State-to-state modeling of a nitrogen plasma applied to the atmospheric entry problems

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In the purpose of understanding the complex chemistry and predicting the different chemical species during the planetary entry phase of a spacecraft, a time-dependent Collisional-Radiative model for N_2 is performed for high temperature conditions. The CR model involves 5 different species (N_2, N, N_2^+, N^+ and e-) and is based on a vibrational and electronic state-to-state approach. Three calculation types can be performed: the gas relaxation at constant pressure and temperature, the crossing of a strong shock wave and the freezing of the chemistry obtained in a divergent nozzle.

As illustrated by the dramatic crash of Columbia in 2003, the atmospheric entry phase constitutes the most critical step of a spatial flight. During the entry of a spacecraft, the incident flow reaching the fuselage is hypersonic ($v \approx 10$ km s^{-1}) and compressible: a shock layer is formed and the gas (initially cold and neutral) undergoes a rough increase of pressure and temperature. The composition of the gas is then incompatible with these new conditions: they lead to the activation of a complex chemistry which forms excited and ionized species. The plasma produced by these reactive processes interacts with the spacecraft which must be consequently protected by a Thermal Protection System (TPS). The TPS is damaged in part owing to the convective, radiative and reactive species fluxes, the latter resulting from the catalysis at the wall. We can see clearly that a precise characterization of this reactive mixture is required to estimate the species fluxes, and to predict the damaging and the sizing of the TPS as well.

To address the Earth and Martian entry problems, the elaboration of a Collisional-Radiative (CR) model, using a vibrational and electronic state-to-state approach, is the only way to understand the involved complex chemistry. For Martian entries, the elaboration of a CR model named CoRaM-Mars is in progress and in the continuity of CoRaM-Air [1,2], already elaborated for atmospheric Earth entries.

During this communication, we focus our attention on the detailed chemical kinetics of a N_2 gas mixture, owing to its significant amount in Earth and Mars atmospheres. Thus, the elaborated CR model takes into account 5 differents species : N_2, N_2^+, N, N^+ and electrons. Moreover, the model is vibrational specific only on the electronic ground state $N_2(X^1\Sigma_g^+)$ (68 vibrational levels) and electronic specific on the others electronic states of N_2 (11 electronic levels), N_2^+ (6 states), N (251 states) and N^+ (9 states).

As the temperature and pressure can be high in the shock layer, different elementary processes must be accounted for: vibrational excitation/dissociation, electronic excitation/ionization for atoms and diatomic molecules and others elementary processes such as charge exchange or dissociative recombination are taken into account. In the present work, elementary radiative phenomena have been neglected. Once the database for the different species and the different elementary processes carefully implemented, three kinds of calculation can be performed.

The first calculation corresponds to the relaxation at constant pressure and temperature for an ionization or recombination situation. For example, Figure 1 illustrates the relaxation of cold N_2 gas at 50 Pa and 250 K, suddenly heated at 10,000 K under a pressure of 80,000 Pa (see comments in the caption of Fig.1). The second corresponds to the crossing of a strong shock front under steady state conditions and Rankine-Hugoniot assumptions. The vibrational, electronic and kinetic temperatures can be estimated throughout the shock layer. Finally, the third type of calculation corresponds to the flow of hot gas along the divergent part of a nozzle.

During the conference, the database for the different species and the different elementary processes will be detailed. The results for the three types of calculations will be presented.

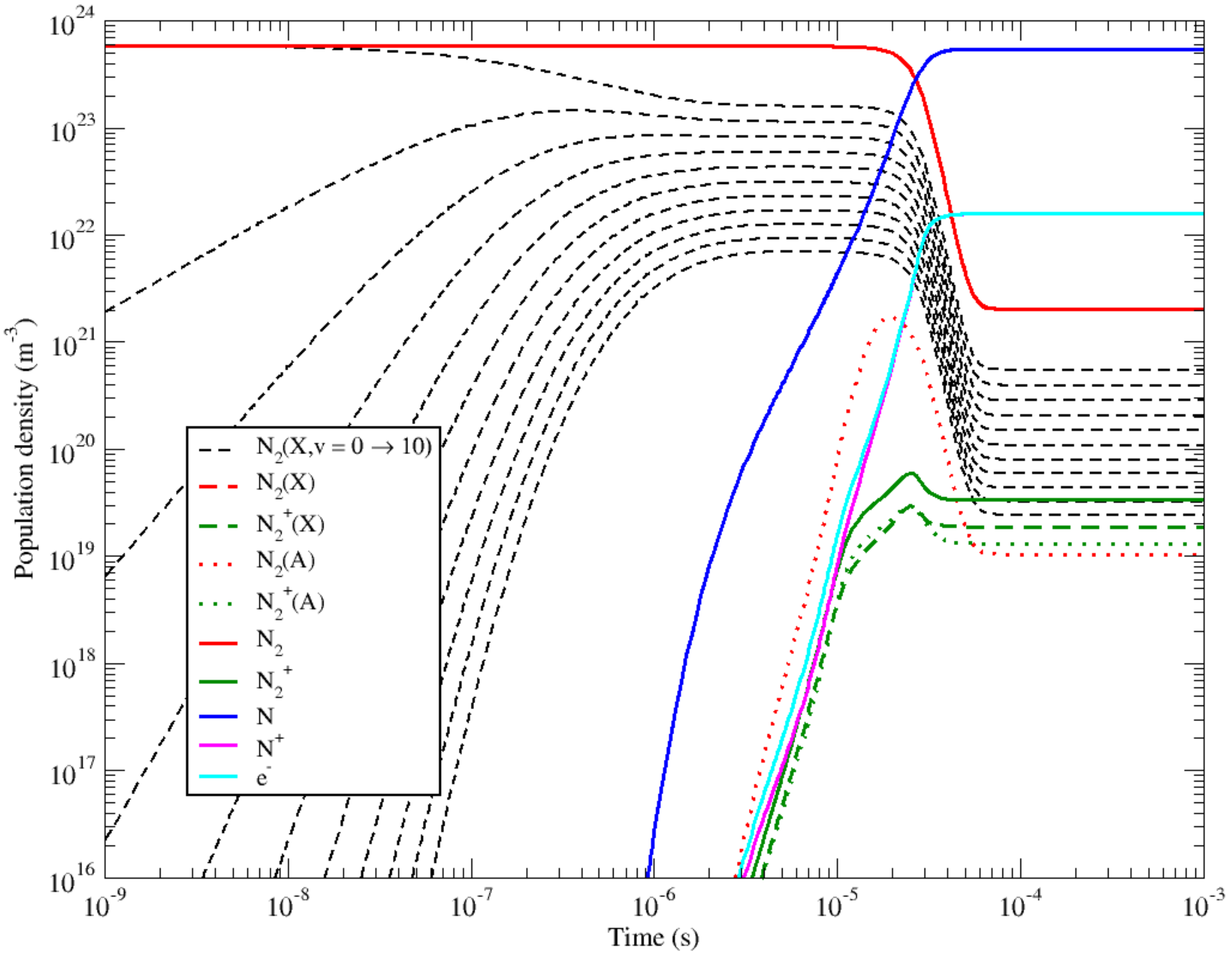

Fig. 1: Population density time-evolution of N_2, N_2^+, N, N^+, electrons, the ten first vibrational levels of N_2, the two first electronic levels of N_2 and N_2^+ during a Fire II test-case [3] (80,000 Pa - 10,000 K). These evolutions, obtained when radiation is neglected, follow three successive phases. Between 10^{-9} s and 2×10^{-5} s, vibrational levels of $N_2(X)$ are populated owing to the sudden increase of temperature and allow the dissociation. Between 2×10^{-5} s and 10^{-4} s, the first electrons, created by heavy-induced collisions, allow the electronic excitation and the ionization of atoms and molecules. Finally, after 10^{-4} s, the numerous collisions between the different particles tend to stabilize the plasma. A steady-state is quicly reached. Since radiatiation is neglected, this steady-state corresponds to chemical equilibrium.

References

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