HiSST: 2nd International Conference on High-Speed Vehicle Science Technology

11–15 September 2022, Bruges, Belgium

Laser Induced Velocimetry of Hypersonic Flows

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Abstract

The development of hypersonic airbreathing propulsion systems, such as scramjet engines, represents a great technological challenge, mainly due to the complex aerothermodynamic processes observed during the flight within the sensible atmosphere. With the advent of new computers and more sophisticated programs, the design and evaluation of performance in virtual environments has assumed a mandatory character over the past two decades. However, considering the complete cycle of technological readiness, *in loco* evaluation, concerning direct and indirect measurements of parameters associated with the exposure both systems and subsystems to hypersonic flight conditions, are also essential steps for innovative projects. Hence, the relevant role that the ground test devices present in the state-of-art researches is the mitigation of major risks associated to the expensive in-flight tests of the integrated systems. Thus, the present work had as objective the characterization of flows produced in the T2 Hypersonic Shock Tunnel installed at Institute of Advanced Studies, IEAv. Flow velocities were determined by the laser-induced fluorescence velocimetry, LIF, of NO species intrinsically formed and available at free-stream conditions. Results showed a reasonable agreement between experimentally and theoretical velocity values, ca. 5%.

Keywords: *Shock Tunnel, laser induced fluorescence, velocimetry, Flow diagnostics.*

Nomenclature

A/A^* – exit-to-throat area-ratio
D_D – diverging section
D_G – Nozzle throat
v – velocity
v_T – theoretical velocity
t_d – delay time inserted between the camera and the laser
t_G – camera's exposure time
t_L – associated with the duration of the laser pulse time
t_c – corrected delay time
x – displacement measured
δx – associated systematic error

1. Introduction

The project and development of advanced vehicles flying at hypersonic speeds represents a major technological challenge. The tools commonly used for vehicle design validation are ground testing, computer simulations and flight tests. However, all of them have limitations, requiring a joint approach to mitigate risks and costs, thus achieving a robust development methodology[1].

One of the most used ground test device is shock tunnels, in which a flow moves towards the model simulating, thus, a flight in a certain set of atmosphere conditions. These devices use a shockwave that moves through a high-pressure reservoir to create very high temperatures and pressures. Then, this stagnated gas is expanded through a nozzle into a test chamber, over the model. The limitation of this type of installation is the test time, which is restricted to milliseconds due to the shockwave transit time and tube length. Despite this limitation, these installations are widely used, allowing the evaluation of several aerodynamic parameters from well-instrumented models.

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However, ground tests present some difficulties regarding the gaseous fluid behavior, as they are subjected to high pressures and temperatures. At 2500 K, for example, many molecules become vibrationally excited, and above 4000 K their complete dissociation occurs. The effects of temperature are most noticeable in hypersonic flows, simply because temperatures of this type are significantly higher[2]. Increasing the flow temperature causes deviations from the ideal gas law and the diffusion effects become more intense. As a result, the thicknesses of the boundary layers become large, making their interactions more prominent. In addition, during the process of expansion through the hypersonic nozzle, the gas tends to freeze, resulting in a gas mixture condition that does not resemble that of a flight[1]. Thus, flight tests are proposed to investigate phenomena that are beyond current ground testing capability and to clarify physical behaviors that numerical experiments have not deciphered.

Thus, as important as the use of ground tests for the development of hypersonic vehicles, is the characterization of the flow produced by these facilities. Knowing the flow gas properties ahead of the model, for example, significantly reduces errors associated with measuring Mach number and temperature[3]. Speed is one of the most important parameters in the characterization of a flow, since with this parameter it is possible to predict other tunnel properties, such as stagnation conditions. Its measurement corresponds to one of the most common wind and shock tunnel challenges and has been responsible for the continuous improvement of flow characterization techniques, since a simple physical probe to complex laser-based techniques[4].

The determination of flow velocity is not different from that established in its classical definition: the velocity of a body in a given dimension is the ratio between its displacement and the time taken to cover such a distance. If conceptually it seems trivial, the establishment of a measurable spatial reference within the time scales available on ground testing devices, typically in the order of hundreds of nanoseconds, is a major experimental challenger.

One of the first attempts to estimate the velocity of gases in motion was the use of direct flow sensors, such as static or full pressure sensors, and hot-wire devices, where velocity fluctuations are monitored in function of the variation of the electric current[5]. However, this class of intrusive sensors admittedly has the disadvantage of causing sensitive changes in the investigated flows, those with hypersonic regime[6,7].

As an alternative to intrusive probes, methods based on monitoring the optical properties of chemical species present in the flow, such as natural emission, scattering, absorption, fluorescence (induced or natural), refractive index variation, etc.[8] have been developed. These include the ability of collecting light efficiently from the testing volume using an optical arrangement that is sensitive to short test times.

For aerodynamic research in flows, the choice of spectroscopically adequate but chemically inactive species is limited[9]. A species widely used in this research area is nitric oxide (NO) which, despite being toxic, is not corrosive, its absorption bands are accessible to dye lasers and the variation of its vapor pressure with temperature is similar to nitrogen. The nitric oxide LIF is an optical measurement scheme particularly adequate for use in shock tunnels[10]. NO is generated naturally by the heating process, with a maximum formation around 4000 K, by shock during typical operation of a device such as a hypersonic tunnel, making the toxic gas handling system not necessary for seeding the species in the flow.

Thus, the method used to determine the flow velocity in this work was the Laser Induced Fluorescence Velocimetry (LIF). This technique is based on the tagging of a given chemical species present in the flow, which in this case, NO radical. Tagging process is carried out selecting a convenient laser wavelength able to bring the chosen species to allowed electronic excited states. Once in this condition, a species fraction suffers a decay process, emitting light, a process known as fluorescence. During the fluorescence period, the laser illuminated region ("tagged") can be recorded and used as a spatial reference. As the time between camera frames is known, flow velocity can be calculated. The technique principle is shown in Figure 1.

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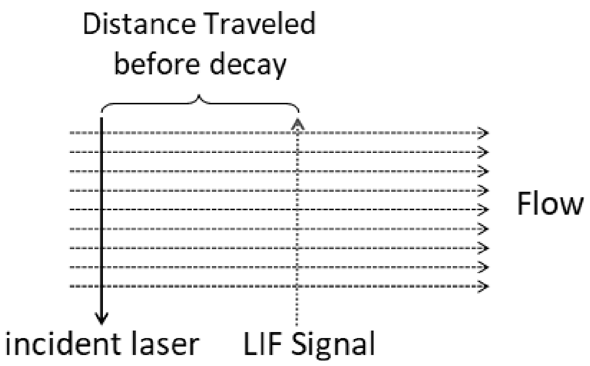

Fig 1. The principle of laser-induced fluorescence velocimetry

2. Methodology

The T2 pulsed hypersonic shock tunnel is in the laboratory Prof. Henry T. Nagamatsu at the Institute for Advanced Studies Institute of Advanced Study (IEAv) and was used for the implementation of the LIF velocimetry technique in this work. The tunnel has a test time in the order of 10^2 to 10^3 μs, a specific stagnation enthalpy that can attain the value of 6 MJ/kg and is operated in the over-tailored condition[11],[12].

Basically, the T2 tunnel consists of a conductive cylindrical tube divided into two reservoirs, one 1.8 m high pressure driver and one 6.4 m low pressure driven tube. The driver session was filled with helium and the section driven with atmospheric air and both were kept at room temperature. To maintain the pressure difference between the two sections there is a double diaphragm system (DDS), which was filled with argon at an intermediate pressure (11.4 MPa) to prevent early diaphragm rupture. A nozzle at the end of the tube is responsible for expanding the flow towards the test section, which has a cylindrical shape 60 cm long and 40 cm internal diameter and has optical windows, necessary for flow visualization and application of laser techniques. A dump tank is connected to the end of that last section to accommodate and decelerate the gases from the experiments. Table 1 shows the nozzle used for the implementation of the technique on T2, with the throat diameter (D_G), divergent diameter (D_D) and the exit-to-throat area-ratio (A/A^*)[13]. For the experiments, a pressure of 10 kPa on the driven and 20.7 MPa on the driver was used.

Table 1. Nozzle throat (D_G), diverging section (D_D) and exit-to-throat area-ratio (A/A^*).

D_G (m)	D_D (m)	A/A^*
0.02	0.30	225.0

The tagging system was formed by a double frequency dye laser system with Coumarin 450 (Sirah, Precision Scan, Grevenbroich, Germany), with an output wavelength of ~225 nm (a second harmonic generator), pumped by a Nd:YAG laser which 10 Hz pulses (LPY7000, Litron, Rugby, United Kingdom); a vacuum cell coupled to a monochromator; and a photomultiplier. A previous calibration based on the fluorescence spectra of a NO(A) at 0.01 atm was performed before each measurement to verify the tuning between the laser emission line and the NO(A) radical absorption line. This cell was positioned so that it was in the laser's line of incidence and in front of a monochromator coupled to a photomultiplier, which was connected to an oscilloscope. To direct the beam in the test section, a cylindrical lens was used, while a cylindrical lens was used to direct the emission signal in the monochromator, both with a focal length of 10.0 cm.

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Thus, the laser emission wavelength was tuned to the maximum emission of the radical, found in the oscilloscope. Moreover, to detect the exact moment of laser output at each shot, a photodetector was inserted into the dye laser cavity and connected to the oscillograph responsible for recording all experimental signals. It is possible to establish the distance and time between the flow illumination and fluorescence, thus enabling the determination of velocity.

Flow images were recorded by a 12-bit intensified coupled device charge camera (Image Intense; LaVision, Göttingen, Germany), resolution of 1040×1376 pixels and minimum exposure time of 5 ns, positioned at right angles in relation to the laser beam. A NO filter was inserted into it, so that only the radical fluorescence of the Q1(3) transition could be detected, and to protect the camera from high intensity from scattering. Finally, an in-house trigger device, based on the Arduino board (Uno R3 16 MHz), guaranteed the synchronism between the shock tunnel, tagging laser and imaging system.

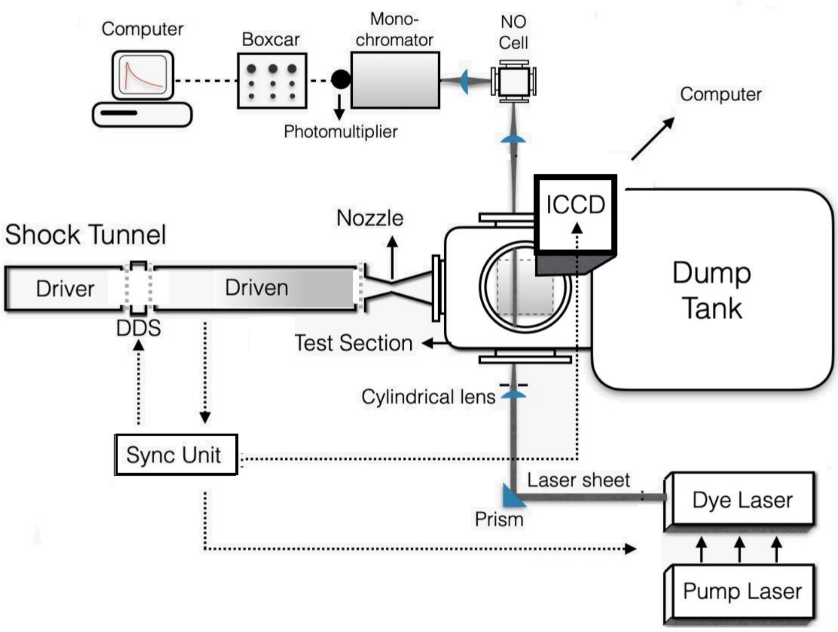

Fig 2. Experimental configuration of the velocimetry system.

4. Results

Figure 2 shows the images of the static reference and the fluorescence tagging obtained in one of the velocimetry experiments. As noted, the fluorescence image has a wider profile when compared to the laser profile. This is due to a combination of three factors. The first one occurs in the flow tagging stage. Laser marking is not instantaneous, thus, during this time the flow displaces, resulting in a tagging greater than the initial one. The second effect is caused by time-convolution of camera pixels, and as the flow convects downstream, the spatial LIF signal is registered by the camera during a given interval. Thus, a convolution of the LIF signal occurs and the resulting registered image becomes wider than an instantaneous image. The third effect is associated with the LIF intensity decaying caused by the deactivation process. As the flow evolves, the LIF intensity decays exponentially.

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Furthermore, the static reference image is characterized by better viewing contrast. This occurs for two reasons: i) this image is obtained from an average of approximately 200 images of the laser beam scattering in the test section, and ii) due to the high coherence and intensity of the laser beam, whose light is scattered by several particles present in the testing section. It is necessary to detect an average of laser images, rather than a single image, because this procedure reduces measurement uncertainty, since the velocity is calculated from the comparison with the flow tagging in a single shot. The image of the fluorescence tagging, on the other hand, does not represent an average of images, but a single image, in which the emission of light from the decay of the radical along the flow is detected. Thus, its contrast is smaller, since the LIF technique is selective, that is, it involves the excitation process of a specific radical line, which is present at a low density in the flow.

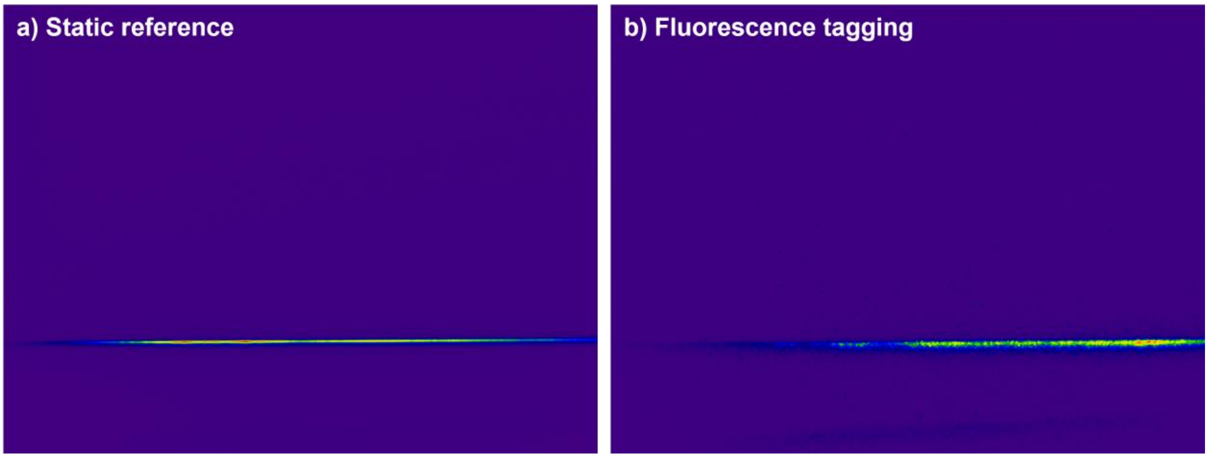

Fig 3. Images of a) reference tagging and b) flow tagging by fluorescence. The T2 shock tunnel was operated at 20.7 MPa on the driver and 30.0 KPa on the Driven.

Previous studies14 have indicated that, to determine the time interval used in laser velocimetry, it is necessary to consider the camera's opening time. For this, two simplifications were imposed: the width of the laser beam was considered infinitesimal, and the exponential decay of fluorescence was neglected. In fact, the width of the laser beam does not introduce a systematic error in the measurement because this width does not change the center of the tagged line. However, the finite width reduces the sensitivity of the measurements as it enlarges the tagged line, making it difficult to identify the center of the line. The intensity of the LIF signal decays exponentially during the measurement time, and if the tagged line were infinitely narrow spatially, the fluorescence would exponentially decrease the distance in the acquired image. However, the systematic error associated with this effect is small compared to other errors in the experiment. Furthermore, it was assumed that the laser pulse and camera aperture time have squared temporal profiles and diffusion was neglected as it acts to amplify, but not displace, the tagged line of molecules. Figure 4 shows a representation of the fluorescence image obtained at different times of the experiment.

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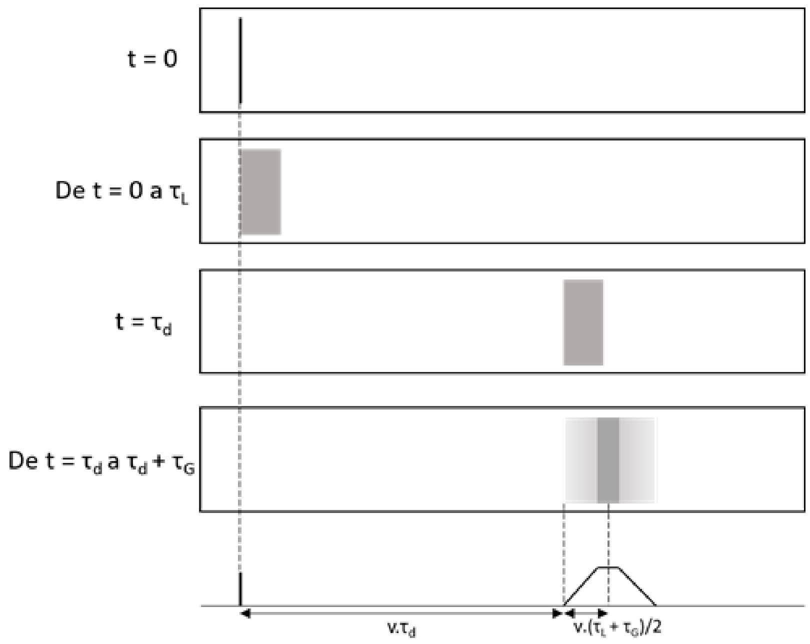

Fig 4. Representation of fluorescence images obtained by the CCD camera at different delay and aperture times during the velocimetry experiment.

The first quadrant (t=0) shows the fluorescence image during the time the laser is on at an infinitesimal camera aperture time. The second quadrant (from t=0 to τ_L) shows the image that would be obtained if the camera remained open for a time τ_L, in which the gas moves during the time the laser is on. Therefore, in this case, the laser marks the flow with a spatial width equal to $v.\tau_L$. If the gas were static, the width of this marking would be infinitesimal, and the image would be identical to the first quadrant. The third panel ($t=\tau_d$) shows how the image obtained would be if a delay time (τ_d) was added to it and if the camera's opening time were infinitesimal. The last quadrant (from τ_d to $\tau_d+\tau_G$) shows the image that would be obtained if the image were delayed by a laser time τ_d and if the camera opening time was τ_G. In this case, the image obtained would be a convolution of the flow marking and the camera opening time. When it is said that the camera remains open for a certain aperture time, it acquires consecutive images, separated by a short time interval, and the resulting image is a superposition of all those obtained in that period. For this reason, the fourth quadrant image is more intense at the center and less intense at the edges. The lighter edge on the left shows that images were taken when the flow was passing through that space and when the flow had already passed through it. And the lighter edge on the right shows that at the beginning of the image acquisition the flow had not yet passed through that region.

Thus, the center of this trapezoidal area is shifted to the right of the left edge of the trapezoid by a distance equal to $(\tau_L+\tau_G)/2$.

Therefore, free stream velocities were calculated from the displacement values between the static references and the fluorescence tagging in the four different laser incidence time. First, the velocities were calculated for each experiment, that is, using the pair of images, reference and tagging and the delay time inserted. The calculated velocity for the experiments is given by Equation 1[14]. The value of t_d is given by the delay time inserted between the camera and the laser for each experiment, t_L is associated with the duration of the laser pulse time in the marking step (10 ± 2 ns) and t_G is the camera's exposure time (150 ± 5 ns) in the detection step, t_d (30 ± 5 ns). The time uncertain results in an overall experimental error of 4%.

$$v=\frac{d}{[t_d+\frac{(t_L+t_G)}{2}]} \tag{1}$$

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The other method used to measure the flow velocity was to image the tagged at different times so that the velocity was determined from the velocity equation, that relates position and time. For that, several experiments were necessary, and each one provided a pair containing a reference and a displacement image. The velocity was obtained, therefore, from the fit linear method relating displacement and delay, as shown in Equation 2, where x is the displacement measured in the time interval t, and δx is the associated systematic error. This method, while requiring more work, removes the need for correction, including unexpected systematic errors.

$$x_m(t) = v.t + \delta_x \tag{2}$$

Table 2 shows the values of corrected delay time, $t_c=(t_L+t_G/2)$, marking displacement, error associated with displacement, the calculated velocity for each point and the theoretical velocity (v_t). To calculate the theoretical velocity, a frozen flow was considered. Figure 5 shows the graph of displacement as a function of corrected delay time.

Table 2. Resume of the experimental data obtained and the calculated velocity values for experiments conducted at P1=30 kPa, A/A*=225

t_C (ns)	$x.10^{-4}$ (m)	v ($m.s^{-1}$)	v_t ($m.s^{-1}$)
180.0 ± 6.0	4.75 ± 0.7	2638 ± 392	
200.0 ± 6.0	5.24 ± 0.6	2620 ± 304	
250.0 ± 6.0	6.98 ± 0.3	2792 ± 144	2600
290.0 ± 6.0	7.70 ± 0.3	2655 ± 132	
290.0 ± 6.0	7.24 ± 0.5	2497 ± 198	

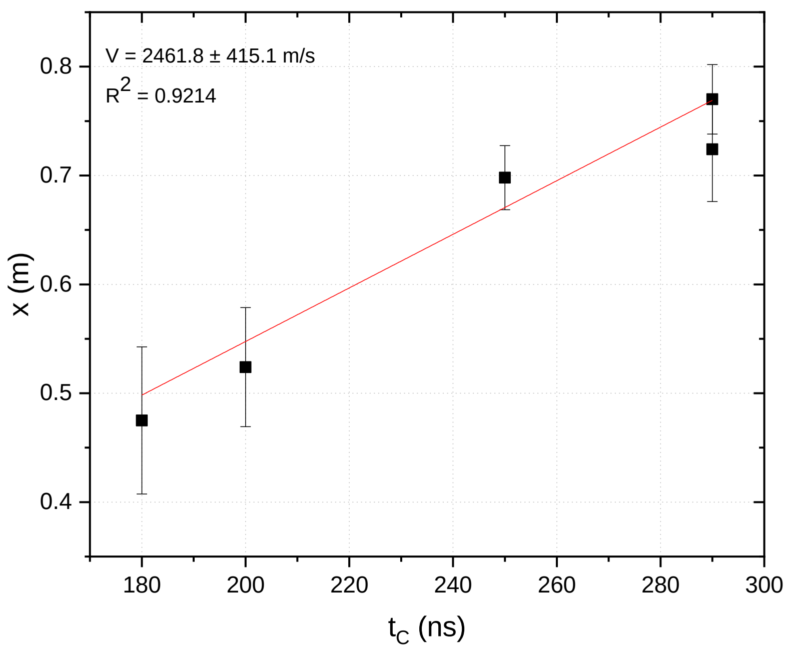

Fig 5. Graphs of displacement versus corrected delay time for experiments conducted at P1=30 kPa, A/A*=225.

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The free flow velocity calculated by the laser-induced fluorescence method was (2.5 ± 0.4) x10^3 ms^{-1} and presented a discrepancy of approximately 5% in relation to theoretical velocity calculated, 2,600 ms^{-1}, assuming a gas frozen flow condition. This discrepancy, however, is lower than the experimental uncertainty concerning time measurements.

5. Conclusion

The nitric oxide molecular tagging velocimetry technique was applied in a shock tunnel, with atmospheric air as the test gas. As the NO radical forms naturally under the operating conditions used, seeding of the radical was not necessary. The free flow velocity calculated by the laser-induced fluorescence method was (2.5 ± 0.4) x103 ms-1 and presented a discrepancy of approximately 5% in relation to theoretical velocity calculated, 2,600 ms-1, assuming a gas frozen flow condition. This discrepancy, however, is lower than the experimental uncertainty concerning time measurements.

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