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Hypersonic Flow of CO_2-N_2 Mixture around a Spacecraft during the Atmospheric Reentry

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Abstract**—**The aim of this work is to analyze a flow around the axisymmetric blunt body taken into account the chemical and vibrational nonequilibrium flow. This work concerns the entry of spacecraft in the atmosphere of the planet Mars. Since the equations involved are non-linear partial derivatives, the volume method is the only way to solve this problem. The choice of the mesh and the CFL is a condition for the convergence to have the stationary solution.

Keywords**—**Hypersonic flow, nonequilibrium flow, shock wave, blunt body.

I. Introduction

THIS article presents the study of a Martian entry with a velocity of 5200 m /s corresponding to a Mach number of 27. The conditions of entry into pressure and temperature are such that p = 7.8 Pascal and T = 140 K. The atmosphere of the Mars planet is composed of 97% CO_2 and 3% N_2. After the detached shock in front of the obstacle, the temperature increases rapidly and the gas becomes composed of 10 species; CO_2, CO, C_2, O_2, N_2, NO, CN, O, N and C. The number of chemical reactions is 79. For the CO_2 molecule, the 3 modes of vibration were considered. All molecules are in vibrational non-equilibrium. The nonlinear partial derivative equations system which governs this flow is solved by an explicit unsteady method [1]-[3]. The coupling between vibration and dissociation (CVD) is taken into consideration. For this type of flow, the boundary conditions must be well respected to ensure convergence [4]. The main purpose of this kind of research is to estimate the heat shield and also the pressure drag to predict the protection against the melting of the materials used and the additional force to be added to slow down the machine until landing.

II. Governing of Equations

The Euler equations for the mixture in non-equilibrium contain in addition for mass conservation, momentum and energy, equations of the evolution of chemical species (CO_2, CO, C_2, O_2, N_2, NO, CN, O, N, C) and the energy of vibration of the molecules.

The energy e per unit of mass of any species is such as:

$$e = \sum c_{vs}\, T + \sum Y_s\, e_{vs} + \sum Y_s h_{fs}^0 + \frac{1}{2}(u^2 + v^2) \tag{1}$$

h_{fs}^0 is the enthalpy of formation of the species $\boldsymbol{s}$.

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The source term of the chemical equation of evolution of species s is given as:

$$\omega_{cs} = M_s \sum_{r=1}^{r} (\upsilon_s'' - \upsilon_s') J_r \tag{2}$$

where:

$$J_r = K_f \prod_s \left(\frac{\rho_s}{M_s}\right)^{\upsilon_s'} - K_b \prod_s \left(\frac{\rho_s}{M_s}\right)^{\upsilon_s''} \tag{3}$$

υ_s' and υ_s'' are the stochiometric mole numbers of the reactants and products of species s, respectively, for each chemical reaction (r) such as:

$$\sum_s \upsilon_s' A_s \overset{K_f, K_b}{\Longleftrightarrow} \sum_s \upsilon_s'' A_s \tag{4}$$

Both forward and backward reaction rates K_f and K_b are given by empirically expression for any reaction (r).

$$K_f = A\, T^n\ exp\left(-\frac{T_d}{T}\right) \tag{5}$$

The constants $\boldsymbol{A}, \boldsymbol{n}$ and the temperature characteristic of dissociation $\boldsymbol{T_d}$ are given [5].

The term of energy production of vibration ω_{vs} is such as:

$$\omega_{vs} = \rho_s \frac{e_{vs}(T) - e_{vs}(T_v)}{\tau_s} + e_{vs}(T_v).\, \omega_{cs} \tag{6}$$

$e_{vs}(T)$ is the equilibrium energy of vibration at the temperature of translation-rotation expressed as:

$$e_v(T) = \frac{r\, \theta_v}{exp\left(\frac{\theta_v}{T}\right) - 1} \tag{7}$$

The equations can be grouped in form of flux vectors:

$$\frac{\partial W}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} = \Omega \tag{8}$$

where:

$$W = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho e \\ \rho_s \\ (\rho_s e_{vs})_m \end{pmatrix} E \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ \rho u w \\ (\rho e + p) u \\ \rho_s u \\ (\rho_s e_{vs} u)_m \end{pmatrix}$$

$$F = \begin{pmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ \rho vw \\ (\rho e + p)v \\ \rho_s v \\ (\rho_s e_{vs} v)_m \end{pmatrix} F = \begin{pmatrix} \rho w \\ \rho uw \\ \rho vw \\ \rho w^2 + p \\ (\rho e + p)v \\ \rho_s v \\ (\rho_s e_{vs} v)_m \end{pmatrix} \Omega = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \omega_{cs} \\ (\omega_{vs})_m \end{pmatrix}$$

Since the flow is supersonic and after the shock it becomes subsonic, the use of flux decomposition is indispensable [6].

III. Boundary Conditions

Boundary conditions play an important role in determining the flow parameters around the blunt body (Fig. 1). Since the flow is axisymmetric, we have four boundary conditions [3].

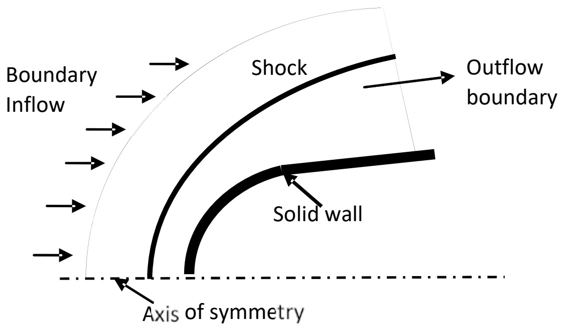

Fig. 1 Computational domain and boundary conditions

A. Inlet Boundary Conditions

At the inlet, all parameters are fixed because the flow is supersonic. The Mach number of the flow is that of the spacecraft. The pressure and the temperature are those of the atmosphere at a given altitude.

B. Body Surface

The slip condition is applied at the wall and the surface body is considered as adiabatic wall.

C. Axis of Symmetry

For two points on both sides of the axis of symmetry, they have the same velocities along x and opposite velocities along the y axis.

D. Outlet Boundary Conditions

Since at the exit of the domain the flow is supersonic, all parameters are extrapolated from the interior values.

IV. Results and Interpretations

Consider an axisymmetric blunt body defined geometrically by hemisphere as shown in Fig. 2, when the ray is denoted by $\boldsymbol{r = 4\ cm}$. The computational domain is limited by the blunt body and an ellipse with $\boldsymbol{a = 1.1\ r}$ and $\boldsymbol{b = 1.65\ r}$. Assume a hypersonic flow-field where the free-stream Mach number equals to $\boldsymbol{27}$, corresponding to the velocity of 5232 m/s. The configuration is at zero degree angle of attack. The Van-Leer flux vector splitting scheme is adapted for this purpose. In our calculations we used a $(\boldsymbol{20x156})$ grid created by an elliptic scheme. Note that grid points are clustered near the stagnation region where the flow is expected to the subsonic. Fig. 2 shows the (20x156) grid, 20 meshes along the axis and 156 meshes along the wall.

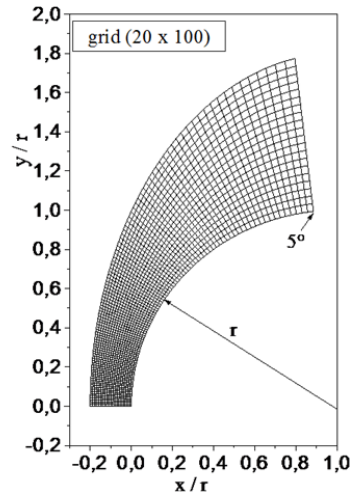

Fig. 2 Grid of solution domain

The initial solution is that of free stream hypersonic flow. All parameters were taken equal in all points of the computational domain. The stationary solution is obtained after 5000 iterations with a $CFL = 0.4$.

Fig. 3 shows the variation of the mass fraction of the species along the stagnation point line between the detached shock and the blunt body. Note that the stand off of the shock is 2.5 mm from the the stagnation point. After the shock the temperature increases rapidly which triggers chemical reactions with the formation of new species due to the dissociation of 66% of CO_2. Virtually all mass fractions are less than 1% except for CO_2, CO and O (Fig. 4). C is almost non-existent.

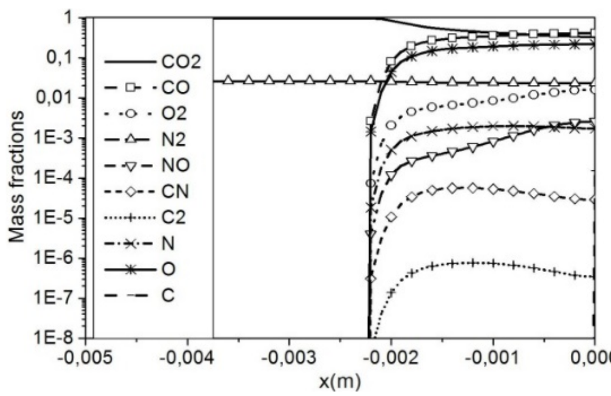

Fig. 3 Mass fractions of all species

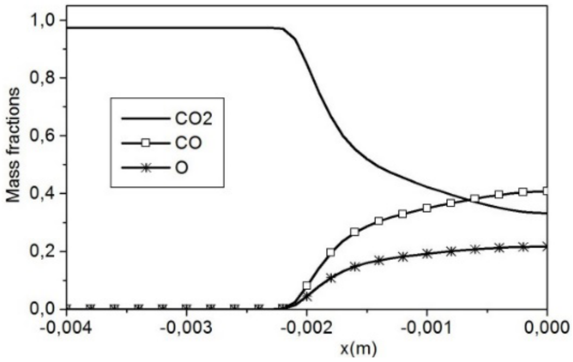

Fig. 4 Mass fractions of CO2, CO and O

After the shock, the translation rotation temperature decreases due to the dissociation on the one hand and the increase in the vibrational energy of the molecules on the other hand , the temperature at the stagnation point is 4914K (fig. 5). In this zone of relaxation, the equilibrium is not yet reached even at the stagnation point except for CO2 (1) and CO2 (2). The pressure is 7541 Pascalat the stagnation point (fig.6). The vibrational temperatures along the wall of the body is shows in figure 7. As for the flow around the obstacle, we gave exemple of the variation of the mass fraction of CO2 (fig.8) and the CN (fig. 9).

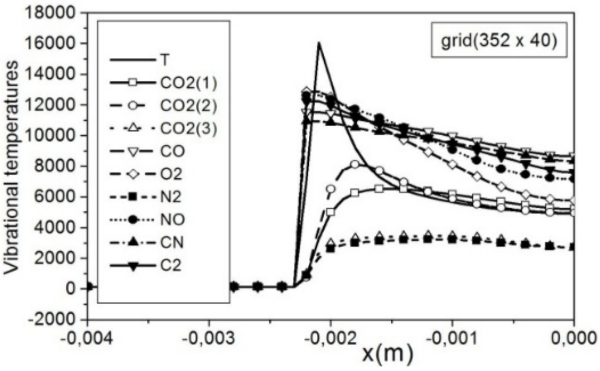

Fig. 5 Vibrational temperatures

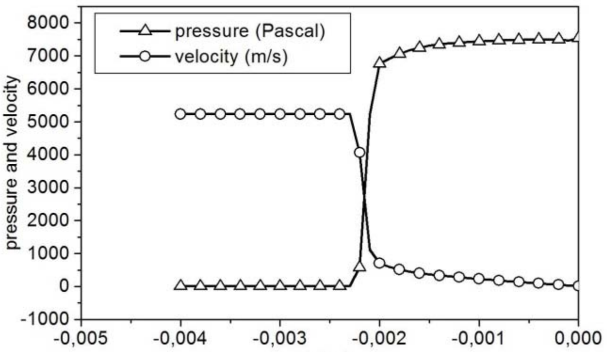

Fig. 6 Pressure and velocity along a stagnation point line

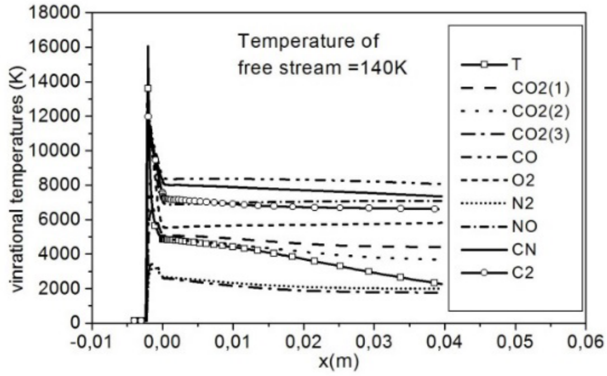

Fig. 7 vibrational temperatures

V. CONCLUSION

In conclusion, we have taken into account the existence of N2 in the composition of the atmosphere of the Mars planet although its mass fraction does not vary but it contributes in the chemical reactions of other species. At this phase of the atmospheric entry, the temperature immediately after the shock is of the order of 18000k then it decreases to reach the 5000K at the stagnation point and then it decreases as the flow accelerates from again along the wall of the blunt body. The chemical composition of the gas and the vibration temperatures of the molecules between the shock and the nose of blunt body gives information on the state of the flow for the codes validation. The position of the shock may also be used as an index.

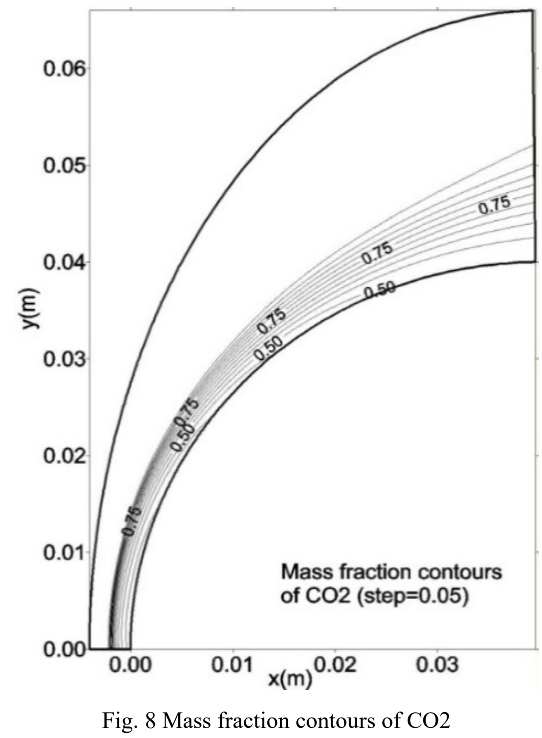

Fig. 8 Mass fraction contours of CO2

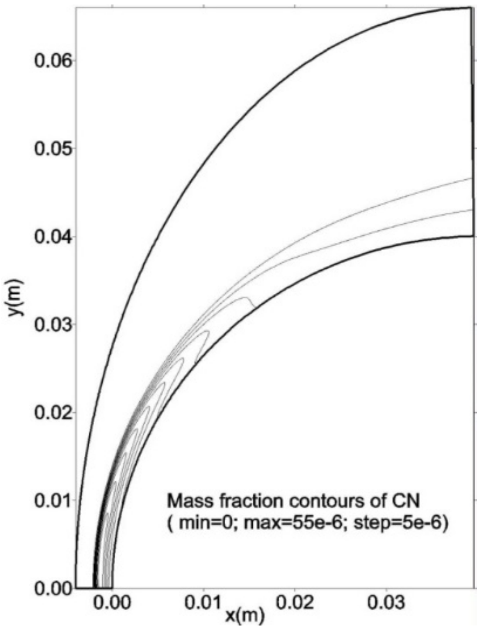

Fig. 9 Mass fraction contours of CN

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