Proceedings of ENCIT 2010

13rd Brazilian Congress of Thermal Sciences and Engineering
December 05-10, 2010, Uberlandia, MG, Brazil

TWO-DIMENSIONAL SIMULATION OF ABLATION DUE TO AERODYNAMIC HEATING IN THE SARA SUB-ORBITAL PLATFORM

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Abstract. *Space and sub-orbital vehicles reach high velocities within atmosphere, about 100 km over Earth's surface. Such high velocities result in aerodynamic heating and air temperature surpasses 2000^o C at the stagnation point. Besides the effects of high temperatures on the mechanical behavior of the structure and on-board devices, it is mandatory to preserve the payload, by using an efficient TPS (Thermal Protection System). Along the year,s ablative materials have been effectively used as TPS of space vehicles. In order to obtain the temperature profile and the heat load, the energy conservation equation has to be solved togetherwith the moving boundary problem concerned to the ablation process. The coupling between the heat transfer processes in the surface and within the layers represent an additional difficulty. A common approach is to consider the heat conduction as one-dimensional, in the normal direction relative to the local surface. However, such hypothesis becomes inaccurate as temperature gradients in the tangential direction, change of material or a great thickness variation occur. In this work, the computational simulation of the ablative process in the vicinity of the stagnation point during the flight of SARA Sub-orbital Platform via an interface tracking method is presented, taking into account the effects of the two-dimensional conduction in the wall layers. Such procedure will allow a more accurate dimensioning of the TPS, contributing for project optimization.*

Keywords*: Ablation, TPS, Aerodynamic heating.*

1. INTRODUCTION

Aerodynamic heating is a consequence of the hypersonic flight within the atmosphere, i.e., below 100 km of altitude. Depending on the velocity and trajectory, the air temperature around the nose top may surpass 2000^o C at the stagnation point (Machado and Pessoa Filho, 2007). In such a situation aerodynamic heating plays a very important role in the vehicle design. Besides the effects of high temperatures on the mechanical behavior of the structure and on-board devices, it is mandatory to preserve the payload, by using an efficient TPS (*Thermal Protection System*). TPS design is a critical aspect of the rocket design, since under dimensioning may result in loss of payload and over dimensioning implies in increasing weight and cost. Along the years, ablative materials have been effectively used as TPS of space vehicles. In these processes the kinetic energy of the rocket is converted into heat, which consumes the TPS through ablation (Rogan and Hurwicz, 1973). It is a complex phenomenon, related with diverse simultaneous physical processes (Silva, 2001).

The coupling between the heat transfer processes in the surface and within the layers represents an additional difficulty. The external heat exchange occurs by convection and radiation, and the heat transfer to the wall (TPS and structure) occurs by conduction. The convective heat transfer coefficient can be estimated through some engineering methods, based on empirical results. In order to obtain the temperature profile and the heat load, the energy conservation equation has to be solved. A common approach is to consider the heat conduction as one-dimensional, in the normal direction relative to the local surface. However, such hypothesis becomes inaccurate as temperature gradients in the tangential direction, change of material or a great thickness variation occur (Mazzoni et al., 2005). The full calculation using a discrete method implies in great computational effort, including the grid generation and the solution of a boundary-moving problem. An alternative to this approach may be the use of the interface tracking method, proposed by Unverdi & Trygvason (1992), which allows obtaining a solution for the coupled ablation-conduction problem in the whole domain, considering the full physical model.

Concerned to hypersonic flight, sub-orbital platforms are a low-cost alternative for micro-gravity research. The SARA sub-orbital platform illustrated in Fig. 1 is being developed by IAE/CTA for this application. Its mass is 250 kg for a payload of about 25 kg. The sub-orbital version is designed to provide 6 minutes of micro-gravity environment. In the future, the orbital version is expected to reach an orbit of 300 km around the Earth during 10 days (Moraes, 1998).

This paper is an extension of the work presented by Machado (2008) and deals with the application of the interface tracking method to the aerodynamic heating analysis of the SARA Sub-orbital Platform. Its structure is built with composite material and aluminum. The TPS design of this vehicle has been done using the simplified approach described above (Mazzoni et al., 2005). Any improvement in this procedure would result in a better vehicle performance or cost reduction. The objective of this work is to present a computational simulation of the ablative process in the vicinity of the stagnation point during the flight of SARA via the interface tracking method, applied to a multilayer region. Such procedure will allow applying more complex models for ablation, taking into account the presence of various ablative and structural layers and providing a more accurate TPS dimensioning.

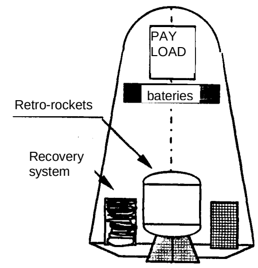


Figure 1. SARA sub-orbital platform and its internal systems.

2. PHYSICAL PROBLEM AND MATHEMATICAL MODEL

2.1. Aerodynamic heating

Figure 2 shows altitude and velocity maps for SARA (Moraes, 1998). It reaches the speed of 9300 km/h while still flying within the earth's atmosphere. For practical purposes, continuous flow regime is assumed to exist for altitudes below 90 km. Beyond 90 km, it is assumed free molecular flow. This altitude is normally taken as the limit of continuous flow for space vehicles, considering their size, speed and atmospheric density. To predict the heat transfer on SARA, it is necessary to know pressure, temperature and velocity fields around the rocket. That can be accomplished by numerically solving the boundary layer equations. However, such a procedure is expensive and time consuming. In the present work a simpler, but reliable, engineering approach is used. The following simplifying assumptions are made:

- Zero angle of attack;
- SARA rotation around its longitudinal axis is neglected;
- Atmospheric air is considered to behave as a calorically and thermally perfect gas (no chemical reactions).

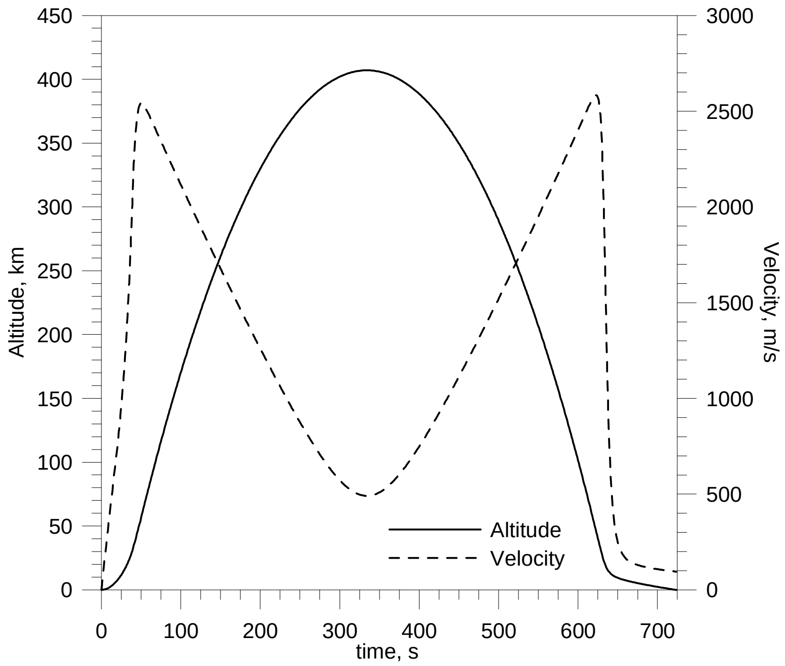


Figure 2. Altitude-Velocity map.

The free stream conditions ahead of the nose cap are those given by v_∞, T_∞, p_∞, corresponding, respectively, to velocity, temperature and pressure. By knowing v_∞ and altitude, as function of time, together with an atmospheric model (U.S. Standard Atmosphere, 1976), it is possible to evaluate the free stream properties. For supersonic flow ($M_\infty > 1$), which begins at 8 s (altitude of 2 km), a detached shock wave appears ahead of the nose. By using the normal shock relationships (Anderson Jr., 1990), it is possible to calculate v_1, T_1 and p_1 after the shock.

The heat flux over the external surface was calculated through the Zoby's method (Zoby et al., 1981; Miranda and Mayall, 2001). Details of the solution can be found in the work of Machado (2008). The convective heat transfer coefficient is calculated along the y-coordinate that is measured along the body´s surface: $y=0$ corresponds to the stagnation point, and R is a geometric parameter shown in Fig. 3, were the red line represents the nose cap surface.

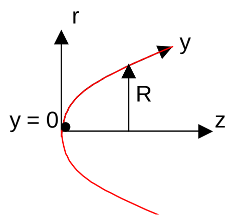


Figure 3. Coordinate system.

It should be pointed out that such a procedure is performed along the payload's surface (following the y-coordinate), for different trajectory times. Therefore, H=H(y,t). The variation of the convective heat transfer coefficient (H) and the recovery temperature (T_{aw} or T_r) at stagnation point are shown in Fig. 4. An energy balance at the surface, accounting the radiative heat transfer, provides the heat absorbed by the wall.

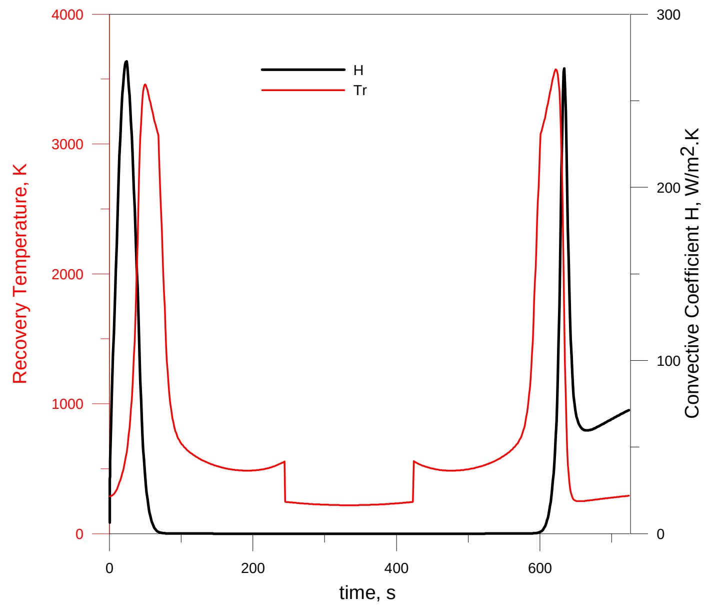


Figure 4. Recovery temperature and convective heat transfer coefficient at stagnation point, during SARA trajectory.

2.2. Heat conduction and ablation

Once the convection heat transfer and the adiabatic wall temperature are known, wall temperature distributions can be obtained. SARA nose cap is covered with a composite material (Si-Phenolic), which works as an ablative TPS. Until the ablation temperature is reached, a transient heat conduction process occurs. Once the TPS surface reaches the ablation temperature, its thickness is reduced; therefore, a transient, coupled conduction moving boundary problem appears. Although ablation in a composite material is a complex phenomenon, involving simultaneously physical and chemical processes, in this work it will be treated as a single-phase change problem, where a representative value for the latent heat of sublimation will be used as the heat of ablation. Such a technique allows for the estimation of the instantaneous position and velocity of the moving boundary corresponding to the surface of the nose cap (in the following sections called as the interface between the solid region and the airflow).

The set of equations used to represent the physical problem is written according to the interface tracking method (Juric, 1996). The nose cap and the surrounding airflow are represented as parts of a continuous domain of calculation. The application of the energy conservation principle to an infinitesimal volume element in the mathematical domain, Fig. 5, leads to a partial differential equation for the temperature, namely:

$$\frac{\partial(\rho.C_p.T)}{\partial t} = \nabla.K\nabla T + Q \tag{1}$$

where K is the thermal conductivity and Q is a source term that accounts the net heat exchange at the boundary:

$$Q = \int_A q\delta(x - x_F)dA \tag{2}$$

where *x* is the position in the coordinate system, and *q* is the source term of energy per unit of surface of the interface:

$$q = \rho L V + H(t,y)\left[T_F(t,x_F) - T_{aw}\right] + \varepsilon\sigma\left[T_F^4(t,x_F) - T_\infty^4\right] \quad (3)$$

where *L* is the heat of ablation, *V* is the interface velocity, T_F is the interface temperature and T_{AW} is the adiabatic wall temperature, also called recovery temperature of the air. One should note that this term might exist in every moving interface. Since the interface between the TPS and the structure is fixed, it yields no source term.

Although the airflow is included in the domain, its effects are implicit in the convection coefficient *H*. As a consequence, this region is considered adiabatic, and the heat capacity and thermal conductivity are assumed to be null. Once ablation temperature is reached, the interface condition becomes:

$$T_F - T_A = 0 \quad (4)$$

3. METHOD OF SOLUTION

The moving boundary problem was solved by the Interface Tracking Method, introduced by Unverdi & Trygvason (1992), and employed by Juric (1996) in the solution of phase change problems. In this method, a fixed uniform Eulerian grid is generated, where the conservation laws are applied over the complete domain. The interface acts as a Lagragean referential, where a moving grid is applied. The instantaneous placement of the interface occurs through the constant remeshing of the moving grid, and each region of the domain is characterized by the Indicator Function, which identifies the properties of the wall and the air around it.

This method allows for the representation of any geometry used in the TPS, and also the characterization of every wall layer (structure plus TPS) separately. It is accomplished without a high increase in the computational cost and does not need any pre-processing (construction of unstructured grid or coordinate transformation). In this work, this method is employed to estimate the ablative performance of the TPS, considering a two-dimensional approach in both, the heat conduction and the moving boundary problem.

The interface is represented as a parametric curve, *R(u)*, which is smooth enough so that one can define the curvature and the normal and tangent vector at every point of the curve. The interface points are interpolated by a Lagrange polynomial, which allows obtaining the geometric parameters and rebuilt the curve grid, keeping the distance *d* between the Lagrangean points within the interval 0.9 < d/h < 1.1, where *h* is the distance between two fixed grid points, as shown in Fig. 5.

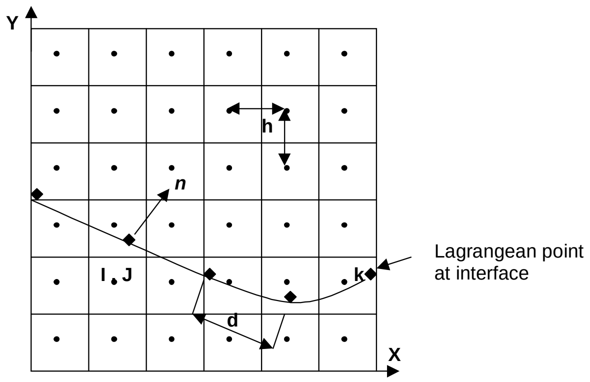


Figure 5. Eulerian and Lagrangean meshes.

The Indicator Function varies from 1 (air) to 0 (solid), and is numerically constructed using the interface curve to determine a source term ***G(x)***. The jump across the interface is distributed over the fixed grid points, yielding a gradient field in the mesh:

$$G(x) = \nabla I = \int_A n\delta(x - x_f)\,dA \quad (5)$$

which should be zero, except over the interface, as represented by the Dirac delta function, δ. However, such a representation is not convenient for a discrete number of points. The Distribution Function is used to represent the interface jump. Such a function is similar to a Gaussian distribution function and its value depends on the distance $|\boldsymbol{x}_{ij} - \boldsymbol{x}_k|$ between the Lagrangean and Eulerian points:

$$D_{ij}(x_k) = \frac{f[(x_k - x_i)/h].f[(y_k - y_j)/h]}{h^2} \tag{6}$$

where D_{ij} is the Distribution Function for a point *k* in the Lagrangian mesh with respect to a Eulerian point. One should note that increasing *h*, the interface becomes thicker. The function *f* is the probability distribution related to the distance *h* as:

$$f(x) = \begin{cases} f_1(x) & \text{if } |x| \le 1 \\ 1/2 - f_1(2-|x|) & \text{if } 1 < |x| < 2 \\ 0 & \text{if } |x| \ge 2 \end{cases} \tag{7.a}$$

$$f_1(x) = \frac{3 - 2.|x| + \sqrt{1 + 4.|x| - 4x^2}}{8} \tag{7.b}$$

The divergence of the gradient field is found by derivation of Poison's equation:

$$\nabla^2 I = \nabla.G \tag{8}$$

Despite being considered constant in each phase, the properties inside the domain must be treated as variable in the formulation. A generic property ϕ (ρ, μ, *Cp* or *K*) is expressed as:

$$\phi((\mathbf{x}) = \phi_l + (\phi_v - \phi_l)\, I(\mathbf{x},t) \tag{9}$$

The coupling between the moving mesh and the fixed grid is done at each time step, through the Distribution Function, that represents the source terms in the balance equations and interpolate the fields with infinitesimal discontinuities into a finite thick region at the interface.

The initial interface shape, $\boldsymbol{R}(u)$, is first specified and then the Indicator Function is constructed. From the initial conditions, the property and temperature fields are determined. Out of the ablative period, the interface temperature keeps bellow the ablation temperature, and the energy equation is solved as a pure heat conduction problem, via the Finite Volume Method, employing an explicit time marching schedule.

As the interface reaches the ablation temperature at a given point, an iterative process starts up, in order to determine the interface velocity at each time step, which must satisfy the temperature condition, Eq.(4), at that interface point. The process goes on until the point temperature is equal to ablation temperature. The steps to be followed are:

1. Using the current value of $\boldsymbol{V}$, the interface points are transported to a new position, calculated explicitly through the equation $\boldsymbol{V}^n = (d\boldsymbol{x}_f/dt).\boldsymbol{n}$, where $\boldsymbol{n}$ is normal unitary vector;
2. Density and specific heat are calculated at the new interface position;
3. $\boldsymbol{V}^{n+1}$ is estimated via Newton iterations, using a numerical relaxation schedule.
4. Heat flux *q* crossing the interface is calculated through Eq. (3) and distributed into the fixed grid;
5. According to the boundary conditions, energy equation, Eq. (1), is used to obtain the temperature at time step $n+1$;
6. Temperature is interpolated to find T_F at the interface;
7. The jump condition is tested and if it is lower than the reached tolerance, the fields of viscosity and conductivity are updated for the new position, and one step in time is advanced. If that is not the case, a new estimate for $\boldsymbol{V}^{n+1}$ is calculated and the process returns to step 5.

The convergence criterion used in step 7 is the residual in Eq. (4). Once it has reached the desired tolerance, convergence for interface velocity is assumed. Otherwise, the velocity is corrected via Newton Iterations, given as:

$$V^{n+1} = V^n - \omega.R(T) \tag{10}$$

where ω is a constant and $R(T)$ is the residual for the temperature jump condition at the interface. Iterations are repeated until $R(T)$ in every point become smaller than the prescribed tolerance. The optimum value for ω is found by trial-and-error, at the beginning of the calculation. The method was applied to a single phase change problem, and its solution was compared with the analytical solution (Ruperti, 1991), resulting in an good agreement.

In the case of more than one interface, an Indicator Function is created for each interface, in order to characterize every region concerned to the interfaces individually. Therefore, in a region *i*, a generic property is estimated as:

$$\phi = \sum_{i=1}^{NFC} \phi_i \, Ig_i \tag{11}$$

where *NFC* is the number of interfaces. Ig_i is the Global Indicator Function for any *i* region, obtained from the Indicator Function of each interface. It is given as:

$$Ig_i = I_{i-1} - I_i \tag{12.a}$$

$$I_0 = 1 ; I_{NFC} = 0 \tag{12.b}$$

If there are more than one moving interface, the source term *Q* has to be extracted from a modified form of Eq.(2):

$$Q = \sum_{i=1}^{NFC} \int_A q_i \delta_i (x - x_{Fi}) dA_i \tag{13}$$

The convergence criterion and velocity correction are the same as that for the case of one interface, but they are extended to all interfaces at each time step.

4. RESULTS

The results were obtained for the region near the stagnation point of SARA, Fig. 6, which corresponds to a circular sector with radius of 280 mm. Note that the Y(capitol)-coordinate has a different meaning of that shown in Fig. 3. Since the flight is considered with zero angle of attack, the problem is considered to be axy-symmetric, and only the half of that region has to be simulated. A 32 x 5 points grid over a domain of 32 mm x 5 mm was employed to simulate the heat transfer and moving boundary problem, with a tolerance of 10^{-6} for the residual in Eq.(4). A resulting 10 points Lagrangean mesh was obtained for the external interface and a 10 points mesh for the interface between the TPS and aluminium. Properties considered for Si-Phenolic composite were (Gregori et al.,2008): Cp = 1256 J/kg.K, ρ = 1730 kg/m^3, K = 0.485 W/m.K, L = 12 MJ/kg, T_A = 538^o C, and ε = 0.8. For the aluminum (Da Costa et al., 1996): Cp = 500 J/kg.K, ρ = 8000 kg/m^3, K = 16.2 W/m. As initial condition, temperature in the whole domain was taken as T_0 = 27^o C.

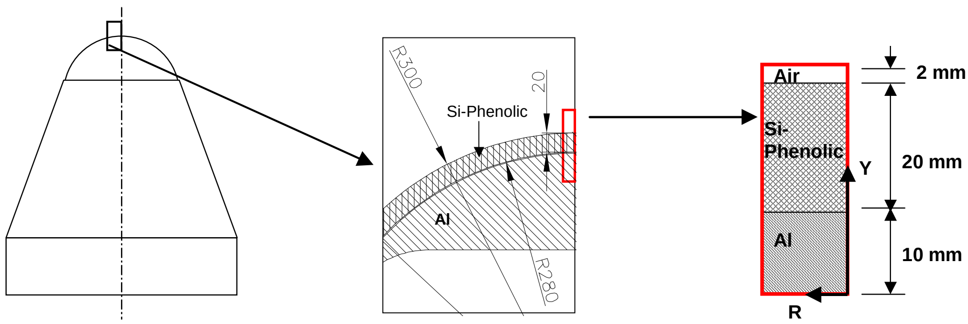
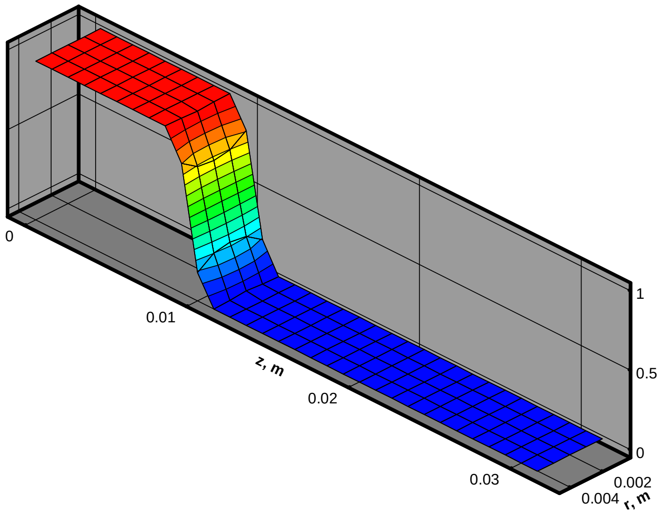
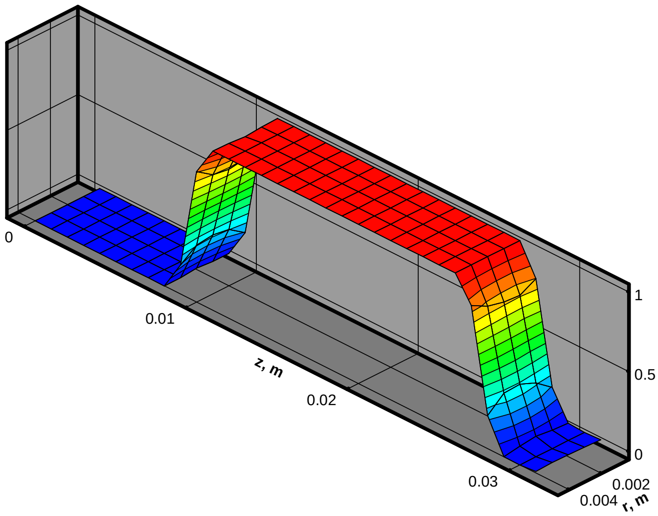


Figure 6. Domain of calculation, layers and dimensions.

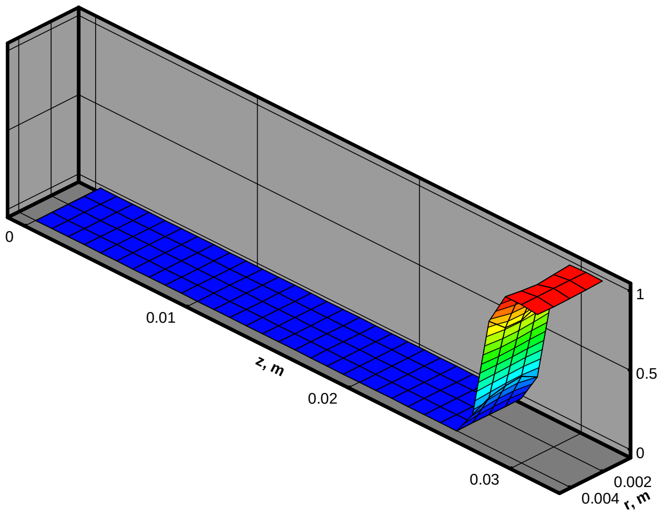
Figure 7 shows the Global Indicator Function distribution at $t = 0$ for each layer. In Fig. 8.a-c, the red region corresponds to the aluminum, the TPS and the surrounding air, respectively. The colored wall between each two regions represents an interface. Since rough meshes were used, the interfaces are not exactly represented as a discontinuity, but have a discrete thickness, which reduces as more points are added to the grid.



(a) Structure(Al)



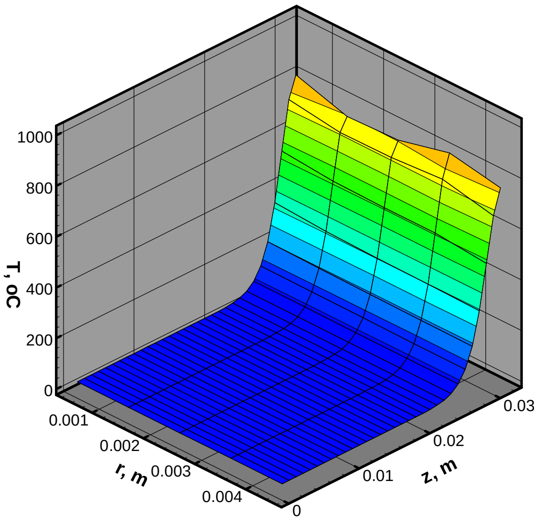
(b) TPS (Si-Phenolic)



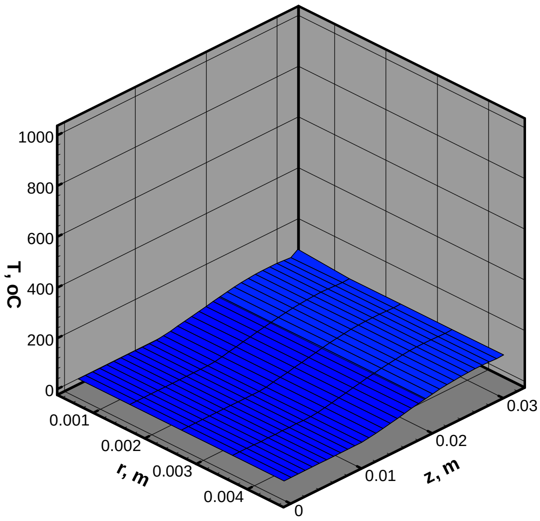
(c) Air

Figure 7. Global Indicator Function for each layer.

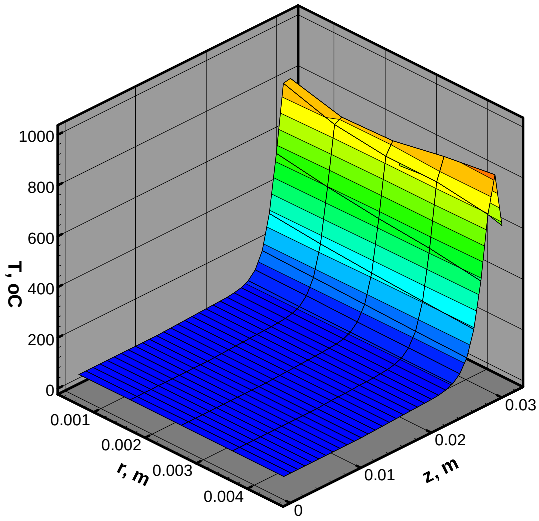
Figure 8 shows the temperature distribution in different times. The temperature peak in the interface corresponds to the ablation temperature when the interface moves. At the final time, when the airflow is cooling the surface, the interface becomes a heat sink, and the peak transforms into a valley. One can observe that the region of aluminum keeps at constant temperature, due to its high thermal conductivity. The heat transfer between the air and TPS external surface is implicit in the film coefficient.



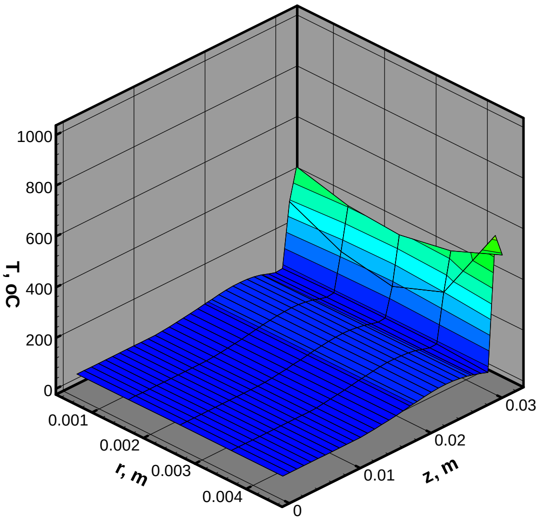
(a) Ascendant period (45 s)



(b) After ascendant period (270 s)



(c) Ablation at reentry (630 s)



(d) Final time (724 s)

Figure 8. Temperature distribution with the time.

Figure 9 shows the interface position with the time, after two periods of ablation (ascendant and reentry). According to the results, the ablation is stronger at the vicinity of the stagnation point (z = 0). Closer to that point, there will be a larger consumption of material. Zero heat flux was assumed for all sides as boundary condition. As a consequence, the actual heat transfer process is not appropriately represented, since the heat conduction between the domain and the rest of the nose structure was not accounted.

The two-dimensional results obtained by the Interface Tracking Method were compared to those obtained by the one-dimensional Lagrangean solution. Figure 10 shows the internal and external surface temperatures, both at $r = 0$, over the symmetry axis (at $z = 30\ mm$ and $z = 0$, respectively), that correspond to a line crossing the stagnation point. Two temperature peaks are observed, corresponding to the ablation temperature (538^o C), during the ascendant and reentry periods of flight. Between these periods, there is a temperature decrease caused by radiative losses taking place at the external surface. During this time interval there is no heat transfer by convection, since $H = 0$, according to Fig. 4. The results present good agreement between the two methods.

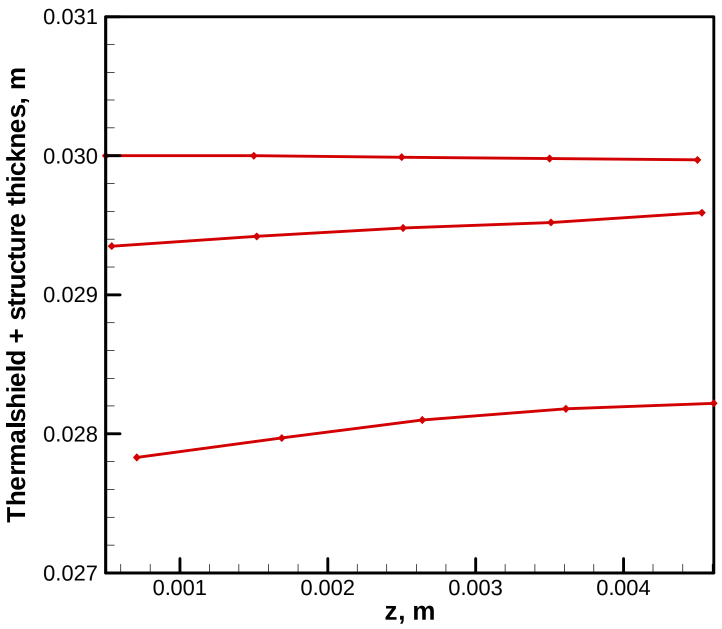


Figure 9. Interface position with time.

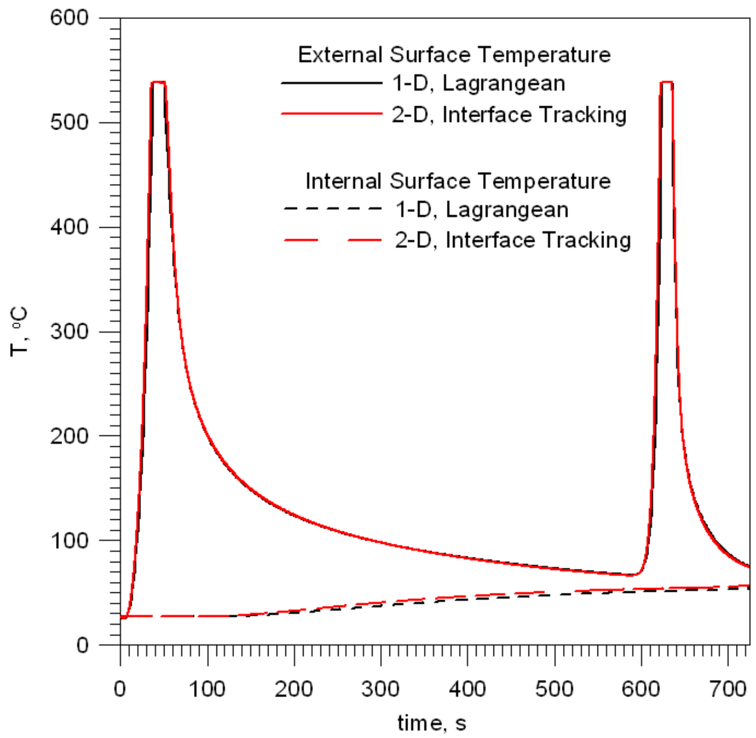


Figure 10. Temperatures at the stagnation point.

5. CONCLUSION

In this work, the two-dimensional transient aerodynamic heating and ablation processes in the region of the nose cap of SARA Sub-orbital Platform was simulated through an interface tracking method, considering the presence of two layers: the TPS and the stainless steel structure. Preliminary results demonstrated that the method is able to capture the temperature peak and to represent the ablation process as a moving boundary problem, in the presence of more than a single layer. Results shall be extracted for more refined meshes, in order to check the method's accuracy.

This analysis can be extended to more regions of the rocket, more layers and other shapes. A more realistic physical model for the ablation in the composite material may now replace the simple one used in this work. The inclusion of the flow field effects, like injection of mass due to sublimation, shall also be incorporated into the simulation.

6. ACKNOWLEDGEMENTS

The authors would like to thank the ***Conselho Nacional de Desenvolvimento Científico e Tecnologico*** (**CNPq**), the Brazilian Federal Agency for Science and Technology, for the financial support during this work.

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