CFD Simulations of Superobital Reentry for a Phobos Sample Return Capsule

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Abstract

A simulation of the reentry flow for a Phobos Sample Return Mission is presented. The initial reentry velocity considered is 11.6 km/s and the capsule has the same forward body geometry as the Hayabusa capsule. The simulations are performed using CFD code SPARK, developed and maintained at IPFN. The heat fluxes along the capsule surface are analysed for several trajectory points, centered in the convective heating peak trajectory point, since the assessment of the total heat fluxes is paramount for the proper design of a TPS. A mesh generation process and mesh convergence study are presented. Two methods for calculating the transport properties, Wilke and Gupta-Yos, are applied and compared. The obtained results are also compared against a previous simulation performed using the same software considering the RAM-C II capsule reentry at 7.65 km/s. For the highest reentry speed, both models diverge more than for the lowest speed. An analysis of thermal nonequilibrium is performed applying Park’s two-temperature model to account for thermal nonequilibrium and compared against thermal equilibrium conditions. Two trajectories for the capsule descent are considered in the scope of project DIVER, a steep and a shallow entry. The stagnation point convective heat flux is analysed at six key points for each trajectory and compared to the Sutton-Graves semi-empirical correlation used in the preliminary design.

Keywords: Reentry, Hypersonic, Aerothermodynamics, Convective Heat Fluxes

1. Introduction

Robotic planetary exploration missions rank among the most challenging endeavours in Space engineering. The Phobos Sample Return Mission was designed to collect samples from the Martian moon Phobos and returning them to Earth. One of this mission’s most critical technologies is the one behind the superobital Earth reentry originating from Mars/Phobos. During Earth reentry, the spacecraft is moving at velocities ranging from 13 to 6 km/s, crossing several hypersonic flow conditions. These velocities lead to the formation of a strong and high-temperature bow shock around the capsule. Because of the high temperature nature of this shock, the heat fluxes that reach the surface of the capsule will exceed what the surface material can withstand. Consequently, the proper selection of a Thermal Protection System (TPS) is very important when designing a reentry capsule. To this effect, an accurate assessment of wall heat fluxes during the high speed, hyperbolic reentry is therefore critical. These heat fluxes can be divided into two types, convective heating and radiative heating. Convective heating refers to the combined effect of the convective heat flux and the conduction heat flux. The radiative heat flux is sourced in the radiation emitted by the ionized flow.

DIVER (Desenho Integrado do VEículo de Reentrado) is a Portuguese consortium project comprising Spin.works, INEGI, IST-DEM and IPFN (Instituto de Plasmas e Fusão Nuclear), funded by Portugal2020. It gathers all the concurrent engineering required in the preliminary design of a reentry vehicle in the Phobos Sample Return mission and aims at demonstrating the national expertise on interplanetary exploration missions design. Two trajectories for the capsule descent are considered, one with a flight path angle (fpa) of -15.9°, Trajectory 15.9, and the other with fpa = -24.2°, Trajectory 24.2. In both trajectories, the maximum value of the reentry velocity is 11.6 km/s.

The purpose of this work is to 1) identify the key trajectory points for the proper design of the capsule; 2) calculate the convective heat fluxes for each trajectory key points; 3) compare the stagnation heat fluxes against correlation values; and 4) provide a first estimate of the heat fluxes for the next phase of the design. In order to accomplish these
During a superorbital reentry, the flow is characterized as a thermal nonequilibrium reacting flow. Consequently, it has to be defined by a multi-component model, which means the gas is treated as a mixture of individual chemical species, mixed in a single phase. Since the gas is not in chemical equilibrium, a chemical-kinetic model needs to be applied to model the gas composition.

During reentry the large amount of coherent kinetic energy in the hypersonic freestream is converted into translational energy of the gas across the strong bow shock wave. This energy is then transferred to the molecules’ internal modes through further collision processes. There are four main thermal energy modes\(^1\): translational energy, rotational energy, vibrational energy and electronic excitation energy [9]. In thermal equilibrium, every species thermal energy is associated to the same characteristic temperature \(T = T_{\text{tra}} = T_{\text{rot}} = T_{\text{vib}} = T_{\text{exc}}\).

However, usually species thermal energy modes are excited differently and thus, multiple temperatures must be considered. This thermal nonequilibrium is taken into account through the use of a multi-temperature model.

Equations (1 - 4) present the conservative equations for a thermal nonequilibrium reacting flow.

\[
\frac{\partial(pu_i)}{\partial t} + \nabla \cdot (pu_iu) = \nabla \cdot J_i + \dot{\omega}_i \quad (1)
\]

\[
\frac{\partial(p\tilde{u})}{\partial t} + \nabla \cdot (p\tilde{u}\otimes \tilde{u}) = \nabla \cdot [\tau] - \nabla p \quad (2)
\]

\[
\frac{\partial\rho(Ei)}{\partial t} + \nabla \cdot (\rho E_i\tilde{u}) = \nabla \cdot \left( \sum \dot{q}_{ci} + \sum \dot{J}_{hi} + \tilde{u} \cdot [\tau] - p \tilde{u} \right) \quad (3)
\]

\[
\frac{\partial(q_{ci})}{\partial t} + \nabla \cdot (q_{ci}\tilde{u}) = \nabla \cdot \left( \dot{q}_{ci} + \sum \dot{J}_{hi} \rho \right) + \dot{\Omega}_k \quad (4)
\]

where \(\rho\) is the density, \(\tilde{u}\) the mean velocity in vectorial form, \(c_i\) the species mass fraction, \(\tilde{J}_i\) the viscous stress tensor, \(p\) the pressure, \(E\) the total energy, \(\dot{q}_{ci}\) the conduction heat flux, \(\dot{\Omega}_k\) the thermal energy associated to each thermal energy mode and \(\dot{\Omega}_k\) the thermal energy source term.

### 2.1. Kinetic Model

In the above stated equation for the species continuity (eq. 1), \(\dot{\omega}_i\) is the species source term that accounts for the destruction and production of species. It is determined by the chemical-kinetic model. Depending on the kinetic scheme considered, the number of chemical reactions and their respective rates are different. The kinetic scheme considered in the present work is the 11-species air model developed by Park [10]. It considers the species \(O_2, N_2, NO, N, O, N_2^+, O_2^+, NO^+, N^+, O^+, e^-\).

### 2.2. Multi-Temperature Model

The two-temperature model by Park[11] is implemented in SPARK. It assumes that the translational energy of the atoms and molecules and the rotational energy of the molecules are characterized by the same temperature \(T_{\text{tra}}\) and that \(T_{\text{rot}}\) characterizes the vibrational energy of the molecules, translational energy of the electrons and electronic excitation energy of atoms and molecules.

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\(^1\)These correspond to velocities above the escape velocity from Earth’s gravity.

\(^2\)Assuming the Born-Oppenheimer approximation.
2.3. Transport Models
The phenomena that take place during reentry lead
to larger changes in the gas mixture transport prop-
terties. Consequently, an adequate model needs to
be implemented. In the equations previously stated
(eqs. 1 - 4), \( \vec{J}_i \), \([\tau]\) and \( qC_{ik} \) define the dissipative
fluxes. In the present work, the mass diffusion flux
\( \vec{J}_i \) is modeled by Fick’s Law of diffusion:
\[
\vec{J}_i = \rho D_i \vec{c}_i
\]
where \( D_i \) represents the \( i \)th species mass diffusion
coefficient. Moreover, it is considered that the vis-
cous stress tensor \([\tau]\) assumes a Newtonian fluid and the Stokes hypothesis
for the normal stresses:
\[
[\tau] = \mu \left( \vec{\nabla} \vec{u} + (\vec{\nabla} \vec{u})^T \right) - 3 \mu (\vec{\nabla} \cdot \vec{u}) I
\]
where \( \mu \) is the viscosity coefficient. Furthermore,
the conduction heat flux in each energy mode, \( qC_{ik} \),
is assumed to be given by Fourier’s Law of heat
conduction:
\[
qC_{ik} = \lambda_k \vec{\nabla} T_k
\]
The most effective way of determining these prop-
eties is by applying approximate mixing rules,
which are simplified forms of the Chapman-Enskog
solution [12]. In this work, two different mixing
rules are applied, the Wilke/Blottner/Eucken model
and the Gupta-Yos/Collision Cross-Section model.

2.3.1 Wilke/Blottner/Eucken Model
Wilke’s Model [13] for gas mixture viscosities was
developed through the application of kinetic the-
ory to the first order Chapman-Enskog relation. It
assumes that all interactions between any particles
present the same (hard sphere) cross-section [14].
The gas mixture viscosity \( \mu \) and the thermal con-
ductivity \( \lambda_k \) for each gas temperature are deter-
mined as follows:
\[
\mu_m = \sum_{i=1}^{NS} x_i \mu_i \phi_i \quad \lambda_k = \sum_{i=1}^{NS} x_i \lambda_{ik} \phi_i
\]
(8)
where \( x_i \) is the species molar fraction and \( \mu_i \) represents
the individual viscosities. \( \phi_i \) is a scale factor
given by:
\[
\phi_i = \sum_{j=1}^{NS} \left[ 1 + \sqrt{\frac{\mu_j}{\mu_i}} \left( \frac{M_j}{M_i} \right) \right] \left[ 1 + \sqrt{\frac{\mu_i}{\mu_j}} \left( \frac{M_i}{M_j} \right) \right]^{-1} \]
(9)
where \( M_i \) represents each species’ (i’s or f’s) molar
mass.
For the species viscosities, curve fits determined
by Blottner [15] are considered:
\[
\mu_i(T_{tra,i}) = 0.1 \exp(A_i \ln T_{tra,i} + B_i \ln T_{tra,i} + C_i)
\]
where \( A_i, B_i \) and \( C_i \) are curve fitted coefficients for
each species.
Eucken’s relation [16] is used to determine each
species thermal conductivity:
\[
\lambda_{tra,i} = 5 \left( \frac{2}{3} \mu_i C_{V_{tra,i}} \right) \quad \lambda_{k\neq tra,i} = \mu_i C_{V_{k,i}}
\]
where \( C_{V_{k,i}} \) represents the specific heat at a con-
tant volume of the \( i \) species in each energy mode.
In thermal nonequilibrium, the contributions of
each species should be accounted for differently in
the mixing rule, according to the multi-temperature
model considered.

The species mass diffusion coefficient is given by
a single binary coefficient \( D \) assuming a constant
Lewis number, \( Le = 1.2 \):
\[
D_i = D = \frac{L e \lambda}{\rho C_P}
\]
where \( C_P \) is the gas mixture total specific heat at
a constant pressure and \( \lambda \) represents the total ther-
mal conductivity of the gas mixture. The Lewis
number \( Le \) corresponds to the ratio of the energy
transport due to mass diffusion relative to the one
due to thermal conduction.

2.3.2 Gupta-Yos/Collision Cross-Section
Model
Another method to calculate the transport prop-
eties of a gas mixture is by using the Gupta-Yos
model [17], a simplification of the Chapman-Enskog
solution. The main difference between the Wilke
and the Gupta-Yos models is that the latter con-

siders each collision’s corresponding cross-section.
Consequently, it is assumed to be more accurate
because the true nature of the viscosity collision in-
egratings of the cross-sections. These collision in-
ergals is taken into account. The collision integrals
are defined as follows:
\[
\Delta_{ij}^{(1)}(T_c) = \frac{5}{3} \left[ \frac{2M_i M_j}{\pi R T_c (M_i + M_j)} \right]^{1/2} \pi \overline{\Omega}_{ij}^{(1,1)}
\]
\[
\Delta_{ij}^{(2)}(T_c) = \frac{16}{5} \left[ \frac{2M_i M_j}{\pi R T_c (M_i + M_j)} \right]^{1/2} \pi \overline{\Omega}_{ij}^{(2,2)}
\]
where \( \overline{\Omega}_{ij}^{(1,1)} \) and \( \overline{\Omega}_{ij}^{(2,2)} \) represent weighted
averages of the cross-sections. These collision in-
egratings are a function of the controlling tempera-
ture \( T_c \) that varies depending on the type of
particles colliding. For collisions between heavy-
particles, the controlling temperature is the trans-

tional/rotational temperature \( T_{tra} \), whereas the
one for collisions involving electrons is the vibra-
tional/electron/electronic excitation temperature
\( T_{vib} \) [5].
For the calculation of the gas mixture viscosity, the mixing rule is used:

\[ \mu^{(1)} = \sum_{i}^{N_S} \frac{m_i x_i}{\sum_{j}^{N_S} x_j \Delta(1)_{ij}} \]  

(15)

where \( m_i \) is the \( i \)th species mass. The translational mode of heavy species \( \lambda_{\text{tra}} \) reads:

\[ \lambda_{\text{tra}} = \frac{15}{4} k_B \sum_{i}^{N_S} \frac{x_i}{\sum_{j}^{N_S} \alpha_i x_j \Delta(2)_{ij}} \]  

(16)

and the translational mode of electrons \( \lambda_e \) is:

\[ \lambda_e = \frac{15}{4} k_B \sum_{j}^{N_S} \frac{x_e}{\sum_{j}^{N_S} \alpha_{e,j} x_j \Delta(2)_{ej}} \]  

(17)

where \( k_B \) is the Boltzmann constant and \( \alpha_{i,j} \) is given by:

\[ \alpha_{i,j} = 1 + \frac{1 - M_i/M_j}{[1 + (M_i/M_j)^2]} \]  

(18)

The global thermal conductivities associated with the rest of the heavy species energy modes, \( \lambda_{\text{rot}}, \lambda_{\text{vib}}, \lambda_{\text{exc}} \) are:

\[ \lambda_{\text{rot}} = \sum_{i}^{N_S} \frac{x_i m_i C_{V_{\text{rot,i}}}}{\sum_{j}^{N_S} x_j \Delta(1)_{ij}} \]  

(19)

\[ \lambda_{\text{vib}} = \sum_{i}^{N_S} \frac{x_i m_i C_{V_{\text{vib,i}}}}{\sum_{j}^{N_S} x_j \Delta(1)_{ij}} \]  

(20)

\[ \lambda_{\text{exc}} = \sum_{i}^{N_S} \frac{x_i m_i C_{V_{\text{exc,i}}}}{\sum_{j}^{N_S} x_j \Delta(1)_{ij}} \]  

(21)

In thermal equilibrium, the total thermal conductivity \( \lambda \) is given by:

\[ \lambda = \lambda_{\text{tra}} + \lambda_e + \lambda_{\text{rot}} + \lambda_{\text{vib}} + \lambda_{\text{exc}} \]  

(22)

In thermal nonequilibrium, the thermal conductivity associated with each temperature mode is calculated by considering the individual contributions of each species according to the multi-temperature model considered, where the global temperature parameter \( T \) is replaced by the appropriate mode temperature.

The mass diffusion coefficient \( D_{ij} \) defines the diffusion velocity of each species relative to the other species and reads:

\[ D_{ij} = \frac{k_B T_e}{\rho \Delta(1)_{ij}} \]  

(23)

An average of the diffusion coefficient relative to the remaining gas mixture \( D_i \) is determined by:

\[ D_i = \frac{1}{\sum_{j \neq i} x_j / D_{ij}} \]  

(24)

### 2.3.3 Ambipolar Diffusion

In an ionized gas, each charged particle induces an electric field, which influences the other particles motion. This results in an increase in the diffusion of the ions, which are pulled by the more mobile electrons, which in turn are slowed down by the heavier ions. The two species finally diffuse with the same velocity, mainly imposed by the heavier species. Since the electro-static forces are not considered in the conservation equations, this phenomena can only be taken into account by artificially introducing this effect in the calculation of the charged particles diffusion. The ambipolar corrections account for this increase in diffusion velocity of ions and decrease in velocity of electrons due to the electrostatic interactions between the two.

For ions, Chen [18] shows that the ambipolar diffusion coefficient is given by:

\[ D_{\text{ion}} = \frac{(1 + T_e / T_{\text{ion}}) D_{\text{ion}}}{(25)} \]

where \( D_{\text{ion}} \) is the ion free diffusion coefficient and \( T_e \) and \( T_{\text{ion}} \) are the translational temperatures of the electrons and the ions, respectively. In thermal equilibrium, this ionic factor is simply equal to 2 \( (D_{\text{ion}} = 2D_{\text{ion}}) \), assuming that all heavy species are in equilibrium with a common translational temperature.

For electrons, the ambipolar diffusion coefficient is defined as [19]:

\[ D_e = M_e \sum_{i=\text{ion}}^{D_{\text{ion}}^2 x_i}{\sum_{i=\text{ion}}^{M_i x_i}} \]  

(26)

This is only valid if all the ions have the same free diffusion velocity and electrical mobility.

### 3. Numerical Setup

After correctly defining the problem, the conditions in which the simulations will be performed need to be established.

#### 3.1. Selection of the Key Trajectory Points

This works' role in the DIVER project is to calculate the heat fluxes present at the wall so that a suitable TPS can be designed. Two separate trajectories were considered and for each of these trajectories, semi-empirical correlations were applied as a first approach, such as it is customary when testing a large number of possible flight profiles and geometries, where full CFD simulations are impractical.

For the convective heating, the Sutton-Graves equation [20] was applied. To analyse radiative heating, the expression developed by Tauber and Sutton[21] was considered. Both assume chemical equilibrium flow. Figure 1 shows the results obtained by Spin.works for the convective (dark blue line) and radiative (light blue line) heat fluxes, the
Table 1: Points where the analysis will be performed for Trajectory 15.9.

<table>
<thead>
<tr>
<th>Velocity [kn/s]</th>
<th>Density [g/m³]</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1 11.58</td>
<td>0.024</td>
<td>292.03</td>
</tr>
<tr>
<td>Point 2 11.21</td>
<td>0.141</td>
<td>230.24</td>
</tr>
<tr>
<td>Point 3 10.07</td>
<td>0.486</td>
<td>257.18</td>
</tr>
<tr>
<td>Point 4 8.63</td>
<td>0.964</td>
<td>270.65</td>
</tr>
<tr>
<td>Point 5 6.89</td>
<td>1.726</td>
<td>266.79</td>
</tr>
<tr>
<td>Point 6 4.22</td>
<td>3.599</td>
<td>252.34</td>
</tr>
</tbody>
</table>

Table 2: Points where the analysis will be performed for Trajectory 24.2.

<table>
<thead>
<tr>
<th>Velocity [kn/s]</th>
<th>Density [g/m³]</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1 11.56</td>
<td>0.048</td>
<td>210.86</td>
</tr>
<tr>
<td>Point 2 11.29</td>
<td>0.178</td>
<td>235.07</td>
</tr>
<tr>
<td>Point 3 10.02</td>
<td>0.758</td>
<td>267.56</td>
</tr>
<tr>
<td>Point 4 8.73</td>
<td>1.451</td>
<td>270.32</td>
</tr>
<tr>
<td>Point 5 6.92</td>
<td>2.776</td>
<td>257.35</td>
</tr>
<tr>
<td>Point 6 4.18</td>
<td>5.888</td>
<td>243.10</td>
</tr>
</tbody>
</table>

Figure 1: Results for the semi-empirical correlations for both trajectories.

Figure 2: DIVER capsule geometry.

drag (dark red line) and velocity (light red line) distributions during reentry and the points where the analysis will be performed (green dashed line) for (a) Trajectory 15.9 and (b) Trajectory 24.2.

Six key points per trajectory were selected to perform CFD simulations. Point 1, 2, 4 and 6 were selected to properly compare the CFD results with the correlations used. Point 3 represents the convective heating peak, it is the most critical point in each trajectory. Point 5 corresponds to the peak in drag, it is the point where the mechanical loads are the highest. Tables 1 and 2 show the selected points data for Trajectory 15.9 and Trajectory 24.2, respectively. The data was calculated considering the US Standard Atmosphere 1976 to model Earth’s Atmospheric profile as a function of altitude.

3.2. Mesh Generation
A mesh generation study was performed considering the initial conditions for the peak heating (point 3) of Trajectory 15.9. Figure 2 shows the capsule geometry where the forward body is highlighted in the drawing. The body is axisymmetric and therefore, only half of the front body will be considered in the computational domain, since a 0° angle of attack is also assumed.

At the end of the mesh generation process, a final mesh configuration was selected. Afterwards, a mesh convergence exercise was performed, to obtain the best results at the least computational effort. Figure 3 shows a comparative analysis of (a) the temperature profiles along the stagnation line and (b) the wall heat fluxes for three mesh resolutions. Ni refers to the number of mesh cells along the stagnation line.

Analysing Fig. 3 it can be seen that Ni = 90 (red line) and Ni = 120 (black line), present closer results than Ni = 45 (blue line). Consequently, it was considered the latter mesh is too rough for the desired simulations. Because the heat flux profiles obtained for Ni = 120 are still 16% higher than for Ni = 90, it was concluded that the most suitable
Stagnation Line Temperature

Temperature [K]

Ni = 45
Ni = 90
Ni = 120

Wall Heat Flux

Heat Flux [W/cm²]

Curvilinear Distance s [m]

Ni = 45
Ni = 90
Ni = 120

Figure 3: Stagnation Line Temperature (a) and Wall Heat Flux (b) profiles for three different values of Ni, where Ni is the number of mesh cells along the stagnation line.

Mesh for the simulations is the one where Ni = 120. More refined meshes were tested, however these did not manage to converge to a realistic flow profile. Figure 4 shows the final mesh. The mesh is refined near the wall to account for the boundary layer.

3.3. Initial and Boundary Conditions

The initial conditions for each trajectory point are detailed in tables 1 and 2. Figure 4 shows the mesh and the boundary conditions considered in the simulations performed in this work.

In addition to the boundary conditions previously stated, a condition will be considered to account for how the flow interacts with the surface. A fully catalytic wall boundary condition is applied, assuming that all atoms/electron-ion pairs which collide with the surface recombine into molecules/neutral species. It represents a pessimistic limit for the overall heat flux (since these catalytic reactions are exothermal).

Figure 4: Boundary conditions considered for the CFD domain.

4. Results

4.1. Impact of Transport Model and Velocity

The following analysis was performed on point 3 of Trajectory 15.9. The results obtained were compared considering two transport models, Wilke and Gupta-Yos. The impact of the velocity was studied by comparing the results obtained in the present work to those obtained by Loureiro [2]. Both simulations were performed on SPARK and considered the same kinetic scheme and thermal equilibrium. In the simulations run by Loureiro the RAM-C II capsule geometry and a reentry velocity of 7.65 km/s were considered.

Figure 5 shows the stagnation line temperature profiles for both mixing rules, at reentry speeds of 10 km/s (a) and 7.65 km/s (b).

Focusing on the results obtained in the present work (Fig. 5a), it can be seen that the greatest discrepancy in the results obtained for each transport model lies in the boundary layer. Around x = -0.0025 m, the Gupta-Yos model (black line) shows a steeper decrease in temperature when compared to the Wilke model (red line). Moreover, the Gupta-Yos model predicts a peak temperature 7% higher than the Wilke model.

Comparing the results obtained for each reentry velocity, there are two main differences. 1) The results agree better at lower velocities. This will be addressed later on at the end of this section; and 2) for the lowest velocity, there is no region where a quasi steady state flow is achieved between the shock wave and the boundary layer. The reason for the absence of this region is that the chemical reactions, in the shock region, occur at a slower rate, when compared to the highest velocity. One would expect the temperature peak value corresponding to the highest velocity to be much higher. However, due to the roughness of the mesh in this area considered in the present work, the shock peak is not fully captured and therefore, the peak temperature
Figure 5: Stagnation line temperature profiles for both mixing rules, for a reentry speed of 10 km/s (a) and 7.65 km/s (b).

appears similar in both cases.

Figure 6 shows the wall heat flux profiles for both transport models, for a reentry speed of 10 km/s (a) and 7.65 km/s (b).

Focusing on the results performed at 10 km/s (Fig. 6a), there is a great difference in the wall heat flux profiles depending on the selected transport model. The peak heat flux obtained is 640 W/cm² for the Wilke model, 19% higher than for the Gupta-Yos model. It can be seen that for both curves, there is a slight disturbance around s = 0.04 m, which is currently attributed to numerical errors. A possible cause for this is the carbuncle problem [22]. It is defined as a local displacement of the bow shock wave shape near the stagnation line, which compromises the accuracy of the heat transfer predictions made by numerical simulations of hypersonic flows.

Comparing the results for both reentry velocities, the heat fluxes at the wall are about three times higher for 10 km/s, which agrees well with the increased temperature gradient at the surface.

Analysing Figs. 5 and 6, the results obtained for both transport models agree better at the lowest velocity. This is related to the increase in the degree of ionization of the flow at higher velocities, because these models were formulated assuming a weakly ionized gas.

4.2. Impact of Multi-Temperature Model

As discussed in section 2.2, Park’s two-temperature model is implemented in SPARK to account for thermal nonequilibrium. Figure 7 shows profiles for (a) the stagnation line temperatures and (b) the wall heat flux for thermal nonequilibrium and thermal equilibrium. This simulation was performed on the same peak heating point for trajectory 15.9, point 3. A fully catalytic boundary condition at the surface and the Gupta-Yos transport model were considered.

Focusing on Fig. 7a, the translational/rotational temperature (red line) profile follows the same overall trend as the temperature profile considering thermal equilibrium (black line), although it does not stabilize. However, the peak in translational temperature reaches 22000 K, 27% higher than for the thermal equilibrium case. The
Figure 7: Profiles for (a) the stagnation line temperatures (b) wall heat flux for thermal equilibrium and nonequilibrium.

Figure 8: Stagnation line profiles for (a) species mole fractions and (b) temperature, pressure and velocity.

vibrational/electron/electronic excitation temperature (blue line) follows a more distinct profile. The discrepancy in the profiles for the translational/rotational temperature and the vibrational/electron/electronic excitation temperature leads to the conclusion that there is a very strong thermal nonequilibrium, as would be expected for the flow initial conditions. Thermal equilibrium is only reached in the boundary layer.

Figure 7b presents the wall heat flux results obtained for thermal equilibrium (red line) and thermal nonequilibrium (black line). Both present the same overall trend after $s = 0.09$ m. Before this point, both heat fluxes present a disturbance at $s = 0.04$ m, supporting the previous assumption of the carbuncle problem. The stagnation point heat flux predicted for the thermal nonequilibrium is approximately 580 W/cm$^2$, 9% lower than the one predicted for the thermal equilibrium case. It would be expected that the heat fluxes at the wall be the same along the capsule since thermal equilibrium is reached at the boundary layer. However, the temperature gradients differ, leading to slightly different heat fluxes. Nonetheless, the differences remain lower than 10% in the critical region of the stagnation streamline, allowing for the use of a more simplified and time-efficient single-temperature thermochemical model in the rest of the analysis.

4.3. Peak Heating Point Analysis
This analysis was performed for point 3 of Trajectory 15.9, a key point in the trajectory for the design of the TPS, since it corresponds to the peak in convective heating.

Figure 8 shows the results for (a) species mole fractions and (b) temperature, pressure and velocity profiles along the stagnation line.

Figure 8a shows that the mole fractions of $N_2$ and $O_2$ decrease after the bow shock ($x = -0.022$ m), whereas the rest of the species mole fractions increase after this point. Gas chemical composition stabilizes from $x = -0.020$ m up to $x = -0.003$ m (the quasi steady state region). Afterwards, concentrations of $N_2$, $O_2$ and NO increase due to the recombination reactions taking place near the capsule surface. This is balanced by the decrease in the molar fractions of species $N_2^+$, $O_2^+$, $NO^+$, $e^-$ and N.
Figure 9: Temperature 2D field.

One would expect the molar fraction of O to decrease at the surface due to the recombination of \( O_2 \) (\( O + O + \text{wall} \Rightarrow O_2 \)), however that is not the case, owing to the fact that this species is involved in more recombination reactions.

Focusing on Fig. 8b, for the shock peak (\( x = -0.022 \) m) there is an increase in temperature and pressure, whereas the velocity decreases. After reaching its peak, temperature decreases rapidly until it stabilizes at 10000 K, from \( x = -0.02 \) m up to \( x = -0.003 \) m. It then decreases abruptly until reaching the capsule surface at \( x = 0 \) m with the imposed wall temperature. Regarding the pressure, it rises until 47.7 kPa in the shock region, at \( x = -0.022 \) m, and remains stable until the capsule wall (\( x = 0 \) m). The velocity drops abruptly from 10000 to \( \approx 960 \) m/s in the shock region and afterwards gradually decreases until \( V = 0 \) m/s at the capsule wall.

Figure 9 depicts the temperature 2D field. It shows the shock wave position very clearly due to the abrupt temperature rise. Towards the outflow boundary condition the temperatures in the shock layer are gradually lower (above \( Y = 0.3 \) m). This is due to the shock wave position relative to the flow. In the stagnation line, the shock wave is normal to the flow and the temperature gradient is very high. Moving along the shock wave, it becomes an oblique shock resulting in a lower temperature gradient.

4.4. Heat Fluxes for Project DIVER

For the key trajectory points detailed in section 3.1, CFD simulations were performed considering the Gupta-Yos transport model, thermal equilibrium and a fully catalytic wall, owing to the conclusions of previous sections. A comparison between the 6 selected points and the continuous correlated data-points for the two reentry trajectories has been carried out.

Figure 10 compares the data obtained in this work with the Sutton-Graves correlation for the convective heat flux along (a) Trajectory 15.9 and (b) Trajectory 24.2.

For both trajectories, some CFD points predict a slightly higher convective stagnation heat flux than the Sutton-Graves correlation. The highest discrepancy (48%) was found for Trajectory 24.2 in the point with the highest velocity, point 1. The peak heating point, for both trajectories is point 4, as opposed to number 3 in the correlation. The discrepancies found between the results are due to the fact that, as mentioned in section 3.1, the Sutton-Graves equation assumes chemical equilibrium. Overall CFD results correlate well with the semi-empirical results, providing confidence to the thermal protections system design process.
5. Conclusions
A successful comparison between the Wilke and the Gupta-Yos transport models was performed for an hyperbolic Earth reentry. It was found that for higher reentry velocities, the selection of the method to calculate transport properties influences the results more than for lower velocities, on account of the increased degree of ionization of the flow.

An analysis of the impact of applying a multi-temperature model was carried out. Park’s two-temperature model was considered. It was concluded that the flow at these reentry conditions, at 10 km/s, presents a very strong thermal nonequilibrium, as would be expected. However, this does not significantly impact the overall aerothermodynamics of the flow due to the fact that the mole fractions of the molecules in the shock layer are very low and thus constitute a very small percentage of the flow composition. In this region, the ions and atoms characterize the flow and hence the vibrational temperature loses its meaning.

The trajectory point corresponding to the peak in convective heating was thoroughly analysed. The species molar fractions validated the assumption of a fully catalytic wall boundary condition.

The stagnation point convective heat flux was analysed for all the key trajectory points and compared to the Sutton-Graves correlation. The results agreed reasonably with the correlation. Discrepancies may be attributed to the fact that the correlation assumes that the flow is in chemical equilibrium.

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References