Modeling of the excitation non equilibrium of CO_2 plasma flows obtained in high enthalpy wind tunnels

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A nonlinear time-dependent Collisional-Radiative (CR) model is developed for pure CO_2 flows obtained in plasma wind tunnels. The main purpose is to estimate the level of the population density of the main excited states responsible for their radiative flux and to identify the main cause of non-equilibrium. As a result, the CR model is included in the general balance equation of the considered species and the elementary collisional and radiative processes are thus compared with transport (convection and diffusion) in terms of influence. The CO_2 flows produced in plasma wind tunnels are generally weakly ionized. The question of the influence of the electrons is often open. The CR model developed in this study can be also used to assess the threshold above which electrons have to be accounted for. The estimate of the characteristic length required for reaching a steady state can also be performed.

The high enthalpy wind tunnels are used as ground test facilities to reproduce in order of magnitude the conditions of the entry phase of a probe or a spacecraft in the upper layers of a planetary atmosphere. When such an entry phase occurs, the interaction between the fuselage of the spaceship and the gas at very high relative speed (v ≈ 10 km s^{-1}) induces the gas → plasma transition near the wall [1]. The temperature reached by the plasma is high (T ≈ 5000 K, 10000 K even higher). Therefore, the fuselage has to be protected with a thermal protection system whose role is to reduce the net energy flux. The case of a Martian entry is specific because the composition of atmosphere (CO_2-N_2-Ar with the relative composition 95%-3%-2%) leads to the formation of C, N, CO, C_2 and CN whose contributions to the energy exchanges either by inner modes relaxation to the wall or by radiation are particularly strong. In this case, the complete understanding of the chemistry of the plasma including the excited states is absolutely necessary. The high enthalpy wind tunnels thus permit the reproduction of the interaction between the plasma and the thermal protection system in perfectly controlled conditions.

The characterization of the plasma flow requires the estimate of the excited states population densities. In the purpose of interpreting the results, the modeling of the flow is performed. The high enthalpy flow is produced at low pressure and high temperature. These conditions generally lead to plasma more or less far from equilibrium. The modeling is thus detailed in the sense it considers the species on their excited states as independent variables. In the present work, pure CO_2 plasmas are modeled.

The time-dependent balance equation of the species X on its excited state i is simplified and obtained under the form [2]

$$\frac{d[X_i]}{dt} = \frac{v}{R}[X_i] - \frac{\overline{D}_{X_i}}{R^2}a_0^2[X_i] + \left(\frac{\partial [X_i]}{\partial t}\right)_{Rad.} + \left(\frac{\partial [X_i]}{\partial t}\right)_{Coll.}$$

by assuming the diffusion mainly due to the fundamental mode with the diffusion coefficient $\overline{D}_{X_i}$. The convection term is simplified by assuming the flow isothermal. v is the longitudinal flow velocity component and R is the typical radius of the plasma ($a_0 = 2.405$). The radiative and collisional contributions account for the influence of radiation and chemistry whose rate coefficients result from the more recent experimental and theoretical data. The flow can be partially opaque. Escape factors are calculated assuming a broadening of the Doppler type. The previous balance equation is applied to the different excited states of C and O listed in the NIST database [3] and to the main electronic excited states of CO and C_2.

The resulting ordinary differential equations set is solved using the DVODE library [4] and leads to the calculation of the excitation temperature of the state i based on the ground state 0 defined as

$$T_{exc}(i) = \frac{E(i) - E(0)}{k_B \ln\left(\frac{Z_{rve}(i)}{Z_{rve}(0)} \frac{[X_0]}{[X_i]}\right)}$$

where Z_{rve}, E and k_B are the rovibronic partition function, the energy of the related state, and the Boltzmann constant, respectively. Typical time evolutions displayed on Figure 1 can be obtained.

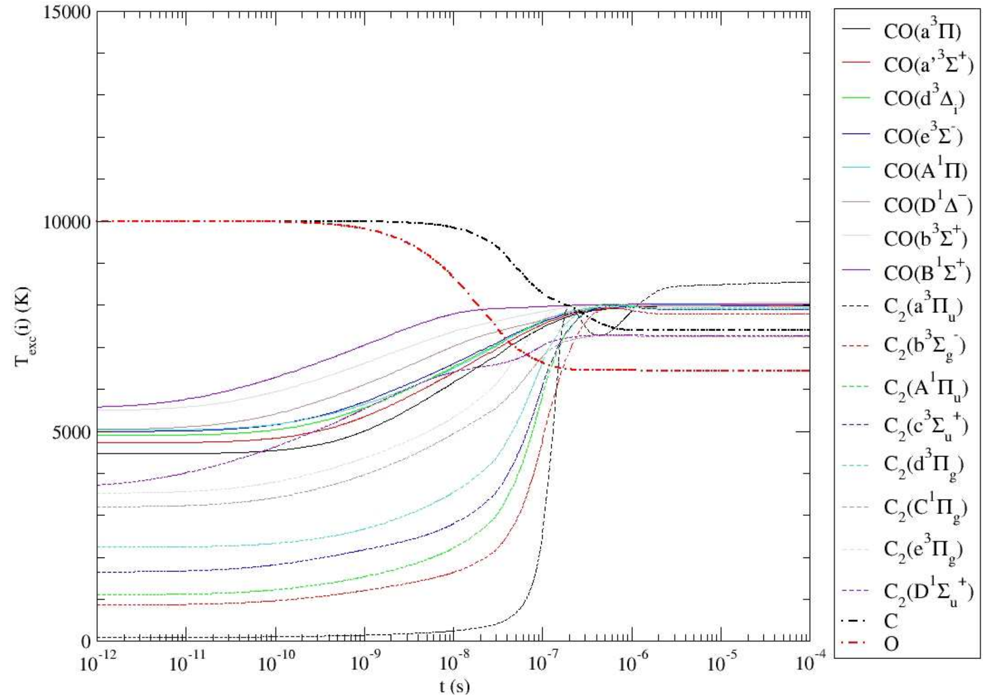

Figure 1. Excitation temperatures time evolutions with radiation and electron induced processes with p = 1500 Pa, v = 200 m s^{-1}, R = 4 cm, T_A = 8000 K, T_e = 10000 K and $n_e = 10^{19}$ m^{-3}.

One can notice the final steady state which corresponds to different excitation temperatures. The plasma is thus far from equilibrium in the present conditions. A detailed analysis of the results put forward the two main cause of non-equilibrium (1) the thermal non-equilibrium through the electron-induced processes and (2) radiation. Moreover, the final steady state is obtained at time t ≈ some 10^{-6} s. From the velocity v = 200 m s^{-1}, we deduce a coupling characteristic length of 500 μm approximately. One can conclude that the densities depend on the local conditions only.

In specific conditions, the atomic or molecular ionic recombination plays a role in the chemistry of the excited states. Our communication will analyze these aspects in detail.

References

[1] M. Panesi, *et al.* (2009) Journal of Thermophys. and Heat Transfer **23** 2 236-248
[2] A. Bultel, *et al.* (2011) Proceedings of the 7th ATS, Bruges, Belgium
[3] http://physics.nist.gov/PhysRefData/ASD/levels_form.html
[4] P.N. Brown, *et al.* (1989) SIAM J. Sci. Stat. Comput. **10** 1038–1051