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Overview of Measurement Techniques at CORIA

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L. Robin*, P. Boubert, A. Bourdon, A. Bultel, B. van Ootegem and P. Vervisch

CORIA / CNRS UMR 6614
Université de Rouen
Place Emile Blondel
76821 Mont Saint Aignan Cedex
France
Lionel.Robin@coria.fr

SUMMARY

At CORIA, three wind tunnels have been built up to simulate reentry conditions of different planetary atmospheres. They have been implemented by numerous optical and probe measurement techniques to carry out flow parameters to improve understanding of the aerodynamic behavior and chemical processes.

1. INTRODUCTION

The overview of measurement techniques at CORIA presented in this paper do not have the aim to provide, nor an extensive catalog of diagnostic tools devoted to the characterization of the plasma flows, neither an extensive catalog of the more suitable lines or molecular species which can be used for characterization of the plasma flows. It will be presented the diagnostic techniques developed at CORIA for plasma flow studies and the major difficulties encountered with measurement techniques used on species of interest, to drawn information of the signing of the flow. The presentation will be support by works and results issued from experimental studies performed on the wind tunnels developed at the CORIA, and operating under different working conditions simulating reentry conditions of different planetary atmospheres

This review starts with a fast overview of the facilities built at CORIA for simulating reentry conditions of different planetary atmospheres. The next part is dedicated to emission and absorption techniques. Then diagnostic methods based on Laser diagnostic will be presented in the third part. Finally, imaging and in situ measurement techniques are reviewed.

2. FACILITIES AND ANALYSIS DEVICES

FACILITIES AND PLASMA FLOWS

At CORIA, the three main facilities consist mainly on two arc-jets and a high frequency inductive torch. They are in operation to generate high enthalpy flows up to 50 MJ/kg for different gas mixtures. Experiments are performed in test chamber with stagnation pressure from 50 Pa up to atmospheric pressure. Working with different gas mixtures, oxidizing or not such as Ar, N_2, N_2-CO_2, Air...., these facilities are well adapted first to simulate the conditions met during reentry of spacecraft in numerous planetary atmospheres and second to improved understanding of the aerodynamic behavior and chemical processes.

- In the two first facilities, the plasma source is a 10-15 kW dc arc-jet facility. The arc is initiated between the tip of a cathode and a nozzle shaped anode. The nozzle is conical both upstream and downstream. The plasma is expanded in test chamber.
  To reduce the contamination of the flow and increase the lifetime of the electrodes, the materials of the electrodes vary depending the gas used. With N_2-CO_2 mixture, carbon electrodes are preferred to the ones generally used with non-oxidizing gas and made of tungsten or copper.
  To increase the temperature and the degree of dissociation, a second stage may be added below the first anode. A secondary arc therefore heats up the primary plasma. This amounts the total electric power of about 30%.

- The third wind tunnel is an high frequency inductive plasma torch (ICP torch, 100 kW, 1.7 MHz). The plasma is ignited in a quartz tube (discharge chamber) placed into inductor before its expansion in the test

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chamber. In subsonic regime, the jet is 80 mm in diameter. By addition of a shaped-nozzle at the exit of the quartz tube, the wind tunnel works in supersonic regime.

On the one side of the discharge chamber the gas former introduces the working gas. Its conception allows proceeding the reliable stabilization of the discharge, to direct the gas flow and to protect the walls of the discharge chamber against an overheating, thus affording the flow purity. The external part of the quartz tube is water cooled to rule out overheating of the quartz tube by the plasma radiation emission.

With no electrode purity of the flow is expected and experiments may be performed with non-oxidizing as well as oxidizing gas mixture such as CO_2, air...

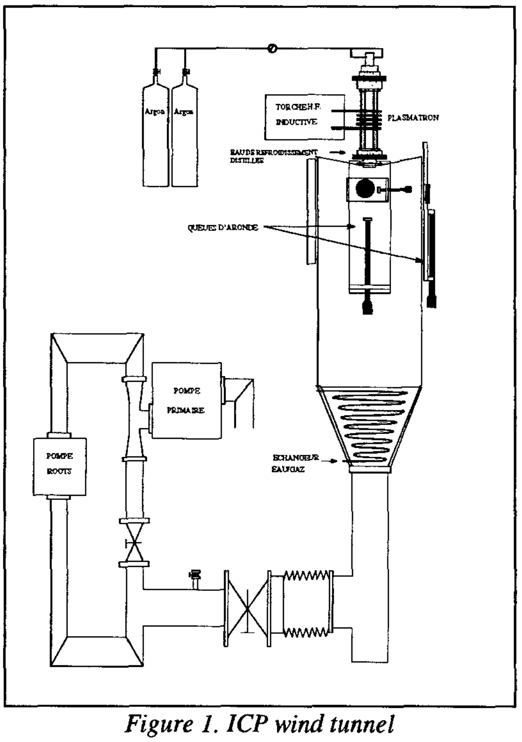


Figure 1. ICP wind tunnel

Experimental works are devoted to characterize flow stream impinging simple models as well as to analyze the transfer processes between gas and wall material. Facilities have been implemented for studies such as, analysis of a low pressure plasma in boundary layer situation [1],[2], study of N_2-CO_2 plasma interaction with a C-SiC tile in low pressure condition [3], analyze of a supersonic turbulent low pressure plasma flow generated for simulating the recombination of charged species [4]...

3. MEASUREMENT TECHNIQUES

For the description and explanation of phenomena occurring in a plasma, it is necessary to determine as many parameters of the plasma as possible with the help of the as many as possible mutually independent methods, as accurately as possible. Among the relevant parameters is the composition of the plasma, the temperature and density of the different atoms and molecules and flow velocities of the individual components of the plasma.

Through the emission, absorption and laser spectroscopy of plasma flows, investigation of the plasma parameters may be done by numerous methods of analysis. The study of intensity of spectral lines emitted by atoms, ions and molecules is extensively used with assumption that level population satisfied a Boltzmann distribution law and that the medium is optically thin. With plasma displaying an appreciable absorption, the determination of temperature and number density is drawn from the absorption coefficients of resonance lines.

Among the methods of plasma diagnostics cited above and used at CORIA, attention is done to carry out measurements with the well-adapted method suitable to the operating plasma flow condition of interest.

3.1. Diagnostics devices

- DETECTION DEVICES

Different spectrometers and gratings are available at CORIA to spectrally analyze emission and absorption spectra of plasma flow in the spectral range of 120 nm to 10 µm. Species such as N, N_2 , O, O_2 C, C_2, CO, CO_2, NO, SiO, SiO_2.....are well identified. In the UV and far UV with holographic grating (4230 groves/mm), the highly resolving spectrometer has permit to record the resonance line of nitrogen ($^4P \rightarrow ^4S^0$: 119.955 nm) with a resolution of 1/100 Å. In the UV-visible spectral range, the molecular spectra of numerous species have been well observed with high resolution of the vibrational and rotational structures. Spectra analysis allowed the signing of the flows and identification of species. Depending of the structure of molecular spectra, the spectra are recorded with highly or partially resolution, or are fully degraded to be matched with synthetic spectra for temperature and density measurements [5].

For single point measurement the light intensity of emitting species is generally recorded on a photomultiplier. For light-of-sight and 2D measurements, the used of Intensified Charged Coupled Detector (ICCD) is commonly used. Time resolved light emission (LIF diagnostics) for single point or integrated light emission may be easily analyzed by means of 2 GHz numerical oscilloscope.

- LIGHT EMISSION SOURCES

Numerous emission and absorption continuous sources (tungsten, mercury, xenon, deuterium lamps and a krypton pumped monomode Dye laser,...) are available from Ultra-Violet to InfraRed spectral range. They are used for spectrometer wavelength calibration and laser wavelength calibration. In the UV from 180 to 300 nm, the large continuum of the W, Hg, Xe and D_2 lamps provide useful sources for absorption spectroscopy.

On the other hand because of the low radiation emission of such lamps especially in the far-UV down to 120 nm, the plasma team develops particular UV sources adapted to particular experimental works (see § Emission and absorption sources).

The highly resolving Dye Laser with a spectral resolution of 10^{-4} *nm* is suitable for line broadening measurement by absorption in the visible spectral range (680 –780 nm). In addition, it permits an accurate velocity measurement by Doppler shift.

Laser induced fluorescence (LIF) is a powerful technique which provides local information of the flows parameters with a much lover detection limit than the usual absorption sources. The LIF technique is well known at CORIA and has been extensively used and developed to study high enthalpy flows. The different sources available, not only for LIF, but also for Rayleigh and Raman measurements are:

- The Krypton pumped monomode Dye (SPECTRA PHYSICS) laser. It has been recently modified at CORIA. The slow motorized wavelength scanning has been replaced by an electro-optic LiNBo (Boro-Silicate of Lithium) photo-refractive crystal whose optical index varies with the applied voltage. Then, the ring cavity length changes and the laser is tilted in wavelength. The method will allow scanning frequency in the turbulent time scales. Up to now, this device is under-development. With this method we expect to measure simultaneously the temperature, number density of excited states and velocity by laser induced fluorescence in a turbulent plasma flow.

- The excimer laser (LPX 150/50T LAMBDA PHYSIK) used with ArF (193.4 nm) or KrF (248.0 nm) gas mixture. The radiation is of about 180 mJ at 193.4 nm and 250 mJ at 248 nm, with a pulse duration of 10 ns at FWHM. The excimer laser consisting in two separate cavities may be used indifferently in broadband mode or narrow-band mode, respectively with resolution of 0.5 nm FWHM and $1.2\ 10^{-3}$ *nm* at HWHM. In narrow-band mode, the pulsed radiation can be tuned with a step increment of $2.2\ 10^{-4}$ *nm* on the full spectral range of the broadband emission.
The coupling of the excimer laser with a high pressure Raman Shifter Cell filled with suitable gas (H_2, D_2...) allows to shift the incident laser radiation to wavelength of interest, corresponding to excitation wavelengths of molecules on both sides from the initial 193.4 and 248 nm excitation wavelength. The excimer laser working with ArF and KrF gas mixture provide a fruitful diagnostic tool for the whole species present in air plasma and at the vicinity of materials such as C-C, SiC-SiC and C-SiC immersed in plasma flow.

- A pulsed Optical Parametric Oscillator (OPO SPECTRA PHYSICS) pumped by Nd:YAG. The OPO provides a powerful and monochromatic radiation ($0.3\ cm^{-1}$ *FWHM*) from IR (2 μm) down to UV (15 mJ at 226 nm). The spectral range can be extended further in the UV using a Raman Shifter Cell.

- A Raman Shifter Cell filled with specific gases and coupled with the excimer laser at 193 or 248 nm allows to enlarge the spectral range of the excitation wavelengths from the excimer laser radiation.

3.2. Emission and absorption

Emission and absorption spectrometry of atomic and molecular species has been extensively study in plasma flows from VUV to IR spectral range to provide information on number density species and temperature. Although emission and absorption spectrometry provides information on the medium, attention is done on the on the relevance of the deduced parameters.

- INTEGRATED LIGHT EMISSION AND ABSORPTION

Emission or absorption measurements are not punctual measurements and the recorded intensities have to be considered as integrated along the light-of-sight of the observed signal. In a non-absorbing medium without number density and temperature gradient, the local intensity may be easily drawn from the recorded intensity signal. The main difficulty encountered appears in an inhomogeneous medium, in presence of a non-axis-symmetric flow and of an optical thick medium. For emission or absorption measurements, the light intensity recorded is providing from the light emitted along the line-of-sight and is resulting from the summation of numerous individual locations which are different in density and temperature. Local measurement can be only derived with an axis-symmetric geometry if an Abel's inversion is applied:

$$i(x)=2\int_x^R \frac{i(r)rdr}{\sqrt{r^2-x^2}}$$

The reverse relation is given as:

$$i(r)=-\frac{1}{\pi}\int_x^R\left(\frac{di}{dx}\right)\frac{1}{\sqrt{x^2-r^2}}dx$$

where i(x) is the integrated light-of-sight signal intensity and i(r) the radial (or local) signal intensity.

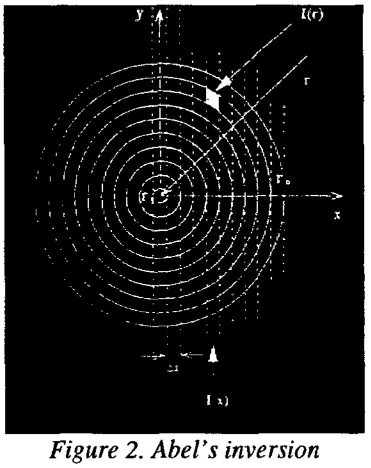


Figure 2. Abel's inversion

A Beer's law may be added to the Abel's inversion to correct the self-absorption of the medium. For that, a separate absorption measurement have to be done.

- MEASUREMENT OF THE GROUND AND EXCITED STATES

While emission spectroscopy provides information on the upper excited levels of atoms, molecules and radicals, the absorption spectroscopy allows to probe the metastables and fundamental ground states.

As a general rule, emission or absorption measurement gives only information on the population density of the emitting or absorbing levels of atoms and molecules. If the collisional coupling between the various energy levels of the atoms or molecules is very efficient, then a Boltzmann equilibrium assumption may be assessed to deduce from emission or absorption measurements the whole concentration of species of interest and the temperature.

As the emitting or absorbing levels concerned in the visible or near UV spectrum are generally issued from excited electronic levels of atoms and molecules, the population density is only representative of a finite proportion of the entire species population density. The main part of the particles are on the fundamental level or on the nearest electronic levels such as the metastable states. In expanding flow, emissive levels are populated either by recombination of the parent ions or by exchange of excitation with another molecule. So, they are highly weakly coupled with the fundamental level and then more representative of the whole species population density. Then, by emission and absorption measurement, it isn't relevant to deduce the species population density according to a Boltzmann equilibrium distribution. We have also to notice that the emissive levels being weakly populated, the rotational distribution can be very sensitive to selective rotational population rate by chemical reaction and even measurement of the ground and nearest excited states. As mentioned above, only absorption measurement on the fundamental or nearest electronic levels may provide with a good confidence the species concentration. Generally, the radiative transition taken into account are in the VUV region. The difficulty provides mainly from the lack of efficient absorbing source, added to the difficult operating conditions in the UV spectral range imputed to the O_2 molecular Schumann Runge absorption band.

- EMISSION AND ABSORPTION SOURCES

The usual calibration sources and absorption lamps available (W, Hg, Xe and De) are used to provide absolute calibration of number density and absorption spectroscopy. Attention has been done in the UV spectral range because of the high resolution suitable to the analysis of rovibronic structure of molecular spectra and broadening of line. By this way, UV detection and particular UV sources has been developed for emission spectrometry and overall, UV absorption down to 120 nm. As it has been yet noticed, the main difficulty for these UV source and more generally for UV spectrometry, is the strong absorption by the O_2 Schumann-Runge absorption band and transmitivity of optical glasses down to 250 nm. So, it is required the use of specific optical windows (MgF2 and LiF below 180 nm) and to set optical arrangement and detection device in vacuum or in low-pressure conditions, or in inert gas atmosphere.

Different UV-sources have been developed for particular experimental works, to produce stable and reproducible media with a continuous or discontinuous highly light emission spectrum on a broad spectral range.

An example of a discontinuous UV source with a specific optical arrangement is presented here. It consists in an atmospheric Argon-plasma seeded with nitrogen in low concentration [5]. This source has been used as high emission UV source to involve absorption of the resonant and metastable states (120 to 180 nm), in a low pressure nitrogen plasma flow. The high-pressure Ar-N_2 medium provides suitable N-atomic lines broadening to be used as absorption source on the N-atomic spectrum emitted from the low-pressure nitrogen plasma. The complete optical arrangement is set at 3 10^3 $mbar$, and optical windows and lenses are made of MgF_2, 2 mm thick. In the 120-200 nm spectral range, the UV emission spectrum points out neither the presence of the Lyman-Birge-Hopfield, nor the Vegard-Kaplan system. The spectrum is a discontinuous spectrum of atomic nitrogen lines. The hydrogen line $L\alpha$ set at 121.6 nm, the resonant oxygen line (130 nm) and carbon lines (165 and 193.1 nm) are also observed. From the atomic nitrogen highly resolved absorption lines (down to 1/1000èmenm), the number density of the metastable states $2P \rightarrow {}^2P^0$ (174.272, 174.525 nm) and $2P \rightarrow {}^2D^0$ (149.262, 149.267 and 149.467 nm) has been determined. On the other hand, the self-absorption in the UV atmospheric source precludes direct measurement on the resonant transition ${}^4P \rightarrow {}^4S^0$ (119.955, 120.022, 120.071 nm). In this case, populations have been determined using a model including first the emission measurements after an Abel's inversion and second a correction from the self absorption by the medium, in agreement with the absorption lines profiles recorded.

An other example is the development of experimental source to increase the potentiality of studies in the UV down to 120 nm. It consists of a dielectric barrier discharge (DBD) in rare gas to produce excited dimmers sources as Ar_2, He_2, Ne_2 and Kr_2. De-excitation of these molecules produces intense radiation in the ultra-violet spectral range 100 – 300 nm. At low pressure conditions, the DBD source emits a discontinuous spectrum mainly constituted by the resonant lines of the rare gas. With increasing pressure, the spectrum is shaded off in a continuum highly lightening favorable to absorption spectroscopy. The DBD is made of a quartz tube (500 mm length and 5 mm) used as dielectric with two metallic electrodes painted on its external surface. Micro-discharges are generated with a power supply generator (7 kV – 20 kHz) and provide a high electronic number density $\left(10^{20}-10^{21}\ m^{-3}\right)$ with electron energy levels up to 20 eV and a lifetime of about 100 ns, depending from the gas mixture. The integrated light emitted by the DBD source produces thus high radiation (few mW) in the sight-of-light of the quartz tube. It is noted that from the quality of the gas mixture will depend the light emission from the DBD source. It has been observed that presence of impurities may produce an abundant spectrum of the impurity itself, and releases the excimer emission. The future of DBD sources is promising and always under development at CORIA. It is driven by the opportunity to probed the ground levels of atomic species (O, N, C...) and molecules (CO, SiO...) in planetary atmospheres such as the Earth and Martian ones in order to better understand the chemical mechanisms in heterogeneous and homogeneous situations.

3.3. Laser diagnostics

By comparison with usual emission and absorption methods, the laser diagnostics present advantage of local and/or 2D measurements with high selectivity of species of interest. Laser diagnostics are extensively used for temperature and density measurements by comparisons with computed synthetic spectra.

Molecular spectra are calculated for the main species observed in reentry conditions such as the earth or mars atmospheres (i.e.: N_2, O_2, C_2, CO, CO_2, NO, CN...), and for the main species observed in studies of plasma/surface interactions (i.e.: SiO, SiC, SiO_2 ...).

From high monochromatic light emission laser source adds to the possible spectral tilting in wavelength, velocity measurements may be carried out.

The main laser diagnostics used to probe the plasma flows are summarized hereafter.

- RAYLEIGH SCATTERING

The Rayleigh scattering is the elastic interaction between the incident laser radiation and gas molecules, so without excitation wavelength dependence in regard to the molecule probe and thus without interaction with the internal energy molecular mode. Because intensity of the scattered light is proportional to the number density of gas molecules, the Rayleigh scattering is a suitable method to determine the gas number density.

One of the advantages of Rayleigh scattering in comparison with the Raman light scattering is that Rayleigh cross sections are in three orders of magnitude greater than the corresponding vibrational Raman cross sections. Thus the Rayleigh scattering is the strongest of the molecular light scattering techniques well adapted to the number density measurement, as well as at low gas density than in higher pressure conditions. In an other side, one disadvantage of the Rayleigh scattering is that it is an elastic process, and thus not species specific. In addition, Rayleigh scattering may occur at any excitation wavelength, the shorter wavelength being more efficient because of the Rayleigh scattering cross section evolution with ν^4. Since the Rayleigh light scattering is observed in coincidence with the excitation wavelength, the signal can be overlapped with Mie scattering (20-fold greater than the Rayleigh signal) and parasite reflections from surfaces surrounding the incident radiation.

Rayleigh scattering has been used extensively in low-pressure high enthalpy wind tunnel for total number density measurements and also in well identified medium for calibration of the fluorescence signal intensity. For example, the used of high energy density of excimer laser in the far UV is well suitable to achieve total number density measurements in medium with pressure down to 1 mbar.

Depending on species present in the plasma flow and operating conditions, attention has to be done with Rayleigh measurements. It is necessary to tune the excitation source wavelength out of absorbing transitions of species present in the flow, in order to avoid overlapping of LIF and Rayleigh (for example with ArF excitation in presence of NO molecule). It is also noticed that as total number density is directly proportional to the Rayleigh signal and determined at the same wavelength than the excitation source, the reflection of the incident excitation radiation may enhances the effective Rayleigh scattering signal and thus provides an erroneous value of the total number density.

- SPONTANEOUS RAMAN SCATTERING

The Raman scattering is the inelastic interaction between the incident light and the electronic-mediated vibrational-rotational modes of the molecules. The inelastic process is described by an energy exchange between the incident photon and internal energy modes of the scattering molecule. Thus implies that the scattered photon may gain or loss energy and that the Raman signal can be spectrally observed at different wavelengths, shifted from the incident radiation. The spacing energy between the incident and scattered photon corresponds to the excitation energy of the molecule, and thus is specific of the molecule excited.

The scattering light spectrum consists of Raman Stokes, Rayleigh and Raman Anti-Stokes lines. The incident photon excites a molecule from rovibronic levels of the electronic ground state, from the lower vibrational levels to a upper virtual one. This level de-excites to rovibronic levels of the electronic ground state with radiation emission at shorter, identical and higher wavelengths than the one corresponding to the excitation energy of the molecule, respectively named the Raman Stokes, Rayleigh and Raman Anti-Stokes scattering. Only the Rayleigh scattering remains unshifted in regard to the excitation radiation.

Intensity of the Raman scattering is dependent from the vibrational number density of the probed molecule, and then depends from the rovibronic levels thermally populated. The scattered spectrum, spectrally resolved allows to identify molecular species according to the energy spacing between the incident and scattering radiation. This implies that Raman scattering may provide simultaneously, multiple species concentration and temperature measurements. Since Raman scattering may occur at any excitation wavelength and because spontaneous Raman scattering involves only transitions from the electronic ground states, it is possible to measure the number densities of stable species, such as N_2, O_2, CO, CO_2, SiO, SiO_2.... The only limitation to this technique is the weak light emission imputes to the lower values of the Raman scattering cross sections. Thus, accurate Raman scattering measurement will depend first on the energy spacing between the excitation wavelength and the scattering Raman signal, and second from the relative ratio between Rayleigh and Raman scattering cross sections.

- LASER INDUCED FLUORESCENCE

Laser induced fluorescence is an electronic absorption process that produces relatively high signal intensity with high spatial resolution. Except the resonant fluorescence emitted at the same wavelength than the excitation one, the fluorescence spectrum is normally red-shifted from the excitation wavelength and thus easier to discriminate. Fluorescence intensity is directly proportional to the molecular number density and can be used to measure the concentration. However, quenching effects imputed to collisional partners present in the gas mixture, pressure and temperature can reduce the fluorescence signal intensity.

Up to now, in the spectral range of the ArF laser at 193.4 ± 0.5 nm, experiments were performed extensively on O_2, NO_ε. For molecules such as CO, NH_3 and H_2O, the fluorescence may also be observed via the multi-photons photo-dissociation processes. For CO molecule, it has been pointed out that through the different CO excitation pathways by means of an ArF excitation source, only the three photons process may be retained. The difficulty provides in this case to an absolute number density measurement.

The spectral energy distribution of the excimer shows us strong absorption region dues mainly to absorption of the laser radiation by the intense O_2 Schumann-Runge bands and by absorption of HF and C molecular species, HF and C being considered as intra-cavity impurities. Gaps in the spectral energy distribution takes on particular importance in the excitation process of atomic or molecular species, because they prevent or degrade excitation of the species of interest, and modify the general feature of the fluorescence or excitation spectra. For example, a good knowledge of laser radiation spectral energy is needed to understand and improve some particular fluorescence phenomena such as the photo-dissociation of the carbon monoxide. In addition, as usually done, the matching of experimental spectra with computed ones may be greatly influence by a non-constant energy density of the laser source and provides non negligible discrepancies inherent only to the badly knowledge of the excitation mode. This may be harmful to number density determination and temperature when this latter is drawn from line ratio.

- RAMAN SHIFTER

As a result of the Raman lines emission is the use of the incident laser emission as a pump laser to provide via the Raman Stokes and Raman Anti-Stokes scattering of a suitable molecule, a new set of excitation wavelengths shifted from the incident one, to induce fluorescence of molecules such as CO, SiO, O. It is noticed that the Raman Shift effect may be observed only in gas with high Raman cross section such as H_2, D_2, HD and CH_4 (respectively, 4155, 2987, 3628 and 2917 cm^{-1}). The efficiency of the process remains lower, less than 10% on the first stokes and is decreasing for higher components.

For experiments performed at CORIA on interaction plasma/surface studies, interest has been focussed on the CO, SiO, O molecules excited via a Raman Shifter Cell pumped by an ArF excimer laser

Carbon monoxide fluorescence (CO)

The carbon monoxide fluorescence is induced at 230.1 nm from the H_2 2nd Stokes issued from the Raman Shifter Cell pumped with ArF excimer excitation source. Efficiency is less than 10%, but only few mJ are necessary to induce the CO fluorescence $(B^1\Sigma^+,\ v'=0 \leftarrow X^1\Sigma^+,\ v''=0)$ in low pressure conditions set at 50 mbar. Fluorescence is detected in the visible spectral range from 450 to 560 nm.

Oxygen fluorescence (O)

The oxygen fluorescence is induced at 226 nm from a two-photon process, from the fundamental $2p^3P$ to the atomic excited state $3p^3P$. The fluorescence light is detected in the visible from direct de-excitation, either from the transition $3p^3P \rightarrow 3s^3S$ at 845 nm, or from the transition $3p^5P \rightarrow 3s^5S$ at 777 nm, after collisional transfer from the $3p^3P \rightarrow 3s^5P$. The usual excitation may be provided from a doubled and mixed Nd:YAG; the radiation is closed to 226 nm, with energy of about few mJ. Whatever the gas used in the Raman Shifter Cell pumped by ArF or KrF excimer laser, no light is emitted at the wavelength of interest. On the other hand, if we consider the summation of the second and third stokes generated from the Raman Shift Cell filled with Deuterium (8 bars) and pumped by ArF excitation source, then light emitted from the Raman Cell is tuned on the oxygen transition $2p^3P \rightarrow 3p^3P$ which one may be excited. The major difficulty is imputed to the filtering of both transitions among the other stokes, and to the focussing two transitions of different wavelengths at the same measurement point. The method is promising in plasma studies and in catalysis studies in which oxygen is considered as major specie.

Monoxide silicate fluorescence (SiO)

In the spectral range 230-232 nm, the SiO absorption spectrum via the $(A^1\Pi,\ v'=1 \leftarrow X^1\Sigma^+,\ v''=0)$ transition is in coincidence with the second stokes of Hydrogen (H_2) pumped with ArF excimer laser. Because of high transition probability, this vibrational sequence can be easily excited at 231 nm. The more critical point for the SiO molecule provides from the spectral range of fluorescence de-excitation at 240 nm, in coincidence with the emission band of NOγ. The SiO spectrum shape is well characteristic and defined with a bandhead set at lower wavelengths and rotational structure varying extensively with the rotational temperature. SiO molecule expected to be produced by catalytic parietal recombination in air plasma / SiC interaction, may be a suitable specie for temperature measurement.

3.4. Measurement from molecular spectra

Analysis of molecular spectra provide information on the signing of species present in the flow and information on temperatures and densities. The band spectrum of diatomic molecules allows:

- the determination of the temperature and particles densities from absolute intensity of individual bands.

- determination of the rotational temperature from the relative intensities of the rotational lines within a band.
- determination of the vibrational temperature via the relative intensities of several bands belonging to the same electronic transition.

When temperatures and densities are drawn from comparison with computed synthetic spectrum, accuracy will depend on the bands system analyzed, the temperature levels considered and accuracy of the computed spectrum in regard to the particular recording experimental conditions. The computed spectrum have to be as accurate as possible and include correction for apparatus function of the optic detection device, constituted mainly by the monochromator used as a narrow or broad band-pass filter over the full spectral range of the molecular of interest.

At CORIA, the synthetic spectra of numerous diatomic molecules met in re-entry conditions have been calculated in emission and are also available in absorption. For species probed by laser excitation, excitation and fluorescence spectra have been built. It is important to note that generally comparisons between experimental and synthetic spectra are carried out for flows at low or moderate temperature. For high temperature medium, the high rotational and vibrational levels have to be considered for a best synthetic spectra description.

As previously mentioned, with a nom-homogeneous flow, numerous spectra will be necessary to calculate from the Abel inversion the spectrum in a single point measurement. High or low resolution spectra may be used to determinate the temperature value.

The rotational temperature is determined from the relative intensities of the rotational lines within a molecular band. When frequency of heavy particles collisions with an upper excited state of molecule is at least 5-fold greater than the radiative transition probability, then a Boltzmann equilibrium between rotational levels and the upper electronic excited states of molecules may be expected. Taken into account the strong coupling between translational and rotational energy states, the rotational temperature derived from experiment will be then given as the kinetic gas temperature.

The vibrational temperature is determined from the relative band intensities of the same electronic state. A Boltzmann equilibrium between the vibrational energy levels of the upper excited state is expected if the frequency of inelastic collisions (energy exchange between vibrational level) is higher compare to the electronic transitions probability.

For non resolved rotational structure, an experimental spectrum is commonly spectrally degraded to record the general envelop shape of the spectrum. It is then compared with a synthetic spectrum computed with identical apparatus function. Rotational and vibrational temperatures of the synthetic spectrum are adjust up to the general feature of the computed spectrum coincides exactly to the experimental one.

In non equilibrium plasma, it is commonly observed that $T_{gas}<T_{vib}<T_{elec}$ because molecular vibrational energy levels are both influenced by heavy particle collisions and by electronic collisions.

3.5. Velocity measurement

Velocity measurements are performed considering a Maxwell velocity distribution of emitting species which move according to the mean velocity of the flow. The light emitted from species and observed along a line of sight different from the direction of the flow, is shifted by the quantity corresponding to the mean velocity component of the molecule in the direction of observation. For observation in the direction of the particle mean velocity, the light emitted (or line profile) is blue-shifted. Conversely, it is red-shifted with the same absolute shift value for observation in the direction opposite to the mean movement of the flow stream. For observation perpendicularly to the flow axis, the light emitted is unshifted. The shift in wavelength is given as the Doppler shift and expressed as:

$$\frac{\Delta\nu}{\nu}=\frac{v}{c}\cos\theta$$

where ν is the frequency, v the velocity and c the light speed. θ is the difference angle between the flow axis and the light of sight of observation in a direction such as 0<θ<π/2. Experiment may be carried out either from lines emission, or from absorption or fluorescence analysis.

4. OTHER DIAGNOSTICS

- LANGMUIR PROBES

The Langmuir probes are used to determine the behavior of the electrons in plasma flows. With plasma out of equilibrium with the different energy modes, electronic temperature as well as electronic number density may be determined from electrostatic Langmuir probe measurement.

When an electrode is immersed in an ionized gas, an electrostatic sheath is formed if its potential is set at a different potential than the plasma one. Due to the electric field perturbation, charged species are repulsed or attracted, collide with the electrode and provide an induced current. The study of this current provides the charged species characteristics. The electrostatic probes consist of two cylindrical metallic wires shielded with a thin ceramic sleeve. Their dimensions are such that assumption of uncollisional sheath surrounded the probe is respected (ratio to the Debye length (sheath thickness) to the mean free path of the medium of interest), to apply the Laframboise theory. Typically probes are 0.05 mm radius and are aligned on the flow axis. Measurement close to model surface is provided with wires implanted on the surface as flush probes. The small size provides local measurements and reduces depletion of low energy electrons. One probe yields the plasma floating potential. A sawtooth voltage is applied with a low frequency (1-2kHz) to the other probe. The temperature of thermal electron is drawn from the second derivative of the intensity versus voltage probe characteristic, represented with a straight line for a Maxwellian electron energy distribution. The electron number density is calculated from the probe current value at plasma potential.

It is noticed that electrostatic probes have been adapted to work at high frequencies in order to reach the small time scales of turbulent plasma flows. Indeed, for higher sweeping frequency up to 90 kHz, the noise induced by the RC characteristics of coaxial cables becomes non-negligible and prevents probe measurements of weak current. So, an original setup has been developed for high frequency. The noise reduction is obtained by doubling the measuring circuit by a compensatory one. On one side, the circuit supplies the real probe immersed in the plasma flow, on the other side, one supplies a dummy probe, identical to the first one, placed outside the plasma. The RC cable induced noise removal is obtained by analogic subtraction of both signals. This device was used at 90 kHz to measure the plasma number density fluctuations in turbulent flow and determine the turbulent integral scale of large structures.

Flow velocity may be also provided from crosses Langmuir probes, setting at right angle. The ionic drift current is inefficient on the current for the probe aligned to the direction of the flow axis, but added to it when the probe is placed in the direction perpendicular to the flow. With assumption than the Debye shield is collisionless and that it thickness is smaller than the probe radius, the ratio of the perpendicular to parallel probe current component is given as proportional to the ratio of the flow velocity to the most probable ions thermal speed.

- HEAT FLUX PROBE

The local measurements of the parietal net heat flux exchanged is obviously, a very important parameter for studies of plasma / surface interaction for simulation of reentry conditions in different planetary atmospheres.

The homemade thermo-gauge consists of a constantan foil (Radius 3.8 mm, thickness 0.2 mm) brazed on a copper tube and insert in an insulator shield. Immersed in a radian medium, the heat flux is continuously drained from the sensor to the surrounding body. Due to the low conductivity of the constantan, a difference of temperature occurs between the center and the edge of the foil, which is measured by a thermocouple. The relationship between the thermocouple value and the spectral net heat flux is calibrated by means of a monochromatic source and points out a linear response for net heat flux up to 80 $kW.m^{-2}$. The time rise up is estimated to about one second.

This device satisfies well flux measurements up to 10-100 $kW.m^{-2}$, in the same order of magnitude than those encountered in reentry plasmas. On the other hand, value of the incident flux as to be considered as a mean value when plasma parameters such as the spectral range of plasma emission and thermal conductivity and local kinetic temperature of the plasma are not accurately determined.

- THERMOGRAPHY

The facility devoted to analysis on the parietal net heat flux exchange and to comparative studies on the catalytic behavior of C-C and C-SiC TPS materials immersed in a plasma flow simulating the Martian atmosphere, has been implemented by Infra-Red thermography detection. The Infra-Red camera is cooled with Peltier effect and it analysis spectral range is 2 µm – 5 µm. It is pointed out that accurate 2D temperature field measurement depends mainly from the accurate knowledge of the material emissivity at the detection wavelength.

Analysis of medium may also be performed in the I.R. spectral range by means of classical I.R. plasma emission.

- OTHERS INTRUSIVE METHODS

Others intrusive methods such as pitot probe and thermocouple are also used in plasma flows. In our experimental working conditions and considering the weakness spatial resolution, these devices do not allow to provide more than an order of magnitude of the parameters of interest.

5. SYNTHETIC SPECTRA

Temperatures and densities are derived from the comparison of synthetic spectra with experimental ones [6]. These comparisons also allow to point out the non-Boltzmann distributions of vibrational and rotational populations. At CORIA, the synthetic spectra of all the diatomics species met in reentry conditions have been calculated in emission. Absorption spectra are also available for the same molecules, radicals and ions. It is important to note that generally comparisons between experimental and synthetic spectra are carried out for flows at low or moderate temperatures. At CORIA, we have particularly studied the extension of synthetic spectra to high rotational and vibrational temperatures (for example see Figure 3).

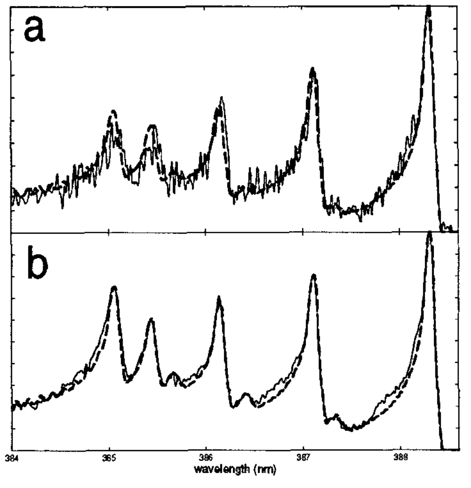


Figure 3. Experimental (solid lines) and synthetic (dashed lines) spectra of CN violet system in alow pressure CO_2N_2 plasma.
(a) exit of the plasma generator T_{rot}=7000 K, T_{vib}=9500 K, FWHM =0.092 nm
(b) over a C-SiC tile T_{rot}=7500 K, T_{vib}=13200 K, FWHM=0.092 nm

These section presents two molecular systems of interest studied in the N_2CO_2 [6] plasma flows analyzed in the different wind tunnels at CORIA.

- CN – red system

CN is one of the most emitting molecules in plasma media produced from mixtures as CO_2-N_2 and CH_4-N_2. Within the visible range of wavelengths, its red system is the main source of molecular radiation with the Swan bands of C_2.

That red system gathers all the rovibronic transitions between the $A^2\Pi$ excited state and the $X^2\Sigma^+$ fundamental state. Its structure is close to the γ and ε bands of NO and to the ultraviolet bands of OH. The spectrum involves 6 main branches and 6 satellite branches. One of the main distinctive features of that kind of system is the signification level of the satellite branches. The high number of branches leads to a real complexity of the spectra. According to the experimental resolution, there is no main bandhead but several secondary bandheads corresponding to the main branches.

The Δv=0 sequence is located in the infrared while the first bands of the Δv=+3 sequence and upper sequences take place in the visible range of wavelengths. Vibrational and rotational structures develop both towards large wavelengths.

The significant emission through this system is more a population effect rather than caused by a short lifetime of the state; indeed, the highest transition probabilities remain lower than 10^5 s^{-1}. $A^2\Pi$ state may be populated by electron collisions if the ionization rate is high enough or by excitation transfer with vibrationaly excited partners such as CO and N2 (v>3).

- CO – fourth positive system

With atomic emission, CO fourth positive system is the more significant source of radiation during a spacecraft entry in the atmosphere of planets such as Mars and Venus. This system is made of transitions between two single states: the excited state $A^1\Pi$ and the fundamental state $X^1\Sigma^+$. The wavelength of the first band origins (Δv=0) is close to 155 nm but in vibrationaly excited media, it is possible to detect some band in absorption over 200 nm. Vibrational and rotational structures develop both towards large wavelengths. In spite of numerous overlapping, the spectra remain little complex since there is only three main branches. Lifetime of state A is very short and thus the fourth positive system owns high transition probabilities. These features make this system very interesting for studies in emission as well as in absorption spectroscopy because of the very low detection limit. However, the location of (A-X) transitions in the wavelength range complicate the experiments. Problems are connected to the absorption of light by Schumann-Runge bands of molecular oxygen below 190 nm. This phenomenon prevents to work with an optical axis under atmospheric air. Vacuum conditions are needed which are different according to the wavelength. A pressure lower than 1 Pa is rated to avoid oxygen absorption problems.

6. STUDIES AT CORIA AND ON SITE CAMPAIGNS

In this section, we present briefly the different studies carried out at CORIA on high enthalpy flows. The objective is to illustrate the potentialities of the techniques developed at CORIA. Further details may be found in the given references.

We show also that the techniques developed at CORIA may be implemented on other facilities with very different working conditions.

6.1. Numerical simulations

In parallel to experiments, different numerical codes have been developed at CORIA:

- Two 2D Navier-Stokes codes for laminar and turbulent flows,
- a 2D parabolic boundary layer code.

The objective is to carry out thorough experiment/modeling comparisons in order to better understand the studied flows. Discrepancies observed between computations and experiments have led us to study in more detail the modeling of numerous terms in conservation equations. New models have been proposed for different rate coefficients (see for example [7]) and energy exchange terms (see for example [8]).

6.2. Experiment/modeling comparisons in a nitrogen plasma jet and boundary layer

Numerous measurements have been carried out in a partially ionized nitrogen flow generated in one of the arc-jet facility of the CORIA [1]. In parallel, two codes have been developed: one for the laminar supersonic free jet [9] and a second one for the boundary layer [10] developed over a flat plate set along the jet axis. The interest and the difficulty of this experiment/modeling comparison was that a good agreement had to be obtained on numerous parameters. This has led us to study in detail the modeling of different terms in the conservation equations. For example, Fig.4 shows the density of atomic nitrogen on the fundamental state (derived from UV emission and absorption spectroscopy) on the jet axis downstream the nozzle exit [5].

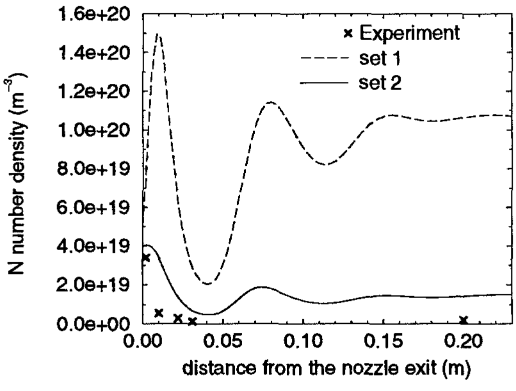


Figure 4. Influence of the kinetic scheme on the calculated N density on the axis of a nitrogen plasma jet.

These experimental data were in total disagreement with classical kinetic schemes (set 1), which predict a strongly dissociated flow. A thorough study of the kinetic scheme and recent measurements of poorly known reaction rates (set 2) have been taken into account, and finally, a fairly good agreement has been obtained with experiments.

6.3. Experimental investigation of the interaction of a C-SiC wall with a low pressure CO_2-N_2 jet

Reentry conditions in the Martian atmosphere have been simulated at CORIA to study the behavior of thermal protection systems (TPS). The model was a C-SiC tile, and the initial composition of the mixture was 50% N_2 and 50% CO_2. The main problem in that kind of study is to generate a plasma which contains atomic and molecular oxygen by means of an arc between two electrodes. Indeed, due to the erosion of electrodes by oxygen, metallic species may be present in the jet. These species as copper or tungsten may modify the chemistry of the jet and even the catalycity of the tile. The solution offered by the use of hafnium or zirconium for the cathode is valid as an insert of these metals at the end of a water-cooled copper rod, and with high flow rates. Indeed, first, at low flow rates, the arc is not carried enough by the gas and is hung on the copper structure of the cathode and second, as zirconium has a low thermal conductivity, a whole zirconium cathode would have a very short life time. So a plasma generator was realized with high-purity carbon electrodes, the low erosion of which, does not pollute the jet. Currently, a new generator using plasma cutting torch technology is developed to work at higher flow rates with a better stability of the jet.

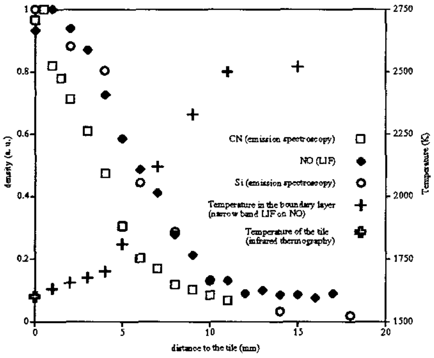
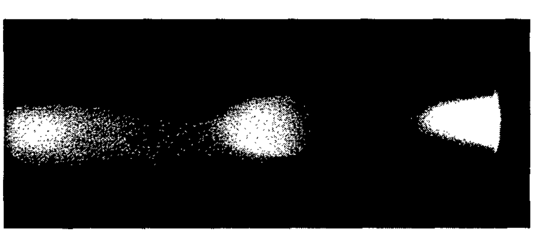


Figure 5. Measured species concentration profiles in the boundary layer over a C-SiC tile in a CO_2-N_2 plasma.

The boundary layer over the C-SiC plate (and for comparison over a carbon plate) was analyzed at a pressure of 100 Pa. Figure shows the measured profiles of NO, CN, Si of and the temperature [3]. Measurements are underway to probe other species as CO, O, N, C, SiO. The ionization degree of the flow is close to 0.05% and the temperature of the tile is 1600 K (measured by thermography).

6.4. Study of a supersonic turbulent low pressure argon plasma jet

In the after-body trailing wake of a ballistic missile, abnormal electron density fluctuations are generally observed. To study this phenomenon, we have considered at CORIA a simplified situation: an under-expanded argon jet which becomes turbulent [4]. The inductive plasma torch conditions are: gas flow rate 2.6 g/s, input power 45 kW, pressure in the chamber 17 mbar. Classical measurement techniques have been used to measure mean parameters in the flow, and fast methods have been developed to reach the turbulent time scales. For example, the electron temperature and density have been measured simultaneously and locally using the fast sweeping method developed at CORIA. It is also interesting to note that the different lasers at our disposal allow us to carry out measurements in extreme conditions.



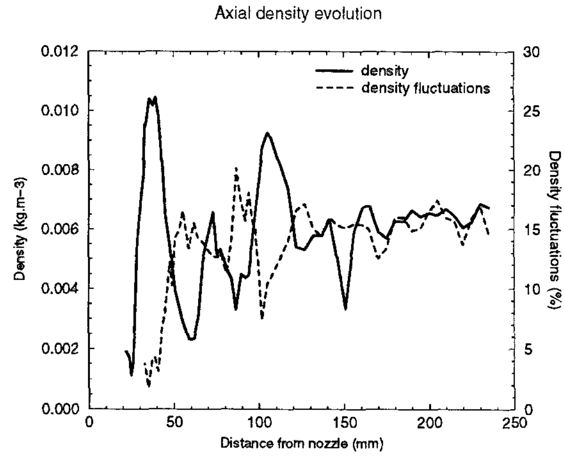


Figure 6. Total density and its fluctuation of an argon plasma jet on the jet axis. Flow conditions are given in the text.

For example, using a UV ArF laser, Fig 6. shows the total density and its fluctuations measured on the jet axis by Rayleigh scattering with a detection limit lower than 100 Pa. In parallel to experiments, a numerical code has been developed to simulate this flow [11]. Comparisons with experiments are underway.

6.5. Study at the Tsniimach Center - Moscow

A measurement campaign cite [12] has been carried out at the central research institute of machine building (TSNIIMACH Moscow) on two facilities:

- the ground experimental Y13PHF high frequency facility devoted to characterize the physico-chemical phenomena encountered in reactive flow/surface interactions,
- the TT1 arc jet facility designed to study the aerodynamics and the heat transfer of supersonic and hypersonic spacecrafts.

The main purpose of this work was to implement the LIF technique to measure species concentrations, velocity and temperature in the incoming flow, boundary layers and shock layers lying at the vicinity of a thermal protection system (TPS) model simulating a misalignment of tiles. The objective of this study was twofold : first to obtain reliable data for validation of numerical codes, second to point out the great potentialities of the LIF technique to study continuous high enthalpy air-flow/body interaction. The technical challenge of the test campaign was the exportation from CORIA to the TSNIIMACH center of the complete set of equipment needed for laser measurements and their implementation on different facilities with an experimental set up, as the whole diagnostic apparatus, fully automated and operating under an industrial environment. The experimental challenge has been to implement a new experimental methodology able to draw simultaneously local parameters in continuous high enthalpy supersonic air flow set for Hermes flight conditions at altitude 50 km and Mach 15.

Fluorescence was induced by a narrow band tunable ArF Excimer laser on NO epsilon-band. Rotational temperature and NO number density have been determined. Moreover, the spatial resolution of the LIF technique permitted accurate characterization of velocity distribution of the impinging free stream as well as in the flow field around specific shaped models. Thickness of the boundary layer and shock were also determined.

On the Y13PHF High frequency 1MW torch (15 MJ/kg, Mach 2.5) more devoted to catalycity studies on TPS materials, it has been determined that, due to the shape of the nozzle, the flow was 3D, and not 2D as expected.

Second, it has been pointed out that presence of N in the boundary layer participates to a non negligible growing of NO and CN at the vicinity of the plasma surface interaction, which is never taken into account in wall catalycity modeling. In the TT1 arc jet facility 10 MW (7.5 MJ/kg and Mach 4.5) studies have been carried out over a shaped model simulating a misalignment of tiles. First, experiments have been performed in the free jet to locate a sufficient homogeneous region to put the wide SiO_2 model and assure subsequently a 2D aerodynamic description of the boundary conditions with flat NO number density, temperature and velocity profiles. Then the spatial resolution of the LIF experimental set up has allowed to carry out a fine description of the velocity, temperature and NO concentration in the boundary layer and in the shock layer down to the surface of the model. This test campaign has demonstrated the potential of the LIF technique for the instrumentation of continuous high enthalpy facilities.

In parallel to experiments, a numerical code has been developed at CORIA to study the flow in the nozzle of the TT1 facility, and the downstream free jet.

On the axis at the nozzle exit, a fairly good experiment/modeling agreement is obtained on velocity, but computations underestimate by about 30 % the translational temperature and overestimate by more than one order of magnitude the NO number density [13]. Similar results have been obtained in the F4 hot shot wind tunnel. In fact, to explain experimental results, a much higher recombination rate of O atoms than the one given currently in the literature, would be necessary. Then, to improve the experiment/modeling comparison, complementary measurements of the O concentration would be of great interest.

6.6. Study at the TCM2 shock tube - Marseille

A measurement campaign was carried out during last summer on TCM2 free piston facility in Marseille (IUSTI-Université de Provence). The main purposes of this campaign were first, to prove the cleanness of the flow during the useful gust, and second to measure the density of nitrogen monoxide in the bow shock layer in front of a 2D model. The challenge was to excite nitrogen monoxide and to record the fluorescence image on an intensified CCD camera in the range of 0.3 ms corresponding to the useful gust. Results and details are presented at this conference in the paper [14].

7. CONCLUSION.

From numerous experiments performed in the wind tunnels available at CORIA and on industrial sites, it is pointed out that the measurement techniques developed at CORIA, and always under development, are well adapted to carry out information on the flow parameters during reentry conditions of different planetary atmospheres. It is also pointed out that in parallel to experiments, the experiments / numerical simulations comparisons are needed to improve the understanding of the aerodynamic behavior and chemical processes in planetary reentry condition.

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