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The study of the convective and radiative heat fluxes to the capsule surface during its atmospheric entry is critical for the design of the thermal protective system. For Mars entry scenarios, where CO2 represents 96% of the atmosphere, the radiative heat flux to the afterbody suffers from large uncertainties - up to 260%. The rapid hydrodynamic expansion of the plasma into the afterbody region results in rapid cooling, chemical recombination, and a departure from equilibrium. This chemical non-equilibrium and the associated radiation are still not accurately modeled, and our goal is to provide experimental data for model validation. Our experiments focus on a fundamental study of the recombination kinetics of CO2 plasmas.

The inductively coupled plasma torch at laboratoire EM2C was used to produce a CO2 plasma at atmospheric pressure. More details of the plasma torch facility can be found in Ref. [4] (see attachment). The CO2 plasma studied here exits the torch through a 1-cm diameter nozzle and is composed of 10% of CO2 and 90% of argon (argon required for stable operating conditions). The plasma is then passed through a water-cooled test-section of various lengths at high speed (~ 500 m/s) to force rapid cooling and chemical recombination. The IR spectra obtained by OES are calibrated in absolute intensity using a tungsten lamp traceable to NIST standards. The calibration procedure considered absorption from cold CO2 and H2O present in the optical path. The complete calibration procedure is described in [5] (see attachment). Figure 1 shows the calibrated and abel-inverted spectrum at the exit of the 35-cm test-section. This corresponds to the local emission at the center of the jet. Emission from both CO and CO2 is present. Several CO/CO2 spectra at different rotational and vibrational temperatures were calculated using the RADIS line-by-line radiative code, in conjunction with the HITEMP-2010 database. The best fit achieved is shown in red. The complete fitting procedure is described in [5] (see attachment).

A 0D chemical kinetic simulation was realized using the Cantera code in conjunction with the Park 1994 kinetics model. The temperature, as measured above using the CO molecular band, was converted into a time-dependent temperature profile, and put into Cantera which then calculates the evolution of the chemical composition. Figure 2 shows the evolution of CO in black and CO2 in red, the dashed lines represent the equilibrium. CO density prediction at 35 cm is in good agreement with our measurement at the exit of the 35-cm test-section. However, the CO2 density is underpredicted by a factor of about 10.

Summary:

An ICP torch was used to produce a CO2/Ar plasma jet at atmospheric pressure. The plasma jet is close to LTE conditions at a temperature of 6650 K. This plasma is then passed at high velocity through a water-cooled test-section that forces rapid cooling and recombination. The thermochemical evolution of the plasma is studied using infrared OES. The measured spectra at the exit of the torch and at the exit of the test-sections are calibrated in absolute intensity and compared with calculations done using the RADIS radiation code. The measurements of temperature and CO/CO2 densities that result provide a test case for comparison with kinetic modeling and CFD predictions. A 0D chemical kinetic simulation was realized using the Cantera code and the Park 1994 kinetics model. CO density prediction is in good agreement with our measurement, however, the CO2 density is slightly underpredicted at the exit of the recombining tube.

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Plasma Ball Formation: an experimental technique to test radiative models in non-equilibrium plasmas

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Background

In hypersonic flights, the energy transfer between the atmosphere and the vehicle depends greatly on gas kinetics, in particular on nonequilibrium vibrational kinetics as well as on dissociation and recombination processes which are similar in many aspects to those met in electric discharges in gases [1]. As mentioned in [1], "the main difference is that in the latter case the vibrational quanta are primarily pumped by electrons while during reentry they are pumped by recombination processes…" This difference may however be suppressed in our setup, thanks to the plasma ball formation (PBF), an acoustic plasma confinement mode we have recently discovered during the development of a pulsed sulfur plasma lamp [2], also observed by a team at UCLA [3]. Indeed, the molecular dissociation is then governed by the pure vibrational mechanisms [2], i.e. by the collisions between vibrationally excited molecules, rather than by electron impacts [4], p. 228. Another similarity between hypersonic plasmas and the sulfur plasma in our device is the radiative energy transfer that arises from the relaxation of excited electronic states of molecules formed in recombination processes, resulting in optical emission spectrum (OES) that does not follow the Planck's law. Moreover, in our device the chemistry is dominated by two-atom dissociation-recombination processes (S2), as in a hypersonic plasma of Earth's atmosphere (N2, O2). In both cases, the chemical kinetics are determined by the excitation-relaxation of vibrational states.

The objective here is to study the non-equilibrium vibrational aspects involved in PBF. This phenomenon is obtained by pulsing the input microwave power with a short duty cycle, at a repetition rate of the order of 30 kHz, providing spherically symmetric compression-expansion cycles for the plasma. During PBF, the plasma is confined at the center of the spherical bulb, extending to half radius. From the measurements of the acoustic resonance frequency, the average sound velocity as well as the average pressure and temperature inside the bulb were found to be 0.60 km/s, 0.52 MPa and 2.2 kK, thanks to a one-node-lumped model [2]. The acoustic waves are necessary for the PBF to take place. However, the exact force balance during the confinement is not yet completely understood, a crucial question this study opens a way to answer by analyzing digital photographs as well as OES. The final goal of this project is to provide physics basis for the design of an experimental device to ease the costly calculations [5, 6] required to simulate atmospheric reentry in hypersonic shockwave conditions. For instance, the bulk viscosity is still a topic of investigation as this property of nonequilibrium gases is extremely difficult to measure [7] and is therefore often neglected, as in [8] for instance. Yet, it introduces a dispersion effect resulting from velocity divergence and in hypersonic reentry it can have an influence on the shock wave structure [9, 10]. This paper shows there are reasons to think that the bulk viscosity plays an important role in the PBF. Moreover, the possibility of it becoming negative does not seem to be considered in the western aerospace community as we only found publications from Russia mentioning "Negative bulk viscosity" in a literature study. Evidence for this sign change, however, could be obtained from the amplification of sound waves that occurs during PBF, as shown in this publication.

Methodology

In this work, we concentrate in two experimental observations of the PBF as follows:

1) Shape analysis for understanding the convective cells and heat transfer inside the bulb.

Digital photographs have been analyzed in order to reveal the exact shape of the plasma ball. The camera was a Panasonic DMC-FZ8 placed behind a green solder filter. The contrast between the plasma ball and the background was increased by digital treatment. The plasma ellipticity was determined by manually fitting an ellipsoid in the high contrast image.

2) Spectral analysis for estimating the vibrational temperature of the S2 molecules.

The OES, emanating from the plasma, was recorded with a CAS 140CT array spectrometer in the wavelength range of 300–1100 nm. The average photon energy was integrated from the spectra. This value was then used as the LHS of the equation (9) of [11] in order to find the corresponding values of the vibrational quantum numbers and the energies of the excited and ground electronic states of the S2 plasma molecules, taking into account their anharmonicity. From the Frank-Condon factors given in [11], the most and second most likely transitions were associated with the peaks in the OES for a discussion of vibrational pumping [12, 13] and its role in the PBF phenomenon. Particular attention is paid to the effect on sound velocity in view of the application to modeling hypersonic plasmas.

Results

The plasma ellipticity was found to be close to one. No expected concavity was observed at the bottom of the ball, due to possible inward mass flow from the peripheral zone to the plasma, like seen in flames. A dissipative structure composed of two convective cells could explain this unexpected observation, as we show in this publication. A non-equilibrium thermodynamic modeling is proposed for the interpretation of this dissipative structure, based on the vibrational excitation gap between the plasma and the surrounding gas. Our analysis of the OES shows that the S2 ground state mean vibrational energy, for a plasma in the spherical mode (PBF), is 1.97 eV, whereas it is at 1.81 eV in the case no PBF, consistent with the observed redshift of the emission peak. This result, the increase of the sum of vibrational quanta in the plasma, suggests that the PBF enhances the vibrational pumping mechanism. The cause of this effect could be related to the sound dissipation due to the bulk viscosity.

Conclusion

This additional vibrational pumping could explain the observed features according to the presented non-equilibrium thermodynamic model. Complementary experimental investigations should make it possible to measure the bulk viscosity. The plasma translational and vibrational temperatures are of particular interest because, being modifiable thanks to the input power control parameters (mean value & modulation), it is possible to study the effect of varying plasma state. Thus, in addition to providing an experimental technique for testing radiative models in non-equilibrium plasma, PBF could open a way to measure the bulk viscosity under controlled conditions, in addition to the sound velocity, so offering an opportunity to improve the models used in numerical simulations of hypersonic flows.

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Summary:

This article shows that a recent discovery in the field of molecular plasma, called Plasma Ball Formation (PBF), could provide a new experimental technique for testing collisional radiative models in non-equilibrium plasmas. Moreover, PBF could open a way to measure the bulk viscosity under controlled conditions, in addition to the sound velocity, thus providing an excellent opportunity to improve models used in numerical simulations of hypersonic flows.

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Shock Radiation Tests for Ice Giant Entry Probes Including CH4