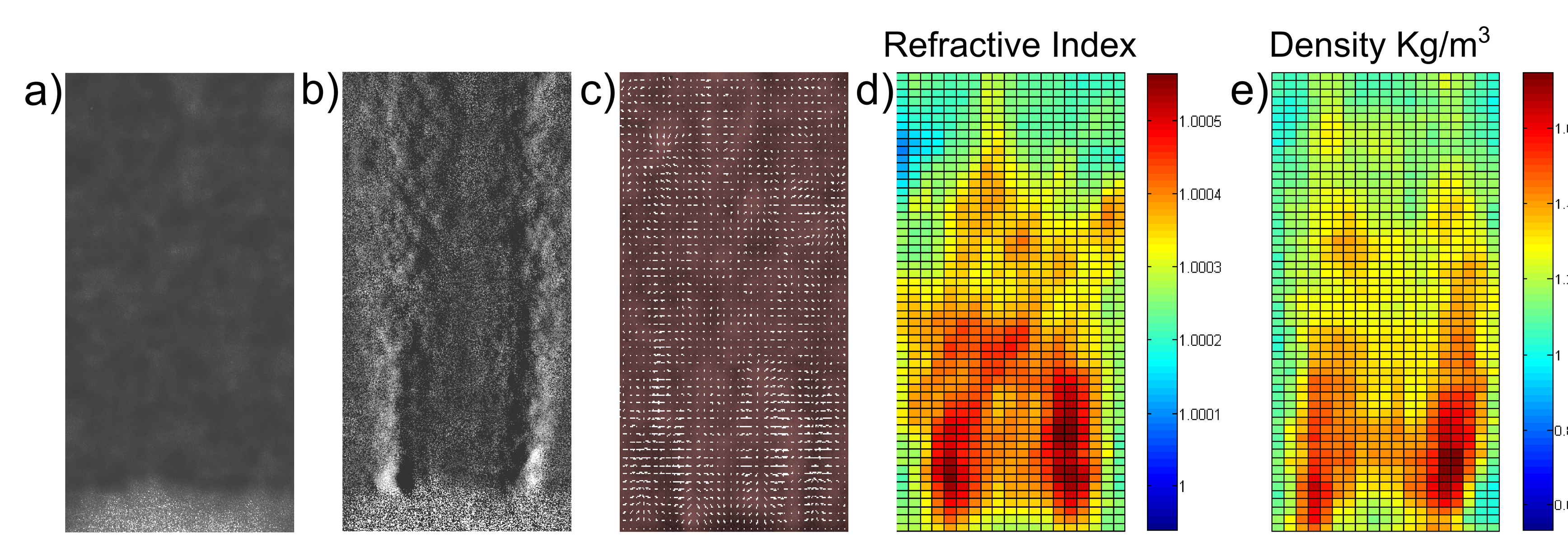

Figure 5 - a) background, b) CO2 free jet, c) displacement field , d) refractive index field and e) density field.

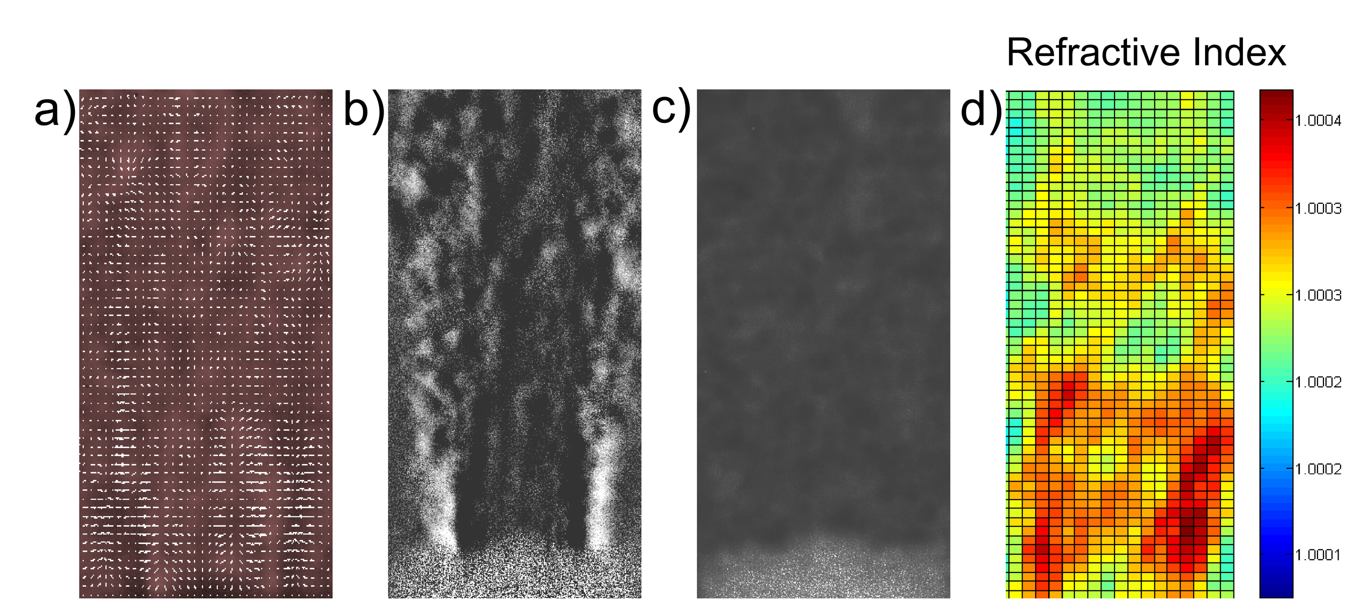

Figure 5 - a) background, b) CO2 free jet, c) displacement field and d) refractive index field.

Conclusions

A reliable BOS technique was implemented. For CO_2, the index of refraction was measured within 0.005% of the expected value and the density within 6.9%. For C_2H_2 the index of refraction obtained is within 0.004 of the expected value. (See table)
0.004% in the index of refraction. It was not possible to estimate the density field since there is no known value for the Gladstone-Dale constant for acetylene.
This non intrusive technique measures changes in the local density.
With this calibration, variations in the density of other gases in specific conditions can be obtained, for example, inside supersonic flows.

Future Work

Refine the boundary conditions to solve Poisson's equation.
Test other gases.
Test other configurations of the dot matrix.
Study the possibility of using the more general Lorentz-Lorenz relationship between ρ and n that doesn't apply only to gases (n>1).Calculate the uncertainty of the algorithm.

References

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