

Heat Flux on the Surface of an Hypersonic Vehicle: a Preliminary Study

I.Armenise ¹, S.Longo ^{1,2} and M.Capitelli ^{1,2}

¹ *IMIP-CNR (Istituto di Metodologie Inorganiche e dei Plasmi, Consiglio Nazionale delle Ricerche), Via Amendola 122/D, 70126 Bari, Italy*

² *Chemistry Department, Bari University, Via Orabona 4, 70126 Bari, Italy and IMIP-CNR, Via Orabona 4, 70126 Bari, Italy*

In the boundary layer of a blunt body flying at hypersonic velocity in an N₂/N mixture, it has been attempted a first state-to-state formulation of the heat flux calculation on the body surface.

In particular, the heat flux on the surface is due to both the temperature jump and the recombination on the surface itself of the atomic fraction produced by the dissociation/recombination kinetics in the flow. We use a self-consistent, state to state 1D model of the boundary layer which has been upgraded in order to incorporate different surface properties. The surface has been considered either non catalytic or partially catalytic. In the latter case three different recombination models have been implemented: the heterogeneous recombination can occur either on the first vibrational level or on the whole vibrational ladder or on the last vibrational level of the forming molecules.

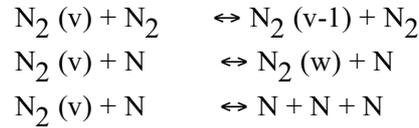
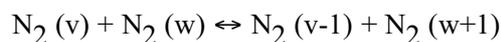
1. Introduction

The determination of the heat flux on the surface of hypersonic re-entering vehicles is a not easy task and it presents many difficulties, specially when the surface is catalytic. It has been demonstrated that to calculate the heat flux on the surface in the same way as the heat flux in the boundary layer gives questionable results.

To investigate this problem it has been used a well tested code solving 1D boundary layer equations [1,2]:

$$\begin{aligned} \frac{\partial^2 C_v}{\partial \eta^2} + f Sc \frac{\partial C_v}{\partial \eta} = S_v & \quad v=0-68 \\ \frac{\partial^2 \theta}{\partial \eta^2} + f Pr \frac{\partial \theta}{\partial \eta} = S_T & \quad (1) \end{aligned}$$

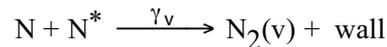
The first 69 equations are continuity equations of each species: the 68 N₂ vibrational levels concentrations and the N concentration, with C_v = ρ_v/ρ mass fraction (ρ_v is the mass density of the vth species and ρ is the total mass density). The last equation is the temperature equation, with θ = T/T_e (the subscript e indicates the external edge of the boundary layer). Sc and Pr are the Schmidt and the Prandtl numbers and f is the stream function. S_v and S_T are the source terms that take into account for the VV, VT molecule-molecule, VT molecule-atom and dissociation/recombination kinetic processes



The boundary conditions [3] are a fixed temperature T_e and its corresponding equilibrium distribution at the boundary layer external edge, on one side, and, on the other side, a fixed temperature T_w and the following mass fraction gradients

$$\begin{aligned} \left. \frac{\partial C_N}{\partial \eta} \right|_w &= \frac{\sum_v \gamma_v}{D} \sqrt{\frac{kT}{2\pi m_N}} C_N \\ \left. \frac{\partial C_{N_2(v)}}{\partial \eta} \right|_w &= - \frac{\sum_v \gamma_v}{D} \sqrt{\frac{kT}{2\pi m_N}} C_N \end{aligned}$$

on the surface. D is the diffusion coefficient. γ_v are the recombination probabilities of the following surface recombination reaction



where N* are the adatoms, i.e. atoms previously adsorbed by the surface, atoms that form a chemical bond with the dangling chemical bonds of the solid surface.

When the surface is chosen as non-catalytic and non-deactivating the mass fraction gradients are set equal to zero.

2. Heat flux

The state-to-state transport coefficients and the heat flux in the boundary layer have been calculated on the basis of the modified Chapman-Enskog theory including the effect of non equilibrium vibrational distributions [3, 4, 5].

In particular it has been found that the heat flux depends on the gradients of temperature, pressure and populations of all vibrational level.

This formulation is accurate and describes well the heat flux in the boundary layer, however it fails when applied to the heat flux on the surface. Many test cases have been found in which the heat flux so calculated in the first cell of the computational grid, that one close to the surface, is higher if the wall is partially catalytic than if it is not catalytic, moreover it is higher if the atoms on the surface recombine on the last vibrational level of the corresponding molecules than if they recombine on the whole ladder or just on the first vibrational level. This is coherent with what we would expect in gas-phase: higher vibrationally excited molecules should transport higher heat flux. On the opposite, the heat flux released to the surface should be lower if the formed molecules are vibrationally excited because in this case more heat is stored in the molecules themselves.

The found discrepancies between the gas-phase heat flux close to the surface and the expected heat flux on the surface come from the bad-posed boundary condition for the temperature.

In particular, to calculate the heat flux through the surface it is mandatory, near the surface itself, to take into account for the Knudsen Layer, whose thickness is of the order of the molecular mean free path and in which the density of the gas is such that it can not be considered a continuum medium.

To overcome this problem and, in a certain way, in line with the study of Hassouni et al. [6], the heat flux on the surface has been calculated as the sum of two terms: the first one is the heat flux due to the temperature jump and the second one is the heat flux due to the recombination on the surface:

$$q_w = q_{Tjump} + q_{wRec} \quad (2)$$

The heat flux due to the temperature jump is

$$q_{Tjump} = (T_g - T_w) 1/4 (C_v^{N_2} n_{N_2} v_{N_2} + C_v^N n_N v_N) \quad (3)$$

where c_v is the specific heat at constant volume, T_g is the gas temperature at the surface, T_w is the wall

temperature, n_{N_2} and n_N are the molecular nitrogen and the atomic nitrogen number densities, v_{N_2} and v_N are the molecular and the atomic nitrogen thermal velocities

$$v_M = \sqrt{\frac{8k_b T}{\pi m_M}}, \quad M = N_2, N$$

T_g can be calculated through the temperature jump formula [7]

$$T_g - T_w = \lambda \frac{\partial T}{\partial y}$$

where λ is the mean free path.

The heat flux due to recombination on the surface is

$$q_{wRec} = \sum_v (\gamma_v n_N v_N (E^{D, N_2} + 3/2 kT - \epsilon_{rot} - \epsilon_{vib}^v)) \quad (4)$$

obviously it depend on the number of nitrogen atoms n_N impinging the surface, on their thermal velocity v_N , on their surface recombination probability γ_v on a vibrational level v of the N_2 molecule and finally on the energy produced in the recombination reaction. With respect to the produced energy, it can be divided into 3 terms: a term including the vibrational accommodation during the recombination, a term due to translation and a term due to rotation.

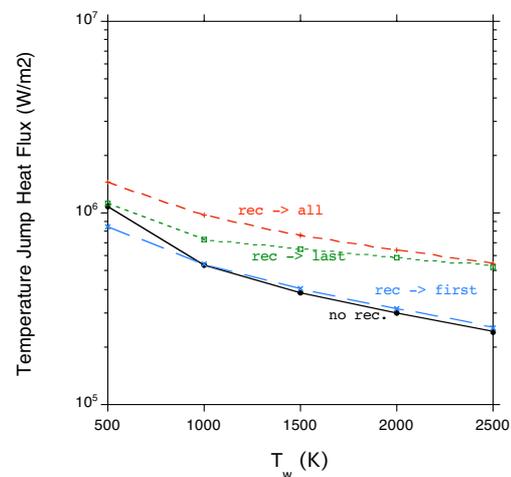


Fig.1 - heat flux on the surface due to the temperature jump

Few test cases have been run at different T_w and with the following input parameters: $T_e = 5950$ K, $P_e = 10^4$ N/m², $\beta = 10^4$ s⁻¹ and the surface recombination probability $\gamma = 0.05$.

In Figure 1 the heat flux on the surface due to the temperature jump has been plotted versus T_w ; its trend follows the trend, versus T_w , of the temperature gradient with respect to the normal to the surface.

In Figures 2, 3 and 4 the vibrational accommodation term of the heat flux on the surface due to the surface recombination, the sum of the translational and the rotational terms of the same heat flux and finally the heat flux on the surface due to the surface recombination (Eq.4), i.e. the sum of the previous three terms, have been respectively plotted versus T_w .

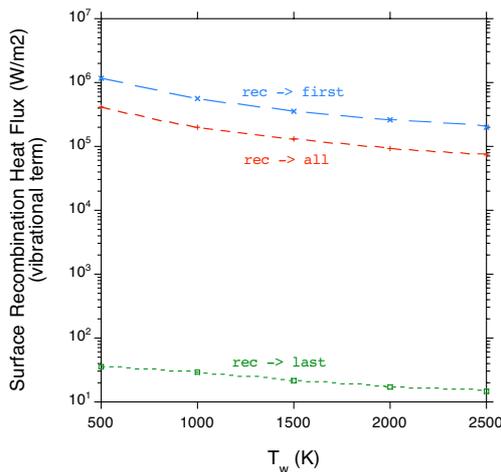


Fig.2 - the vibrational accommodation term of the heat flux on the surface due to the surface recombination

The vibrational accommodation term of the heat flux on the surface due to the surface recombination (see Fig.2) is about half magnitude order higher when the heterogeneous recombination occurs only on the first vibrational level than when it involves all of the vibrational ladder, as expected. Moreover, when the surface recombination happens only on the last vibrational level, it can be neglected in the comparison with the two previous cases. One should note that, in any case, the vibrational accommodation term of the heat flux on the surface due to the surface recombination decreases with the increasing of the fixed surface temperature T_w , as the product $n_N v_N$ does.

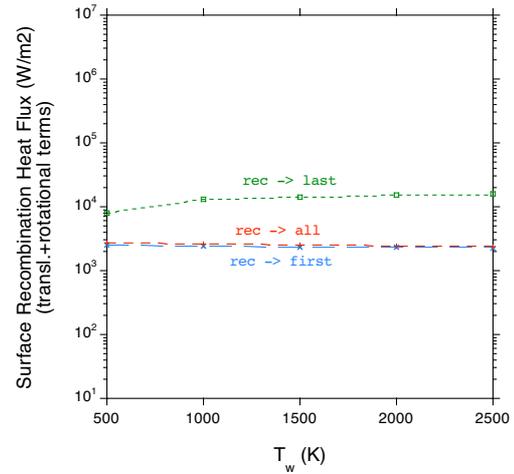


Fig.3 - the sum of the translational and the rotational terms of the heat flux on the surface due to the surface recombination

On the other side, the sum of the translational and the rotational terms of the heat flux on the surface due to the surface recombination (see Fig.3) can reach a value almost one magnitude order higher if the atoms recombine on the last vibrational level of the molecules than in the other two cases; moreover, in the mentioned case, it increases with T_w .

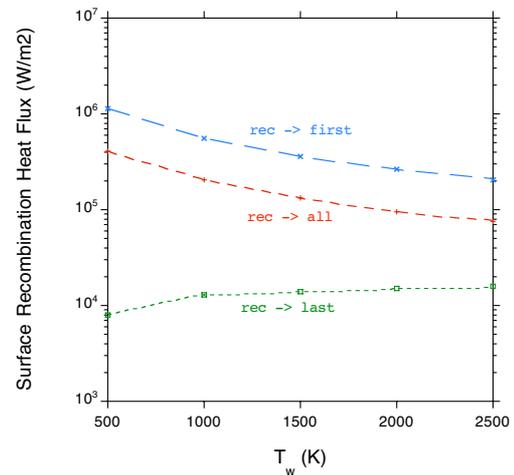


Fig.4 - heat flux on the surface due to the surface recombination

The heat flux on the surface due to the surface recombination (see Fig.4) is just the sum of the previous three terms (plotted on Figures 2 and 3): in the case of heterogeneous recombination on the last vibrational level the roto-translational terms prevail,

whereas in the other two cases the vibrational accommodation term prevails.

In Figure 5 the total heat flux on the surface (Eq.2), calculated as above through the sum of two heat flux terms due to the temperature jump and the heat flux due to the recombination on the surface respectively, has been plotted. Obviously when the surface is not-catalytic only the temperature jump contributes to the total heat flux on the surface. When the heterogeneous recombination happens only on the last vibrational level, the temperature jump prevails on the surface recombination, that can be almost neglected. When the heterogeneous recombination involves the whole vibrational ladder, the temperature jump contribution to the total heat flux is still much higher than the surface recombination contribution. Finally when the surface recombination occurs only on the first vibrational level, the contributions of the temperature jump and of the surface recombination are almost the same: at $T_w \leq 1000$ K the surface recombination heat flux slightly prevails, whereas at $T_w > 1000$ K the temperature jump heat flux slightly prevails.

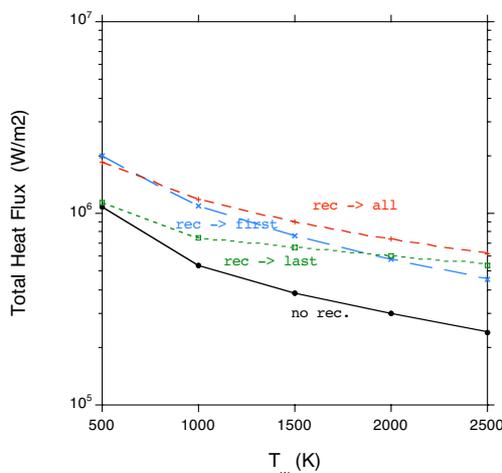


Fig.5 - heat flux on the surface due to the temperature jump and the surface recombination

3. Conclusions

It has been studied the heat flux on the surface of an hypersonic body in an N_2/N gas. The problem is not jet closed at all; among all of the still open questions, just a few examples will be reported in these conclusions.

The boundary conditions of the boundary layer equations (1) should be improved with the inclusion

of the temperature jump instead of a close to the surface fixed gas temperature equal to T_w .

The formulation of the heat flux on the surface presents some approximations, as an example both in the temperature jump calculation and in the heat flux due to surface recombination calculation, where it has not been considered that the ad-atom has not the same energy of the impinging atom.

Finally, all of the comments done about the reported figures are referred to the particular test case studied (T_e , P_e , β and γ). It would be really interesting to investigate the dependence of the heat flux and of its terms on the different parameters involved in the problem.

These are just few of the open questions about this topic, nevertheless they are enough to give an idea of the amount of work that should be done to reach a reasonable understanding of the problem.

Acknowledgment

This work has been partially supported by ASI through CAST project.

References

- [1] M.Capitelli, I.Armenise, C.Gorse, Journal of Thermophysics and Heat Transfer **11** (1997) 570.
- [2] I.Armenise, F.Esposito, M.Capitelli, submitted to *Chem. Phys.*
- [3] I.Armenise, M.Barbato, M.Capitelli, E.V.Kustova, Journal of Thermophysics and Heat Transfer **20** (2006) 465.
- [4] E.V.Kustova, *Chem.Phys.* **270** (2001) 177.
- [5] E.V.Kustova and E.A.Nagnibeda, *Chem. Phys.* **233** (1998) 57.
- [6] Hassouni et al., *Phys.Plasmas* **12**, 073301 (2005).
- [7] E.M.Lifsits, L.P.Pitaevskij, "Physical Kinetics", Pergamon Press, pp.51-52