SIMULATION OF ABLATION WITH TWO MOVING FRONTS IN A ROCKET TPS VIA AN INTERFACE TRACKING METHOD

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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° 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 years 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, along 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 VSB-30 sounding rocket via an interface tracking method is presented, taking into account the effects of the two-dimensional conduction in the wall layers. The ablative model considers the presence of two simultaneous moving fronts, the pyroyisis and char fronts. Such procedure will allow a more accurate dimensioning of the TPS, contributing for project optimization.*

Keywords*: Simulation, Ablation, Moving boundary, TPS, Aerodynamic heating.*

1. INTRODUCTION

Sounding rockets have been extensively used to study the upper layers of terrestrial atmosphere and to provide a micro-gravity environment. IAE has designed, built and launched dozens of such rockets in the last four decades, some of then developed for use by other countries. This is the case of VSB-30, a two-stage sounding rocket developed for use by the DLR (*Deutsches Zentrum für Luft- und Raumfahrt* – German Space Agency). Figure 1 shows a schematic view of VSB-30. The vehicle has a length of 13 m and a diameter of 0.6 m. It is equipped with two solid propellant engines, named S31 and S30 that burns during 15 and 30 seconds, respectively, allowing the payload to reach a maximum altitude of about 280 km, what provides 6 minutes of micro-gravity during flight.

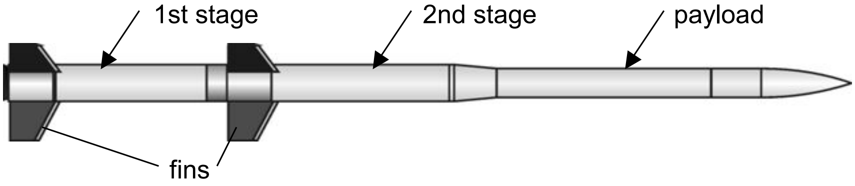


Figure 1. VSB-30 sounding rocket.

As a result of high velocities, the aerodynamic heating appears as an important problem to be considered in the VSB-30 dimensioning. The problem is more intense near the stagnation point. The air compression yields a strong normal shock front around that region, where the air temperature can surpass 2100° C. As a consequence, there is a high heat flux transferred to the surface. Indeed, it is mandatory to obtain an accurate evaluation of this heat flux and the temperatures reached, in order to correct dimensioning the thermal protection.

2. PHYSICAL PROBLEM, MATHEMATICAL MODEL AND METHOD OF SOLUTION

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, H, 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. 2, were the red line represents the nose cap surface.

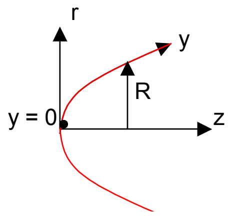


Figure 2. Coordinate system.

Once the convection heat transfer H=H(y,t) and the adiabatic wall temperature (T_{aw} or T_r) are known, wall temperature distributions can be obtained. VSB-30 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.

The set of equations used to represent the physical problem is written according to the interface tracking method (Juric, 1996), and solved through the Fiite Volume Method (Maliska, 1995). 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 layer 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.

3. RESULTS AND DISCUSSION

The results were obtained for the region near the stagnation point of VSB-30, Fig. 3, which corresponds to a circular semi-sphere with radius of 10 mm. Note that the Y(upper case)-coordinate has a different meaning of that shown in Fig. 2 (y). The first is used in the domain of simulation, and the second is used for estimating the aerodynamic heat exchange, which is calculated tangentially to the surface. 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 using a two-dimensional treatment. A 20 x 20 points grid over a domain of 12 mm x 12 mm was employed to simulate the heat transfer and moving boundary problem, with a tolerance of 10^{-6} for the residual. A resulting 26 points Lagrangean mesh was obtained for the interface used to represent the external surface.

Results were compared with the one front model (Machado, 2008), using the same numerical parameters. In that model, a one-dimensional Lagragean approach was used, neglecting the heat conduction in the y-coordinate and employing a moving grid in the normal direction to the surface, in order to follow the interface movement. Ablation was considered a pure phase change problem with only one moving front. Due to the difference among the models, the composite material (Si-phenoic resin) was characterized in a different way, with representative values for ablation temperature and heat of ablation. The properties of resin employed in each model have to be extracted from different literature sources.

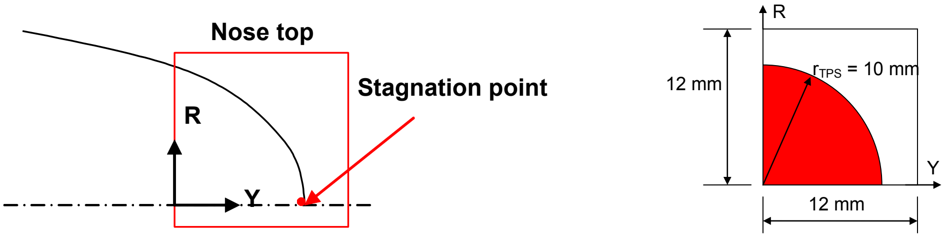


Figure 3. Domain of calculation, regions (TPS in red) and dimensions.

Figure 4 shows the characterization of every region in the domain through the global indicator function, at $t = 0$. In this case, the two interfaces correspondent to the pyrolisis and carbonization fronts are at the same initial position, over the external surface, since the ablative process did not start yet. The colored region corresponds to the interfaces and do not represent exactly the discontinuity, presenting a slope and a finite thickness (about 0.6 mm). This thickness can be reduced through the increase of the number of grid points.

Figure 5 shows the temperature distribution at various moments. Temperature peaks occur in the external surface, in direct contact with the heated air, during the ascension, at 35 seconds, Fig. 5.a, and at 500 seconds during the reentry, Fig. 5.b. One can observe that the temperature of fusion of the char is not reached. Indeed, this surface does not move, since there is no phase change, and only the pyrolisis front moves when the pyrolisis temperature of the resin is reached. The region correspondent to the air does not present relevant temperature changes, once it is considered to be adiabatic with zero thermal capacity.

The results were compared to those obtained through the one layer model, where ablation is treated as single-phase change process. Figure 6.a shows temperature of internal and external surfaces, both at *R = 0*, what corresponds to the stagnation point. The two temperature peaks correspond to the ascension and reentry of the vehicle in the atmosphere, including a period between then where a cooling occurs, due the heat losses by radiation, in the absence of convection.

It is noticeable that the ablative process begins when the external surface reaches the pyrolisis temperature, and the ablation front starts to move. The temperature of fusion of the char is not reached at both peaks, even in the points of maximum temperature. Due the presence of the char layer in the two fronts model, the temperatures reached in the internal surfaces are lower, what indicates that this layer works as a thermal barrier for the virgin material of the TPS.

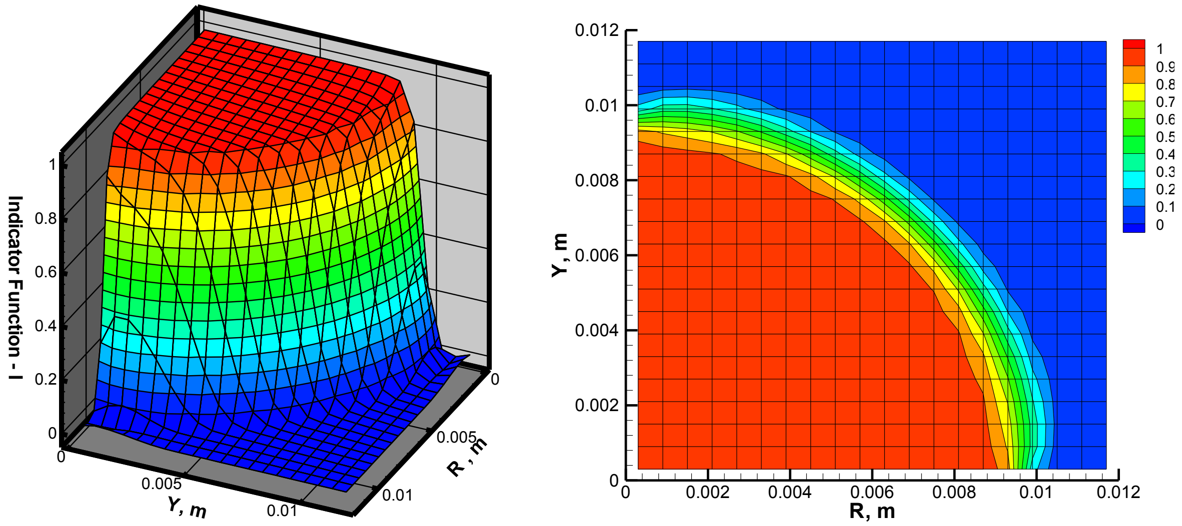
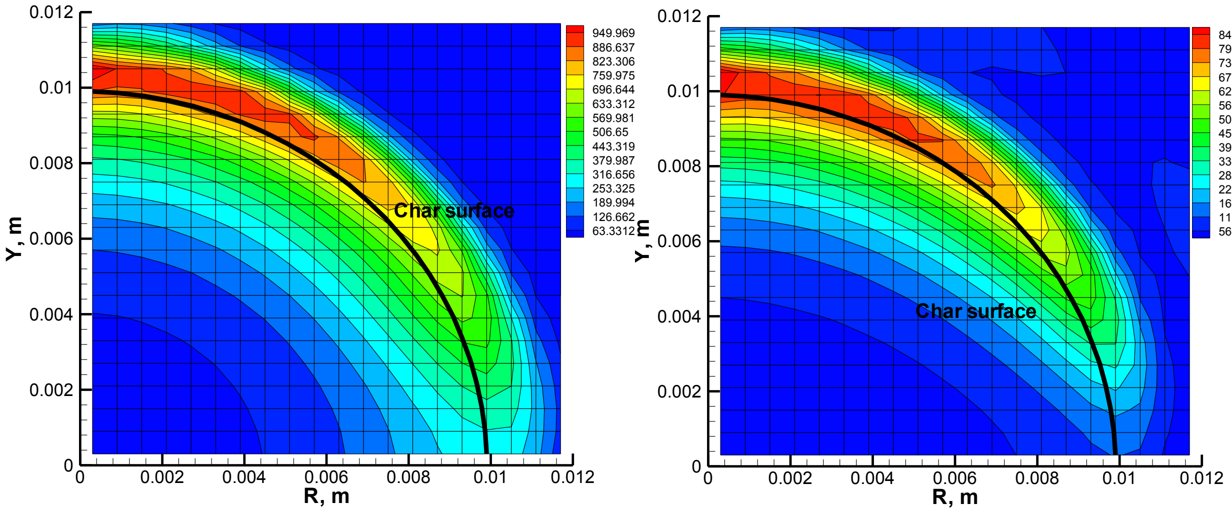


Figure 4. Global Indicator Function for every region: TPS in red and air in blue.

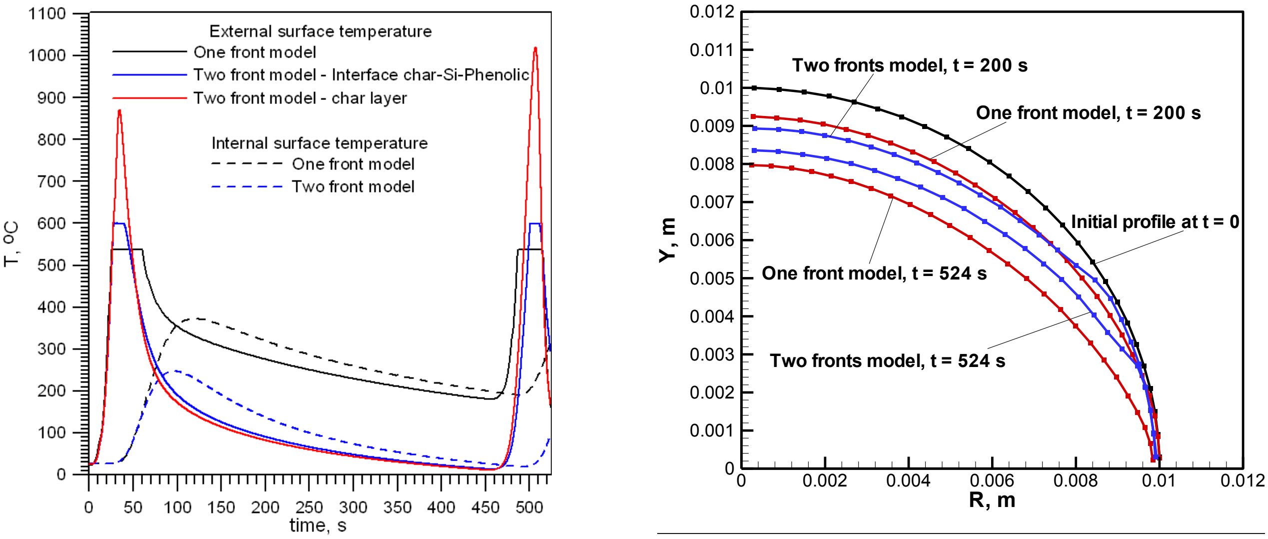


(a) t = 35 s ***(b) t = 500 s***

Figure 5. Global temperature distribution at various moments.

Figure 6.b shows the interface position with the time, after the two ablation periods (ascension and reentry). According to the results, the ablation is more intense closer the stagnation point for both models. However, the two-fronts model indicates a lower material consumption than the one layer model.

Preliminary results demonstrated that the method is able to capture the temperature peaks and to represent the ablation process as a moving boundary problem, in the presence of more than a single moving front, what allows representing diverse physical simultaneous processes. When compared with the one front model, it results in lower temperatures out of the periods of heating, shorter periods of ablation and less consumption of protective material. This analysis can be extended to more regions of the rocket, more layers and other shapes, including more moving fronts, if it is necessary.



(a) Temperature at stagnation point

(b) Interface position

Figure 6. Comparison between results for the ablation models.

4. ACKNOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE

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