Design of a Schlieren system for low enthalpy hypersonic flow visualization in GHIBLI facility and development of image processing and quantitative analysis codes with preliminary application to sonic free jet

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Abstract GHIBLI is a 2 MW arc-jet hypersonic facility located at CIRA premises in Capua (Italy), designed for testing candidate TPS materials for re-entry vehicles. Measured data during cold flow tests, i.e. with arc-heater off, showed the achievement of hypersonic conditions at the nozzle exit. Hence, a Schlieren system has been designed to investigate qualitatively and quantitatively such a low enthalpy flow-jet. The apparatus is a classical Toepler's double lens one. CFD analyses of the free jet were performed to determine the density gradients. On the basis of these results, the limit of sensitivity of the system was determined and the components of the apparatus were dimensioned. A COBLED extended white light source, along with slits made of high reflecting material were experimented. Schlieren images, projected on opaque screen are acquired by a CMOS monochromatic sensor. An image processing code was developed in MATLAB to obtain contrast and clearness enhancement. Quantitative analysis was approached by developing a density-contrast relation, based on schlieren phase-shift effects, modeled under the wave theory of light, and the CMOS tension-charge characteristics. For this purpose, a code named Density from Contrast was developed in MATLAB to measure the luminous intensity of each pixel of captured images and thus compute the density field.

Keywords: Schlieren, Toepler, processing, contrast, phase-shift, COBLED, CMOS, hypersonic

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1 Introduction

The PWT GHIBLI is a 2MW arc-jet hypersonic facility realized at CIRA [1] in order to have a low power and low cost facility, to be used as experimental laboratory. It was designed on the basis of the knowledge gained during the development of the SCIROCCO 70MW facility.

In 2009, during an experimental campaign, aimed to characterize the GHIBLI facility converging-diverging conical nozzle (actively cooled with throat diameter of 9.525 mm and nozzle exit diameter of 152.4 mm), six tests with arc-heater off were performed. Analyzing data collected during the cold flow tests by means of the isentropic equations, it has been observed that low enthalpy hypersonic conditions established at the Nozzle exit section [2].

In Tab. 1 the measurements of the facility process parameters during the cold flow tests are shown, listed by increasing value of the reservoir pressure P_0. The measured quantities are the air mass flow rate $\dot{m}$, the reservoir pressure P_0, the Nozzle exit pressure P_{Exit}, the pressure in the test chamber P_{TC} and the pressure at the vacuum inlet P_{vac}. By using the data in Tab. 1, assuming a reservoir Temperature T_0=300 K and a ratio of specific heat γ=1.4, the flow properties in Tab. 2 were computed by means of isentropic relations.

Tab. 1 Measured data during cold flow tests [2]

Test case	P_0 [bar]	$\dot{m}$ [g/s]	P_{Exit} [mbar]	P_{TC} [mbar]	P_{vac} [mbar]
1	0.72	10	1.6	1.4	1.9
2	1	14.3	1.84	1.9	2.5
3	1.8	26.7	3.82	3.9	5.1
4	2.3	32.5	4.72	4.9	6.36
5	2.6	38.2	5.7	5.9	7.4
6	3.2	45.4	6.9	7.3	9.0

Tab. 2 Computed flow properties by means of isentropic equations [2]

Test case	M_{Exit}	V_{Exit} [m/s]	T_{Exit} [K]	ρ_{Exit} [kg/m^3]	ϕ_{Exit} [mm]	Re/m	δ_{Exit} [mm]
1	4.8	686	50.8	1.10e-02	48	2.11e+06	51
2	4.9	695	50	1.28e-02	49	2.50e+06	50.5
3	4.9	695	50.1	2.66e-02	47.4	5.18e+06	51.3
4	4.9	692	49.6	3.32e-02	48.1	6.43e+06	50.9
5	4.9	699	50.6	3.93e-02	47.1	7.69e+06	51.5
6	4.9	699	50.6	4.75e-02	47.1	9.31e+06	51.5

The flow conditions were further investigated by means of CFD analyses, using the ICEM CFD preprocessor and the FLUENT code [3]. The results from the numerical rebuilding, collected in Tab. 3, match with those derived by isentropic relations. Consequently it was decided to investigate the GHIBLI low enthalpy hypersonic conditions, by means of Schlieren visualization techniques.

Tab. 3 Results from the CFD analysis

Test case	P_{Exit} [mbar]	M_{Exit}	V_{Exit} [m/s]	T_{Exit} [K]	ρ_{Exit} [kg/m^3]
1	1.4	4.75	680	50.8	8.25e-03
2	1.9	4.9	690	51	1.15e-02
3	3.9	4.9	695	51	2.2e-02
4	4.8	4.9	695	51	2.6e-02
5	5.8	4.9	700	51	2.9e-02
6	6.9	4.9	700	51	3.55e-02

2 Preliminary design of the Schlieren system

In order to perform the experimental characterization, the Schlieren apparatus was designed and realized in the PWT instrumentation laboratory [4]. After a preliminary multi-purpose analysis the Toepler's double lens configuration, with horizontal optical axis, was selected. The analysis also put in evidence the necessity to install the electrical devices, i.e. the light source and the capture system, outside the GHIBLI Test Chamber. Therefore, the field of view of the reference optical windows univocally determined the Test Section inside the Test Chamber.

Consequently, the density gradient through the radial direction in the Test Section were deducted from the results of the CFD analysis [3].

A 2D computational domain, composed of the converging-diverging conical nozzle and a cylindrical shaped Test Chamber, was designed and meshed by means of ICEM CFD. The numerical analyses were run with FLUENT code, setting a *Density-based model* and assuming steady-state, axis-symmetric and ideal gas conditions. The turbulence was modeled through the k-ω standard model. The CFD analyses went through the same six test cases discussed in chapter 1. The inlet and outlet boundary conditions are listed in Tab. 4.

Tab. 4 CFD Boundary conditions

T_0=300 K

Test case	P_0 [bar]	P_{TC} [mbar]
1	0.72	1.4
2	1	1.9
3	1.8	3.9
4	2.3	4.9
5	2.6	5.9
6	3.2	7.3

Fig. 1 displays a contour plot of Mach number in the GHIBLI facility nozzle and Test Chamber.

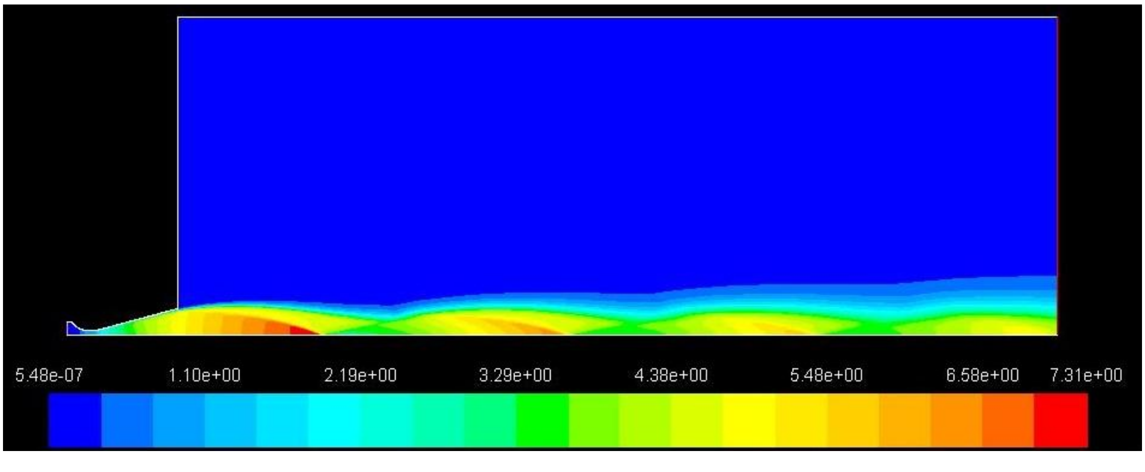

Fig. 1 Contour of Mach number in GHIBLI

Fig. 2 shows five density profiles in the Test Section. Each profile refers to a plane parallel to the nozzle exit cross section, located at different positions along the jet axis, namely at 320, 340, 360, 380 and 400 mm.

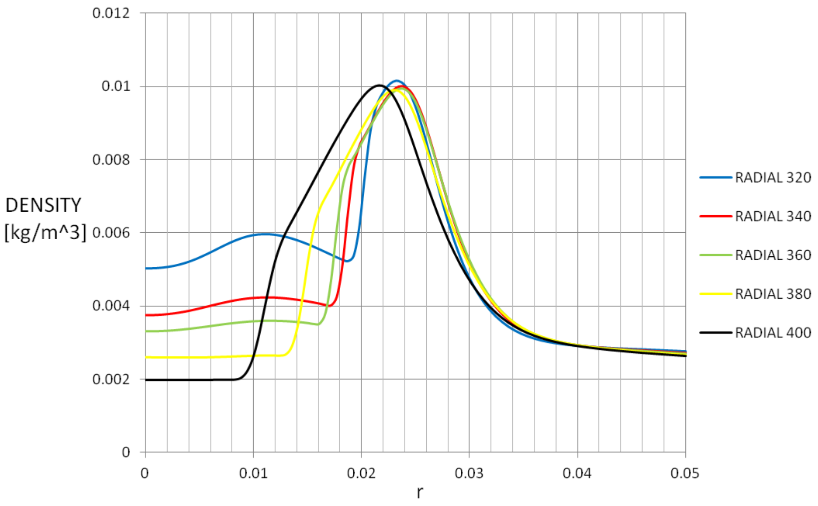

Fig. 2 Radial density profiles in the Test Section computed by CFD

From the plot, it is possible to obtain the values of the density gradient which are related to the geometric parameters of the apparatus through the sensitivity limit equation (1) [5].

$$\left.\frac{\partial\rho}{\partial r}\right|_{min} = \frac{C_{min}\, n_0 a}{G\ L\ f_2} \qquad (1)$$

Where ρ is the density, r is the radial direction, C_{min} is the minimum contrast of the capture system, that is a CMOS device, n_0 is the refractive index of the surrounding medium, a is the knife-edge cutoff, G is the Gladston-Dale coefficient, L is the schliere characteristic length and f_2 is the focal length of the field lens. The value of C_{min}, originally unknown, was initially assumed the same order of magnitude of the human eye and then it was experimentally determined in chapter 6. A commercial biconvex field lens with 70 mm in diameter, f_2=1 m was selected, producing a spot-size of 3 mm. From the CFD analysis contour plots it was measured L=8 mm.

3 Schlieren system description

The Schlieren system is composed by a Toepler's double lens apparatus, and an ordinary personal computer, which allows the remote control of the CMOS capture device. The computer digitally process and analyze, the Schlieren images by means of two codes written in MATLAB and further discussed in the following chapters. In Fig. 3 the optical path, along with the main components of the apparatus, are represented.

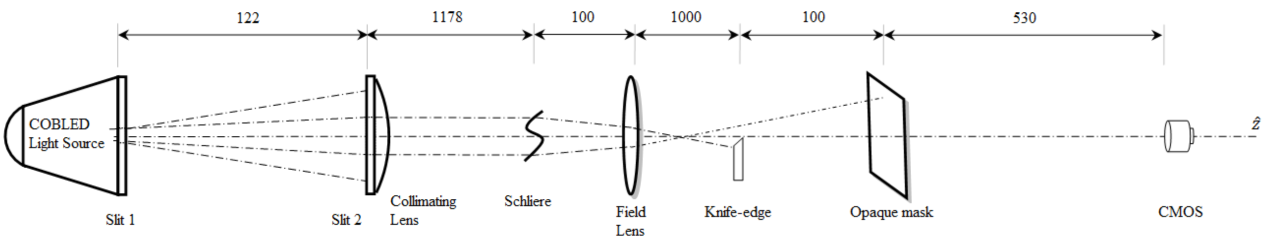

Fig. 3 Schlieren system optical path and main components (length in mm)

A white COBLED spotlight is used as the extended light source. A slit mask, made of high reflecting material, with a square opening with sides of length $\mathbf{1\,cm}$, is applied on the radiating surface. This configuration reduces the spotlight radiation angle from 90° to 9° and increases the actual luminance of the light source, by redirecting the light rays with higher deflection to pass through the opening. A collimating simply-convex lens produces the light beam which interacts with the schliere. A slit mask is applied on it, in order to avoid vignetting. Both the collimating and the field lens are commercial circular ones with diameters of 70 mm. The knife edge filter is a classical razor blade, painted in black. It is placed on a support which allows the knife edge to translate in the vertical direction by acting on a micrometric screw. The images, projected on the opaque mask are captured by a CMOS sensor and stored on the remote PC.

The distance between the collimating lens and the schliere and the distance between the opaque mask and the CMOS sensor are constrained by the geometry of the GHIBLI Test Chamber, wherein the field lens, the knife and the opaque mask have to be arranged, on a support table. In order to determine the right placement of the support table (Fig. 4), a 3D model of the GHIBLI Test Chamber, shown in Fig. 5, was created by means of CATIA.

Fig. 4 Support table in the CIRA PWT instrumentation laboratory

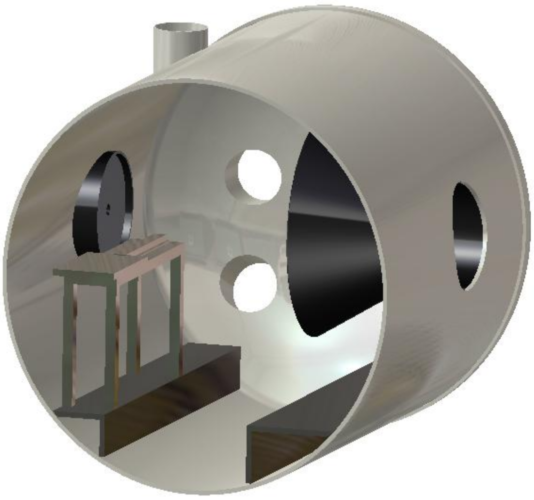

Fig. 5 View inside the 3D model of the GHIBLI Test Chamber

4 Schlieren Image Preprocessor code

In order to improve the quality of the images acquired, highlighting those flow patterns which need to be investigated, a code named Schlieren Images Preprocessor (SIP) was written in MATLAB. It is worth noting that the code is designed to work only on images of a steady state flow.

The SIP code operates over a number N of schlieren images (**I_n**) and on a background one (**B**), which represents the captured area before starting the jet. Once selected by the user, the images are converted to UINT8 data type three dimensional arrays. Therefore, the arrays are linearly combined, through equation (2), in order to produce one single picture (**S**) which best represents the phenomenon.

$$\boldsymbol{S} = \frac{\sum_{n=1}^{N} m_n(\boldsymbol{I_n} - r_n\boldsymbol{B})}{\sum_{n=1}^{N} m_n} \tag{2}$$

Before to run the code, the user must set the value for the weight coefficients m_n and the reduction coefficients r_n. It is worth noting that only positive values are accepted for the coefficient. Overflow is limited by setting an appropriate value of r_n.

5 Density from Contrast code

The photometric method was chosen to derive the density field. A formulation based on the schlieren phase shift effect, the wave model of light and the CMOS tension-charge characteristics was developed in reference [4], resulting in equation (3).

$$\rho_{ave}(x_i) = \frac{C}{GKL}\frac{\lambda_{ave}}{2\pi h\sigma} + \rho_0 \tag{3}$$

Where *h* is the Planck's constant, ρ_0 is the density value outside the jet,, λ_{ave} is the average wave length of the light beam and σ is a constant of proportionality, introduced as follow

$$C \sim \frac{\Delta V}{V} \sim \frac{\Delta Q}{QC_T}K \rightarrow C = \frac{V\Delta Q}{\sigma}K$$

Both λ_{ave} and σ were originally unknown. The former was determined on the basis of the quantum efficiency diagrams of the COBLED and the CMOS devices, resulting in λ_{ave}=550 nm. The value to be assigned to the constant of proportionality σ is discussed in chapter 6.

Once developed the mathematical model, a code named *Density from Contrast* (DfC) was written in MATLAB. Similarly to SIP, one schlieren image and one background image are read and converted to UINT8 3-D arrays, named respectively **I** and **B**. Since the CMOS device is monochromatic, the mentioned arrays can be reduced to 2-D matrixes ($I_{i,j}$ and $B_{i,j}$). A matrix containing the values of contrast can be defined as follow

$$C_{i,j} = \frac{I_{i,j} - B_{i,j}}{B_{i,j}} \quad \forall\, i,j \tag{4}$$

Each element of $C_{i,j}$ is multiplied, through a for loop, by the corresponding one of $S_{i,j}$.

$$S_{i,j} = \frac{\lambda}{2\pi hGK}\frac{1}{L_{i,j}} \quad \forall\, i,j \tag{5}$$

Finally, the density field is obtained as follow

$$\rho_{i,j} = C_{i,j}(for)\ S_{i,j} + \rho_0 O_{i,j} \tag{6}$$

Where $O_{i,j}$ is a matrix of ones.

It is worth noting that, since the schlieren images may contain other subjects, besides the schliere, $\rho_{I,j}$ can contain values which have no physical meaning. The code and the model were validated, by comparison with CFD simulation results, as described in the following chapter.

6 Schlieren system characterization and validation

In order to characterize the Schlieren system and to determine the value of C_{min} a preliminary test campaign on a sonic jet took place at CIRA PWT instrumentation laboratory. The apparatus was set respecting the distances designed for GHIBLI and reported in Fig. 3. In this case the schlieren object was the flow jet of a converging nozzle [4].

The frames captured were successfully processed by means of SIP code, producing a significant enhancement. Also, some relations between the code coefficients and the image quality were put in evidence. In particular m_n and r_n resulted being proportional, respectively, to the clearness and the contrast of the schlieren image (**S**). Some results of digital image processing are shown in Fig. 6.

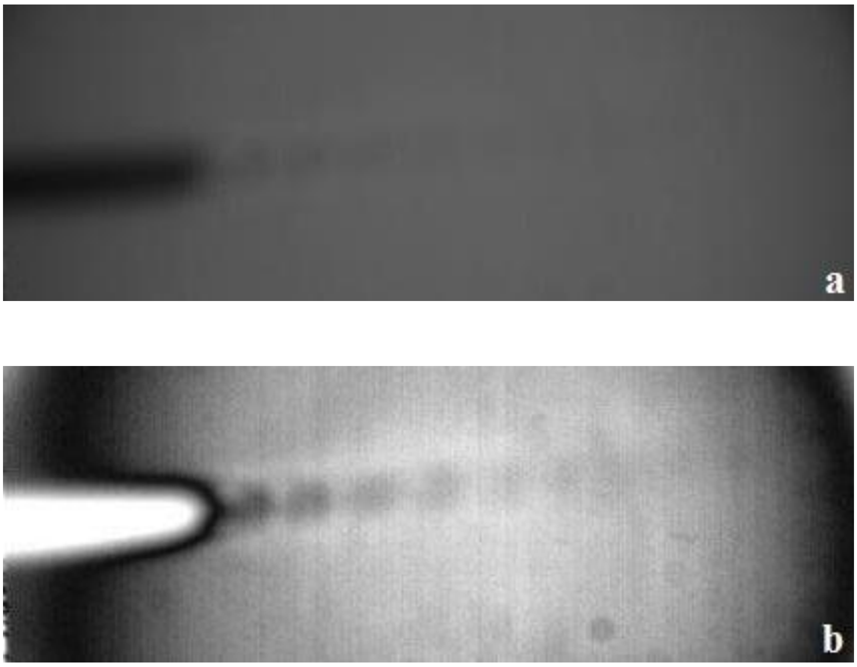

Fig. 6 Schlieren image before (a) and after (b) processing on SIP

The DfC code was tested as well, comparing results from the photometric analysis with those resulting from a CFD simulation of the converging nozzle jet. The key features of the nozzle geometry and the boundary and operating conditions are listed, respectively, in Tab. 5 and Tab. 6. CFD analyses were performed with FLUENT code with the same settings and assumption made in chapter 2. A contour of density is pictured in Fig. 7

Tab. 5 Converging nozzle geometry

Cross section shape	Rectangular
Inlet section size	10.5 mm (b) x 7 mm (h)
Outlet section size	2.3 mm (b) x 1 mm (h)

Tab. 6 Boundary and operating conditions

Region	BC	Value
Inlet section	pressure far-field	7.4 bar
Outlet section	pressure outlet	1.02 bar
Region	**Operating Condition**	**Value**
Inlet section	Reservoir temperature	300 K
Inlet section	Mach Number	10^{-4}

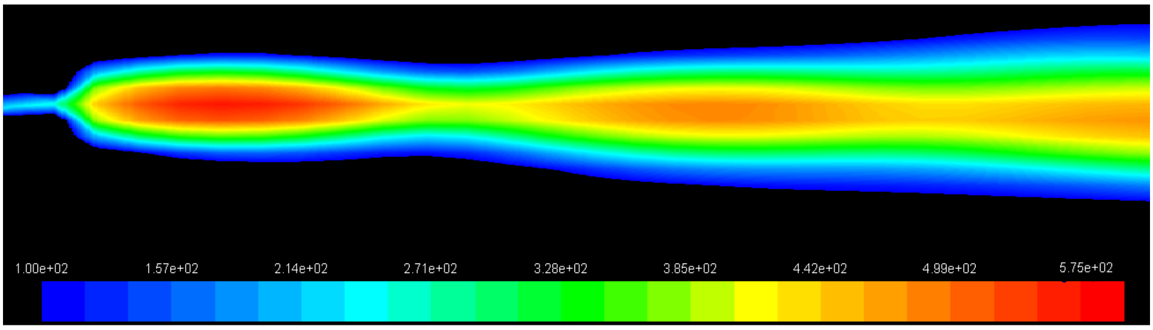

Fig. 7 Contour of density of the sonic jet

Fig. 8 shows the plot of density along the the jet axis of the nozzle, resulting from CFD (black line) and DfC, setting σ=6.5e+33 (blue), σ=7e+33 (red) and σ=7.5e+33 (green).

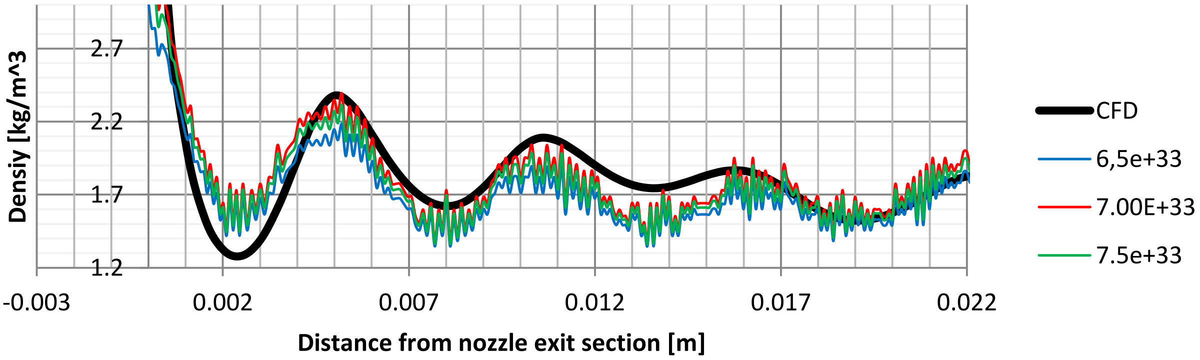

Fig. 8 Density plot along the neutral axis of the convergent nozzle

The order of magnitude for σ was determined in virtue of relation (7), assuming $Q \sim 10^{-19}$ C and $C_T \sim 10^{-14}$ F [6],being respectively the reference charge and the total capacity of the CMOS sensor.

$$\sigma \sim \frac{1}{QC_T} \qquad (7)$$

The curves in Fig. 5 demonstrate that experimental results are in good agreement with the numerical ones, with the best matching occurring for σ=6.5e+33. Assuming this value, the C_{min} of the CMOS sensor was computed, resulting in C_{min}=2.35e-03. Finally it was possible to evaluate through equation (1) the sensitivity limit of the Schlieren system that was found to be compatible with the density gradients predicted by CFD in the Test Section of GHIBLI. In this way it was confirmed the possibility to apply the Schlieren system here described for the low enthalpy hypersonic flow visualization in the GHIBLI facility.

7 Conclusions

In order to characterize the low enthalpy hypersonic jet of GHIBLI facility, a Schlieren system was designed. It was composed by a Toepler's double lens apparatus with COBLED extended white light source and a CMOS capture device. CFD analyses of the GHIBLI hypersonic jet were performed to determine the density gradients and the sensitivity limit of the system. The components of the apparatus were dimensioned accordingly. The Schlieren system was realized and preliminarily tested with a sonic jet of a converging nozzle in the PWT instrumentation laboratory. Two codes, Schlieren Image Preprocessor (SIP), for image processing, and Density from Contrast (DfC), for quantitative analysis, were developed. SIP code generated a well rendered enhancement of the captured images of the sonic jet and the DfC code allowed to obtain results in terms of density values along the jet axis in good agreement with those derived from the CFD simulations of the converging nozzle. The designed Schlieren system and the codes developed for image processing and quantitative analysis proved to be suitable and ready to experimentally characterize the low enthalpy hypersonic flows in the GHIBLI facility.

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