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AEROTHERMODYNAMICS AND GROUND TEST FACILITIES SIMULATION OF PLANETARY ENTRY FLOWS – APPLICATION TO EARTH, MARS AND TITAN ATMOSPHERIC ENTRIES

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ABSTRACT

The knowledge of the aerothermodynamic environment of space vehicles crossing the upper layers of planetary atmospheres at hypersonic velocities represents a critical issue for dimensioning purposes.

In such high-enthalpy flows, dissociation and ionization effects lead to strong departures from chemical and thermodynamic equilibrium. The formation of a highly emissive plasma also implies taking into account radiation emission and absorption effects in the flow, using quantum mechanics calculations.

Different complementary ground test facilities allow the simulation of such entry conditions. At the Laboratoire d'Aérothermique, investigations on Earth, Mars and Titan like plasmas have been conducted over the last years in the SR5 rarefied arc-jet plasma wind-tunnel. Experimental investigations include optical emission spectroscopy (OES) and other measurement techniques. Numerical investigations include the development and validation of the line-by-line radiative code SESAM as well as the modelling of the SR5 plasma flow in a fluid mechanics approach using the Navier-Stokes ARES code and several other internal codes.

The complementary numerical and experimental investigations conducted at the Laboratoire d'Aérothermique allow an improved qualitative and quantitative knowledge on planetary entry flows which will lead to improved design properties and performance of future space vehicles.

1. INTRODUCTION

The challenges associated with planetary entries include, among other problems, many issues like stability and control during the descent trajectories. However these are dependent from the major issue during this descent flights, the aerothermodynamic environment of the flow around such entry vehicles, and the associated aerodynamic efforts and thermal heat fluxes. These are critical for dimensioning issues, as they determine the aerodynamic shape of the vehicle and the size and extent of it's thermal protections. The high entry velocities (which may exceed 10 $\mathrm{km/s}$ for superorbital trajectories) lead to the formation of a very strong bow shock in front of such vehicles, which transforms the translational energy of the gas in internal energy, heating the gas to very high temperatures were dissociation and ionization of the gas chemical species occur. The properties of such high temperature gases are not yet known very precisely, and several investigation programs are carried both on the definition of accurate numerical models, and on the experimental simulation of planetary entry flows in ground-test facilities.

This paper presents an overview of the investigations carried at the Laboratoire d'Aérothermique on the simulation of entry flows for different planetary atmospheres. A description of the physico-chemical properties of these high temperature flows will be firstly provided, followed by a description of the numerical models used for the simulation of such flows, as well as the experimental investigations carried in the rarefied plasma wind-tunnel SR5 using several measurement techniques.

2. OVERVIEW OF THE PHYSICO-CHEMICAL PROPERTIES OF HYPERSONIC ATMOSPHERIC ENTRY FLOWS

Compared to other fluid dynamics fields, the study of hypersonic atmospheric entry flows presents several unique features and difficulties. The presence of a strong bow-shock leads in most cases to strong departures from equilibrium, as well as to plasma formation. This brings the need to define very complex models dealing with high temperature gasdynamics, complex chemistry, and strong radiation phenomena in the flow. Indeed, as Theodore Von Karman said itself in 1958, "...With the advent of jet propulsion it became necessary to broaden the field of aerodynamics to include problems which were treated mostly by physical chemists...". A good reference textbook on this subject can be found in (Anderson 2000).

2.1. Influence of the Flow Rarefaction Degree

Since the most critical phase of an atmospheric entry flight (owing to the heat fluxes by the space vehicle) typically takes place in the upper stages of the atmosphere, it is important to determine if the flow has to be considered as a continuum or a rarefied flow. The Knudsen number ($K_n = \frac{\lambda}{L}$, where λ indicates the flow mean free path and L the object characteristic length) is an nondimensional parameter that aerodynamicists use to characterize the rarefaction parameter of the flow. For $K_n \leq 0.01$, the flow is considered as a continuum, and the classical Navier-Stokes equations allow an accurate description of the flow. For $0.01 < K_n < 0.1$, the flow can still be considered as a continuum, except in the boundary layer which has a thickness typically equal to the flow particles free-path. This problem is usually solved adding a slip-condition to the flow Navier-Stokes equations at the wall boundary. Finally, for $K_n > 0.1$, the flow can't be treated as a continuum anymore, and the aerodynamicist must resort to statistical methods such as Direct Simulation Monte-Carlo (DSMC) for the flow characterization. Although numerical simulations using this method bring a big computational burden comparatively to the Navier-Stokes calculations, it has the advantage of not having a convergence criterium, as each flow particle is treated individually. Instead, calculations proceed until a steady-state of the flow is reached.

2.2. Departure From Thermal Equilibrium

The strong bow-shock encountered in front of a space vehicle during an atmospheric entry also affects severely the flow properties. Indeed, as the flow passes from an hypersonic regime to a subsonic regime trough this shock, kinetic energy is converted into internal energy. The molecules internal modes (electronic, vibration, rotation) become very largely excited to the point were dissociation and ionization reactions can occur. The flow consequently reaches a state of thermodynamic non-equilibrium, as one temperature is no longer enough to allow a complete flow characterization. One has instead to resort to four temperatures to do so. Translational temperature is related to the flow translation energy, vibrational temperature to the molecules vibrational energy[1], rotational temperature to the rotation energy of the molecules [2], and electronic temperature to the energy of the free electrons in the flow[3].

2.3. Departure From Chemical Equilibrium

As stated before, the high temperature and pressure conditions found behind the strong hypersonic bow shock allow the establishment of chemical reactions along the flow path. The chemical conditions of the flow are equally characterized by an nondimensional number. The Damköhler number ($D_a = \frac{t_{chem}}{t_{conv}}$) defines the flow chemical state behind the shock. If the Damköhler number is largely smaller than unity, the chemical conditions of the flow adapt very quickly to the local pressure and temperature conditions over a small length. The flow is then said to be in chemical equilibrium. On the other hand, if the Damköhler number is largely superior to unity, the local thermodynamic conditions change too quickly for allowing a change in the chemical composition. The flow is then said to be frozen. Finally, if the Damköhler number is close to unity, the chemical composition of the flow will vary all along his path. The flow is then said to be in chemical non-equilibrium (although partial equilibrium can appear). Most of hypersonic flows are in a chemical non-equilibrium state, even if the Damköhler number may show strong variations. Typically, chemical equilibrium is found right behind the flow bow shock. Near the flow stagnation point in front of the space vehicle, chemical equilibrium may be reached as the flow speed tends to zero. Finally, as the flow crosses the vehicle in the wake direction, the flow tends to be chemically frozen as it expands and accelerates to supersonic conditions.

Moreover, for a complete and precise calculation, one should consider not only the reactions between different chemical species, but also treat specific exchange reactions of the different species internal modes between each other and with other species, in a so-called state-to-state approach. The computational burden of such models including a large number of reaction sets is nevertheless beyond the present processing and memory capacities of actual computational tools. Some different levels of approaches can however be done, such as assuming a fast equilibration time of the internal modes exchange reactions, compared to the flow residence time (the so called quasi steady-state approximation), or assuming a Boltzmann distribution of the species electronic, vibrational and rotational temperatures (equilibrium of internal modes). A complete discussion on these issues can be found in (Park 1989).

2.4. Plasma Radiation Effects

Radiative emission from the high temperature plasma formed behind the bow shock wave leads to further difficulties in the description of the flow. Among other problems (lure, black-out), the overall influence from the heat fluxes issued from radiation on the thermal protections of a space vehicle cannot typically be neglected[4]. The use of quantum mechanics numerical codes is therefore needed, in order to determine the wavelength-dependent emission and absorption coefficients of specific regions of the flow, taking into account temperature, pressure, chemical composition and distribution of the different species internal modes. Finally, as radiation, not being bound to fluid mechanics laws, is able to transmit information to every region of the flow[5], it is necessary to estimate

[1] Each chemical species may have a specific vibration temperature.

[2] Usually in equilibrium with the translational temperature of the flow, as rotational-translational exchanges are very efficient.

[3] Usually in equilibrium with the temperature of the electrons found in the outer shells of the flow atomic and molecular species.

[4] Radiation fluxes can account for half of the total (convective+radiative) fluxes endured by a heat-shield vehicle during an atmospheric entry flight at superorbital speeds.

[5] In an "optically thin" approach.

the wavelength-dependent radiative transfer from and between all the different regions of the flow. Once more this represents a severe burden for present computational tools, and several approximations have to be made usually (Namely, radiative transfer is usually determined using Monte-Carlo methods).

2.5. Wall catalysis effects

Another challenging problem implies taking into account the effects of the degradation of a space vehicle heat-shield. As there is currently no material capable to withstand the temperatures involved in an re-entry hypersonic flight (up to Mach 30), most heat shields consist in ablative carbon-silica compounds that are degraded throughout the overall descent flight. Pollution of the flow by ablation of the heat-shield, and catalytic effects near the walls also have a non-negligible influence on the flow properties.

The great range of the problems involved, their complexity and heavy computational load, involving competencies from different fields such as fluid mechanics, chemistry and quantum mechanics, explains why the characterization and the simulation of hypersonic flows presents a formidable problem which is still being addressed currently.

3. SIMULATION OF HYPERSONIC ATMOSPHERIC ENTRY FLOWS IN GROUND TEST FACILITIES

In order to achieve a better knowledge of such high temperature flows, and owing to their great complexity (as presented in Sec. 2), both numerical and experimental investigations in ground test facilities have to be performed, in order to avoid resorting to real test flights which present a high financial cost. However, as ground test facilities can only reproduce partially the conditions encountered in an entry flight, sometimes, the need for real demonstration flights can arise (examples include the North-American FIRE I (Cauchon 1966) and II (Cauchon 1967), as well as the BSUV (Erdmann 1991) flight experiments and the more recent ESA sponsored EXPERT program (Muylaert 2003)). Obviously, these kind of demonstrator flights are only limited to Earth atmosphere entries. However, different ground test facilities provide a certain degree of complementarity, allowing the simulation of atmospheric entry conditions. Shock tubes such as the TCM2 facility in Marseilles, France, are representative of the compression flow in front of the vehicle. Plasma wind-tunnels, such as the SR5 arc-jet in Orléans, France, are representative of the high enthalpy ionized expansion flow in the back of the vehicle. Flow properties measurements in such facilities can therefore provide partial validations of the numerical codes used for the simulation of atmospheric entries.

3.1. The SR5 Plasma Wind-Tunnel

The SR5 wind-tunnel low pressure arc-jet plasma available at the Laboratoire d'Aérothermique is used for the simulation of the space vehicles entry conditions in planetary atmospheres (Lago 2001). A specific gas mixture (air , 97% CO_2 - 3% N_2 - Martian atmosphere -, and 99% N_2 - 1% CH_4 - Titan atmosphere -) is delivered into a convergent-divergent nozzle where ionization occurs as the flow reaches sonic conditions. The flow is then expanded in the supersonic regime into a low pressure test chamber. A D.C. vortex-stabilized arc operating at low voltages (50–100 V) and low currents (50–150 A) delivers typical powers of 5–10 kW to the flow in the throat region of the nozzle. The low mass-flow rates (0.1–0.5 $\mathrm{g/s}$) crossing the nozzle allow the obtention of a high specific enthalpy (5–30 $\mathrm{MJ/kg}$) steady plasma jet with a global yield of 50-70% . This level of specific enthalpy obtained with a small mass-flow rate is an advantage because of the low electrode erosion, which allows maintaining a steady plasma jet for several hours with a low level of contamination. The pumping system capacity of 26.000 $\mathrm{m^3/h}$ ensures an ambient pressure of about 5 Pa to be maintained in a 4.3 m long and 1.1 m diameter vacuum chamber during operation of the arc-jet.

Figure 1. View of the SR5 facility

3.2. Investigation Program of the Laboratoire d'Aérothermique on Atmospheric Entry Flows

At the Laboratoire d'Aérothermique, several investigations on the aerothermodynamics of atmospheric entries have been carried regularly throughout the past decades. Previous investigations have included cold-gas measurement campaigns on the ESA sponsored HERMES program in the late eighties among other scientific programs. Current work programs focus on the analysis of the radiative emission of air and CO_2–N_2 plasmas using the SR5 facility, as well as on the development of adequate numerical tools for simulating plasma radiation such as the line-by-line SESAM code. These scientific programs are supported by the French space agency CNES through the MARS PREMIER program and the European space

agency ESA through the AURORA program. Preliminary investigations on the interaction of a plasma plume with a generic object (metallic sphere) have also been carried. Additionally, the plasma flow properties in the plasma generator[6] are studied using several Computational Fluid Dynamics (CFD) tools. This allows determining the plasma flow properties at the exit of the plasma generator to a certain degree of confidence, which proves useful as there is a strong coupling between the plasma thermodynamic state and it's radiative emission spectrum. These two different issues will be discussed in the two next sections of this work.

4. CFD SIMULATIONS OF DIFFERENT CHEMICAL COMPOSITION PLASMAS IN THE SR5 WIND-TUNNEL NOZZLE

Investigations on the physics of the plasma generation in the SR5 facility have been carried using several CFD tools developed and now available at the Laboratoire d'Aérothermique. The plasma generator is split onto two different regions: a nozzle throat where an electrical arc ionizes the flow, and a nozzle diverging section with a conical geometry where the flow is expanded. Several assumptions are made. In the nozzle throat, as the walls are made from heat-refractive tungsten, they are assumed to be adiabatic regarding the flow. Moreover, dissipative effects, turbulence and divergence of the flow are neglected as this is treated using a quasi-1D approach. A given energy quantity $\dot{Q} = UI$ is added to the flow through the electric arc. This is modelled as a uniform energy deposition[7] through the section of the throat. Energy removal in the nozzle throat results uniquely from the water cooling effects of the cathode. This energy amount can be known as the water flow through the cathode, as well as it's entry and exit temperatures, are known. Water-cooling effects also remove a given quantity of energy $\dot{Q}$ in the nozzle diverging section which acts as an anode. Once more, this cooling rate can also be determined, as the same cooling parameters are known. The wall is considered isothermal, and taking into account it's conductivity, a given wall temperature T_w is obtained.

4.1. Obtained Results

Obtained results along the nozzle throat region show a departure from chemical equilibrium, as the arc heathens the flow to the point where dissociation and ionization of the gas begins. A simulation of the species molar fractions evolution along the nozzle throat is presented in Fig. 2 for a Martian-type plasma tested in the SR5 facility.

In the nozzle diverging section, it has been calculated that the strong temperature and density decrease prevents further chemical reactions from happening, meaning that the

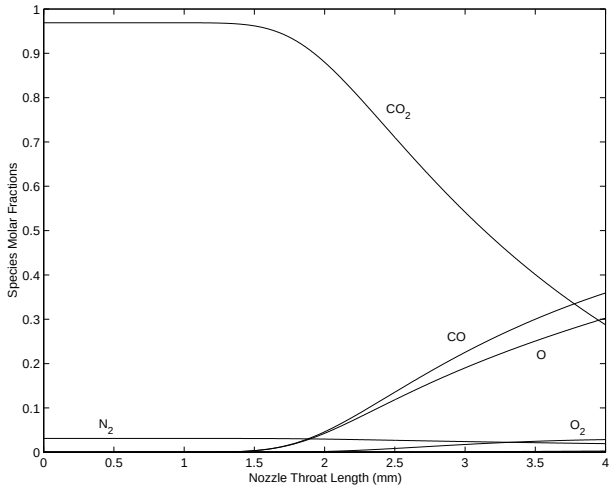

Figure 2. Chemical nonequilibrium inside the nozzle throat for a CO_2–N_2 plasma

chemical composition of the flow remains frozen from the nozzle throat exit to the nozzle exit. This presents an advantage as it is possible to hold the chemical composition as fixed, instead of coupling chemical calculations to flowfield calculations in more complex fluid solvers. However, calculations have evidenced a strong degree of departure from thermodynamic equilibrium, as the molecules vibrational temperatures tend to remain frozen, unlike the flow translational temperature which, as expected, decreases rapidly. Furthermore, it has also been verified that for the considered high temperature range, viscous effects are dominant in the flow. A complete discussion on the influence of all these parameters on different nozzle flows in the SR5 facility can be found in (Lino da Silva 1 2003).

As an additional remark, it is worthwhile to note that the chemical composition of the gas has a strong influence on the parameters of the plasma flow. An evidence of this can be found through comparison of Figs. 3 and 4 where computed values of the plasma flow Mach numbers using the Navier-Stokes code ARES (ARES) are presented for a Martian-like plasma (CO_2–N_2) and a Titan-like plasma (CH_4–N_2).

As it can be observed, a major role is played by viscosity for the CH_4–N_2 plasma as the boundary layer thickness near the wall increases very rapidly, therefore achieving very rapidly a non-negligible influence on the flow conditions at the center streamline of the nozzle. Namely, the Mach number firstly increases, as expected in a supersonic expansion, but starts decreasing gradually afterwards. This is not the case for the CO_2–N_2 plasma, where the boundary layer thickness is more limited, having a lower effect on the Mach number at the center streamline.

The simulated plasmas where obtained with a very similar energy input from the electrical arc. Furthermore, similar flow macroscopic parameters were obtained at the nozzle throat exit. However, as can be seen, the Mach number of the CH_4–N_2 plasma at the center of the noz-

[6] Which is made from a convergent-divergent nozzle acting as an anode, and a cathode which ionizes the gas flow at it's sonic region in the nozzle throat.

[7] More accurate models of the arc energy deposition are being considered using a two-temperatures (T,T_e) approach.

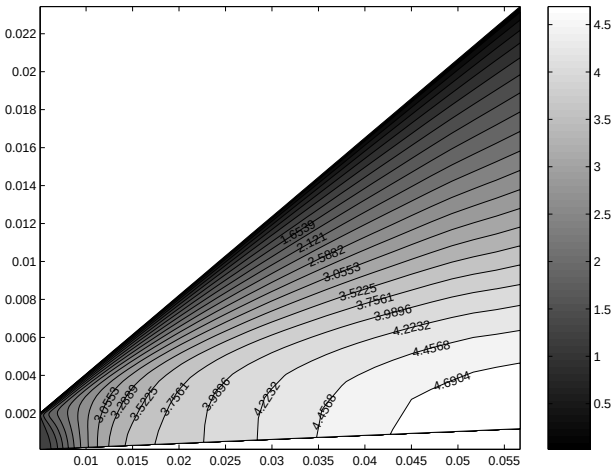

Figure 3. Mach number values inside the nozzle for a CO_2–N_2 plasma

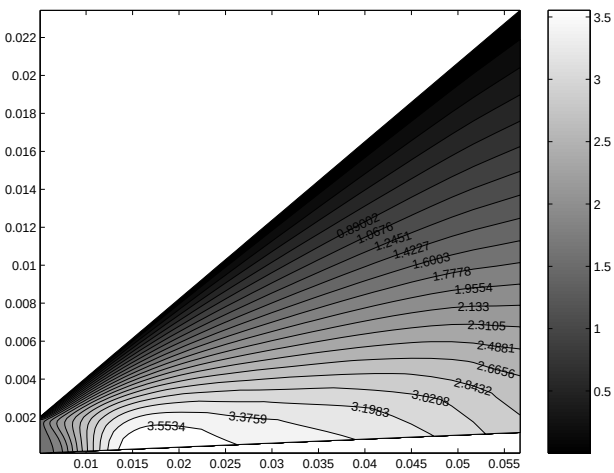

Figure 4. Mach number values inside the nozzle for a CH_4–N_2 plasma

zle exit is limited to M=2.9, whereas a Mach number of M=4.8 is reached for the CO_2–N_2, as the lower effects of viscosity prevented the flow from slowing down considerably.

5. SPECTRAL MEASUREMENTS IN THE SR5 FACILITY AND SPECTRAL SIMULATIONS USING THE SESAM CODE

This section will focus on the experimental investigations carried on the free plasma jets obtained at the exit of the plasma generator and expanding onto the low-pressure chamber of the SR5 facility. As these experimental investigations focus strongly on the radiative aspects of the plasma, this section will describe the different techniques used for the investigation of plasmas spectral emission, and will present some obtained results.

Radiation is a quantum mechanics process which occurs when a specific system undergoes a change from an energy state to another energy state. According to quantum mechanics laws, these constrained states are discrete, except for free particles (such as electrons). Radiation of a specific frequency (e.g wavelength) is emitted when a transition occurs from a higher to a lower level according to Planck's law:

$$\nu = \frac{E_u - E_l}{h} \tag{1}$$

This transition is also reversible, and radiation of a discrete frequency can be absorbed leading to a transition from a lower to a higher level of energy.

Radiation is not entirely discrete however, as perturbations known as broadening mechanisms can occur. These can be considered as perturbations of the initial and final states of a system, therefore leading to the broadening of the spectral lines of radiation emission and absorption. A discussion on all these properties can be found in reference textbooks such as (Herzberg 1965). Also transitions from a bound state to a unconstrained state result in continuum radiation.

Spectral emission of plasmas depends strongly from the chemical composition of the gas, as well as from it's thermodynamic state. As the energy levels of the different species bound states differ, so will the wavelength of the emitted radiation resulting from transitions to lower states. Also, the species thermodynamic state is important. If these are in an unexcited state (so-called ground state), there can be no radiative emission. An illustration of these two concepts is presented in Figs. 5, 6 and 7.

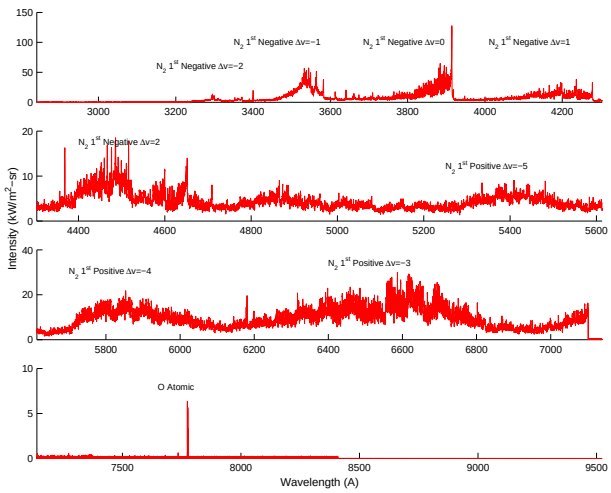

Figure 5. High resolution emission spectrum of an air plasma measured along the line of sight at the nozzle exit

The spectra presented in Figs. 5, 6 has been measured for similar working conditions of the plasma generator. However, the first tested gas was representative of an air-type entry plasma, and the second from a Martian-type entry plasma. As it can be verified, the radiation features differ between the two spectra. For the air-type plasma, the main emitting systems are the N_2^+ First Negative for

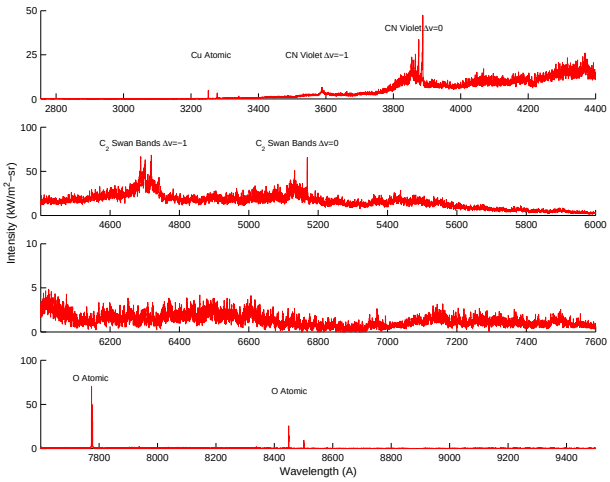

Figure 6. High resolution emission spectrum of a CO_2–N_2 plasma measured along the line of sight at the nozzle exit

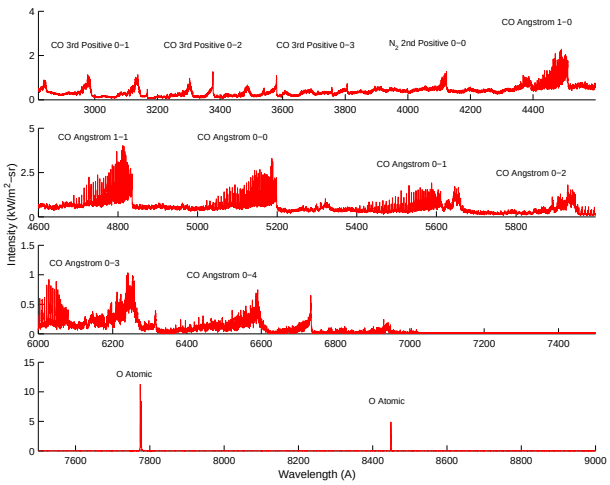

Figure 7. High resolution emission spectrum of a CO_2–N_2 plasma measured in a microwave plasma facility

the vibrational bands Δv=–2,–1, 0,+1,+2 from 320 to 460 nm and the N_2 First Positive for the vibrational bands Δv=–5,–4,–3 from 520 to 800 nm. The oxygen triplet at 777 nm is also observed. For the Martian plasma, strong emission from the CN Violet System Δv=–1, 0 from 360 to 390 nm as well as from the C_2 Swan Bands Δv=–1, 0 from 460 to 520 nm is evident. The oxygen triplet at 777 nm is once more observed.

As previously noted, the thermodynamic state of the plasma is also very important. Fig. 7 shows the radiative emission of a Martian-type plasma with an identical initial gas mixture than the one presented in Fig. 6. However, the measured plasma was obtained in a microwave plasma facility, with a different energy input compared to the SR5 arc-jet, and as it can be verified, emission from CN Violet System, as well as from the C_2 Swan Bands, no longer occurs. Instead, radiative emission from the CO 3rd Positive and the CO Angström systems is observed. As it can be easily seen, although the two studied plasmas have the same initial chemical composition (97% CO_2–3% N_2), the different excitation processes found in the two plasma facilities lead to important changes of the emission spectrum.

Measurements such as the ones presented in Figs. 5-7 are performed through the line of sight. Therefore, obtained results are integrated along the radial profile of the jet. However, the Abel inversion technique allows obtaining the local emission properties of the jet if the radial divergence and the axial gradients of the jet remain limited. Measurements of the radiative emission have to be performed along the line of sight from the center to the boundary of the plasma plume. These need to be taken at the shortest interval where differences between the consecutive measured spectra can be detected. These spectra is then feeded to the mathematic Abel inversion routine which returns the local emission spectra of the plasma.

An example of an Abel inversion performed over a low-resolution spectrum obtained in a air plasma is presented in Fig. 8.

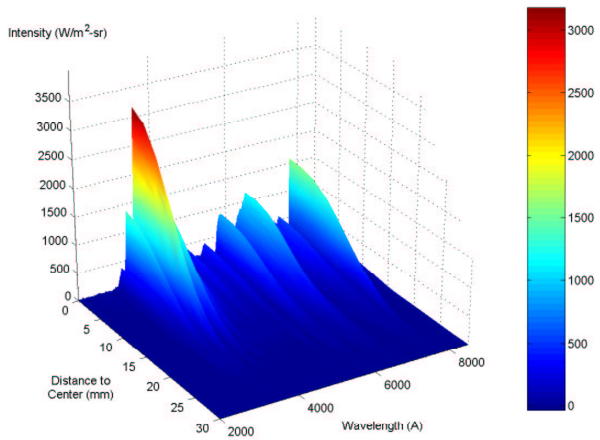

Figure 8. Radial emission profile of the air plasma

5.1. Plasma Radiation Simulations Using the Line-by-Line code SESAM

The different techniques used for the measurement of plasma radiation have been presented in the previous section. This section will focus on the simulation of measured spectra and the retrieval of molecular temperatures using the SESAM code developed at the Laboratoire d'Aérothermique.

Numerical spectroscopic codes are intended at the determination of the emission and absorption coefficients of a gas in a given thermodynamic state. These are usually coupled to CFD codes which calculate the flowfield properties, and to a radiative transfer code which calculates the radiation energy transfer throughout the overall flow.

For validation purposes, these numerical codes can be tested with the simulation of the radiative emission of

a plasma plume in thermochemical equilibrium. This allows determining the plasma macroscopic parameters using a methodology which is described in detail in (Laux 1993), avoiding the use of CFD tools. The radiation transport equation can be solved straightforwardly using the 1D slab approximation. The SESAM code has been validated against an air plasma measured in an Inductively Coupled Plasma (ICP) torch presented in (Laux 1993) and previously used for the validation of the NASA radiative code NEQAIR2. A comparison between the simulated spectrum using the SESAM code and the measured spectrum is presented in Fig. 9. A more complete description of this validation experiment can be found in (Lino da Silva 2 2003).

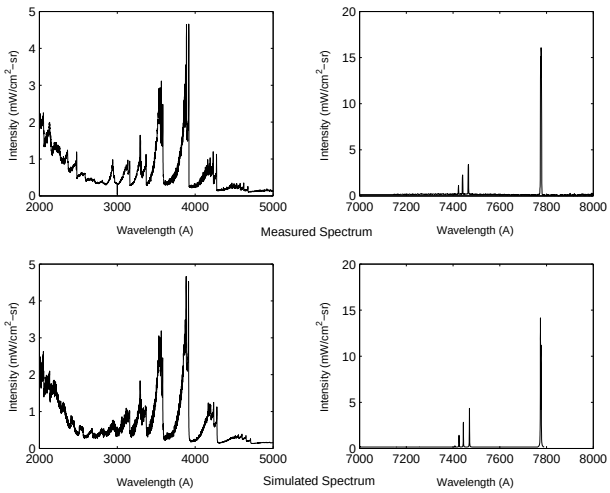

Figure 9. Simulation of the spectral emission of an ICP air plasma using the SESAM code

Line-by-line spectral codes can also be used for temperatures determination in the flow, provided that molecular radiation is observed. Performing a "best fit" of the measured spectrum, one can achieve such values. This means that one has to change the rotational T_r and vibrational T_v temperatures of the simulated spectrum from an initial guess to a final value which corresponds to the actual temperature values of the simulated molecule. Provided that emission from a specific molecular system is observed, this represents a very efficient way of evaluating the molecule vibrational and rotational temperatures to uncertainties down to $\pm$ 100 K. Moreover, as the rotational modes usually need a small amount of collisions to reach equilibrium with the flow translational temperature (5 to 10 collisions), the rotational temperature T_r can be assimilated to the flow translational temperature T. An example of a best fit simulation of the radiative emission of the N_2^+ First Negative System measured at the exit of the SR5 nozzle for an air plasma is presented in Fig. 10.

For this numerical fit, the molecule rotational and vibrational temperatures are found to be T_r=3200 $\pm$ 100 K and T_v=5400 $\pm$ 200 K. This gives a strong evidence of the thermal nonequilibrium state of the plasma at the nozzle exit.

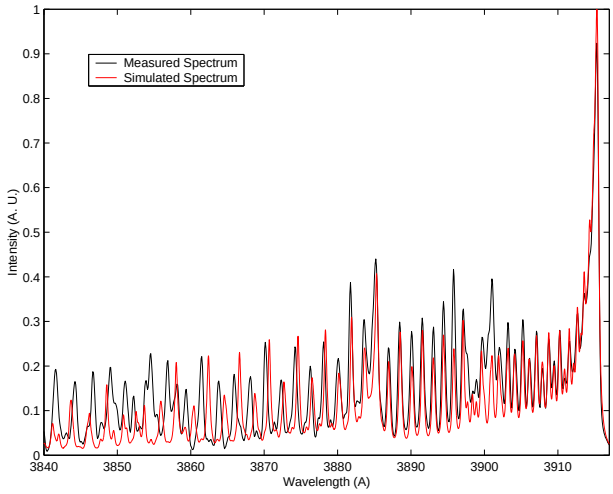

Figure 10. Simulation of the emission of the N_2^+ First Negative System using the SESAM code

5.2. Plasma Plume Interaction With a Metallic Sphere

In this section, a small overview on several preliminary results obtained regarding a free plasma jet interaction with a metallic sphere will be presented. Such investigations are carried over a CO_2–N_2 plasma flow and aim at a better knowledge of the evolution of a plasma through a hypersonic bow shock-wave for such a chemical composition. A photographic view of the experiment performed in the SR5 facility is presented in Fig. 11.

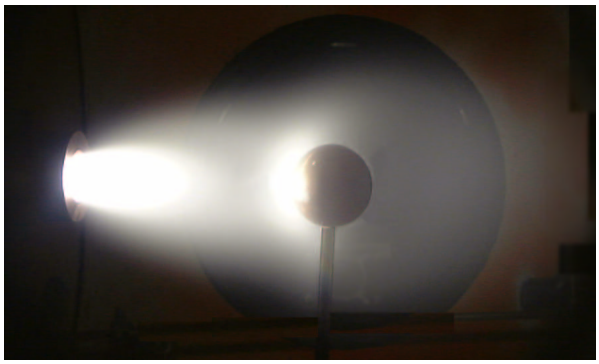

Figure 11. Plasma plume interaction with a metallic sphere for a CO_2–N_2 mixture

As the flow is highly emissive due to it's excited state, variations of the radiation emission intensity can give a good qualitative image of the flowfield conditions. Zones of the flow enduring shocks or undergoing compressions will tend to be more excited, and therefore more emissive. On the contrary, zones of the flow undergoing expansion will tend to cool down and to become poorly emissive. Measurements of the plasma radiative emission in front of the metallic sphere taken using an intensified camera are presented in Fig. 12.

As it can be verified, several features of the plasma flow around the metallic sphere are put to evidence using this

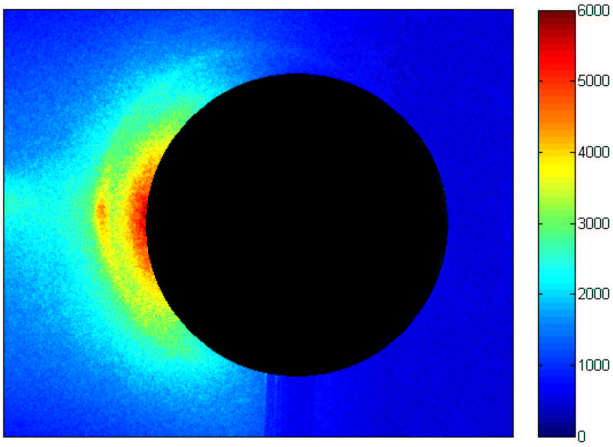

Figure 12. Plasma plume interaction with a metallic sphere measured with an intensified camera

measurement technique. The bow shock-wave in front of the metallic sphere can be observed, as well as a very excited region along the stagnation point in front of the metallic sphere. Also, as expected, it is verified that the flow decays to less excited states as it reaches the region downstream of the metallic sphere. Therefore, this measurement technique proves it's usefulness in order to determine particular regions of interest in the flow where further investigations can be conducted.

6. CONCLUSIONS

The high complexity of hypersonic atmospheric entry flows has been described in this paper, and the importance of the different physico-chemical processes found has been discussed. The large uncertainties associated with these high temperature flows require both elaborate numerical simulation tools and elaborate experimental investigation programs in order to achieve an improved knowledge over those planetary entry flows.

The practical advantages of ground test facilities such as plasma wind-tunnels for reproducing the conditions found during an an atmospheric entry flight have been put into evidence. Several experiments carried over plasmas whose chemical composition is representative of atmospheres of solar bodies such as Earth, Mars and Titan have been described, and the complementarity of numerical simulations and experimental investigations in such plasma flows has been demonstrated. These allow a qualitative and quantitative knowledge of the flow properties. Investigations carried over the SR5 facility, as well as other experimental facilities, allow the enhancement of the available numerical tools for the simulation of hypersonic entry flows. In a near future, accurate knowledge will be achieved not only for atmospheric entries in Earth, but as well for Mars, Titan, and the other solar bodies with the presence of an atmosphere. This in turn will allow an optimization on the shape and the thermal protections of space vehicles designed for atmospheric entries, allowing among other things larger payloads or lower mission costs.

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