In Depth Analysis of AVCOAT TPS Response to a Reentry Flow

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Abstract. Modeling of the high altitude portion of reentry vehicle trajectories with DSMC or statistical BGK solvers requires accurate evaluation of the boundary conditions at the ablating TPS surface. Presented in this article is a model which takes into account the complex ablation physics including the production of pyrolysis gases, and chemistry at the TPS surface. Since the ablation process is time dependent the modeling of the material response to the high energy reentry flow starts with the solution of the rarefied flow over the vehicle and then loosely couples with the material response. The objective of the present work is to carry out conjugate thermal analysis by weakly coupling a flow solver to a material thermal response model. The latter model solves the one dimensional heat conduction equation accounting for the pyrolysis process that takes place in the reaction zone of an ablative thermal protection system (TPS) material. An estimate of the temperature range within which the pyrolysis reaction (decomposition and volatilization) takes place is obtained from Ref. [1]. The pyrolysis reaction results in the formation of char and the release of gases through the porous charred material. These gases remove additional amount of heat as they pass through the material, thus cooling the material (the process known as transpiration cooling). In the present work, we incorporate the transpiration cooling model in the material thermal response code in addition to the pyrolysis model. The flow in the boundary layer and in the vicinity of the TPS material is in the transitional flow regime. Therefore, we use a previously validated statistical BGK method [2] to model the flow physics in the vicinity of the micro-cracks, since the BGK method allows simulations of flow at pressures higher than can be computed using DSMC.

THERMAL RESPONSE MODEL OF AN ABLATIVE MATERIAL

The problem of protecting a space-capsule from the high temperature chemically reacting environment during a reentry mission has resulted in the development and successful use of ablative TPS materials. The main features of an ablative TPS material are illustrated in Fig. 1. Most ablative TPS materials use reinforced composites employing organic resins as binders. The surface temperature of the ablative material rises due to the incident heat flux, with its rate of increase depending on the magnitude of heat flux and the thermophysical properties of the material such as the specific heat and thermal conductivity. The low thermal conductivity of the ablative material effectively concentrates the absorbed heat in the surface region, thereby protecting the inner layers of TPS from significant temperature increases. As the surface material reaches sufficiently high temperature, the resin undergoes the endothermic processes of decomposition and sublimation, known as pyrolysis. The process of pyrolysis produces gaseous products that percolate toward the heated surface and are injected into the boundary layer. The pyrolysis of the resin also results in the formation of a carbonaceous residue that is deposited on the carbon or silica fibers. The resulting surface material is called char. The pyrolysis process is endothermic in nature, thus absorbing a considerable amount of heat as the material ablates. In addition to that, the pyrolysis gases, which are produced due to the decomposition of the resin, are heated as they percolate toward the surface thus transferring some energy from the solid to the gas, also referred to as transpiration cooling. The pyrolysis gases also affect the thermochemical phenomena taking place at the TPS surface, i.e., the countercurrent flow of the pyrolysis gases blowing into the boundary layer alters its gas properties and prevents the shock layer gases from reaching the surface. This process again results in a reduced convective heat flux on the surface.

In addition to this, the surface recession occurs at the TPS surface partially due to vaporization, sublimation and primarily due to the chemical reactions between the surface material and boundary layer species such as atomic oxygen and nitrogen resulting in the consumption of the surface material by the processes of oxidation and nitridation. These processes remove the surface layer and expose fresh ablative material to the hot boundary layer gases. The phenomenon explained above continues until no more ablative material remains. Presently, the substances that are used most extensively as ablators are composite, reinforced char forming organic polymers.

The objective of the present work is to carry out a conjugate thermal analysis by weakly coupling the flow solver

to the material thermal response model, a one dimensional heat conduction equation. The model incorporates the physical processes taking place in the reaction zone of the ablative material, viz., decomposition or pyrolysis and the production of pyrolysis gases affecting the surface chemistry. We make use of the experimental observations found in the literature [1, 3, 4, 5, 6] to construct a realistic material thermal response model, which when coupled with an accurate flow solver describes the overall flow physics fairly accurately at moderate computational expense. When coupled with a statistical DSMC flow solver, this model can predict the TPS response to the reentry flow impact at the high and moderate altitudes, and since the technique can also be coupled with the traditional CFD solvers, the TPS behavior along the reentry entire trajectory can be studied.

The governing heat conduction equation for the rate of change of temperature of a TPS material is given as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(\kappa(T)\frac{\partial T}{\partial y}\right) - \dot{Q}_P - \dot{Q}_T \tag{1}$$

with the following boundary conditions:

$$\kappa(T)\frac{\partial T}{\partial y} = \dot{Q}_{conv} \tag{2}$$

$$\frac{\partial T}{\partial y}\bigg|_{backend} = 0 \tag{3}$$

where κ is the thermal conductivity, C_p is the specific heat capacity and ρ is the density of the TPS material. All of these properties vary with temperature since the material is under heat load. The TPS material chosen for the thermal response study is AVCO 5026-H/CG [1] and in the present work an estimate of its thermo-physical properties is obtained from the Ref. [1]. Within the given temperature range, the thermophysical properties are assumed to vary linearly for both virgin and char materials. During the process of pyrolysis, the material thermophysical properties are obtained by weighted average of virgin and char properties and is given as follows:

$$\xi = (1-f)\cdot\xi_v + f\cdot\xi_c \tag{4}$$

where ξ_v and ξ_c are virgin and char properties, and the factor f represents the contribution of the char part. As the pyrolysis progresses, the virgin material changes to char form and correspondingly f changes from zero to unity. The virgin and char material densities are obtained from the Ref. [1] and are 512 and 320 kg/m^3 respectively. The other important data obtained from Ref. [1] are the start and end temperatures of pyrolysis, which are 588.88 and 811.11 K respectively. During the pyrolysis process, the factor f is determined by assuming a linear variation between the start and end temperatures of pyrolysis:

$$f = \frac{T - T_s}{T_e - T_s} \tag{5}$$

where T is the current temperature, T_s and T_e provide temperature interval in which pyrolysis occurs.

In Eq. 1, the first term on the RHS represents the net heat conducted per unit volume per unit time and depends upon the thermal conductivity, κ, of the material. The second term in Eq. 1, $\dot{Q}_P$, represents the effect of pyrolysis in units of W/m^3. Likewise, the third term, $\dot{Q}_T$ in Eq. 1 shows the effect of transpiration cooling on the thermal response of ablative material in units of W/m^3. The heat transferred per unit area and unit time from the conductive layer of the fluid to the TPS exposed surface is called the convective heat flux, $\dot{Q}_{conv}$. The convective heat load on the TPS surface depends on the trajectory, which in the present work is obtained from Ref. [7] and is shown in Figs. 2 (A) and (B). It is worth mentioning that the trajectory shown is for an atmospheric reentry vehicle (ARV) and is assumed to be close to that of CEV. Thus the thermal response of the TPS material depends strongly on the quality of the flow-field solution obtained by the flow solver (kinetic and/or continuum). The thermal response of the material in turn affects the flow field by the injection of pyrolysis gases into the boundary layer and change of geometry due to the surface recession. In addition to this, the flow-field also changes dynamically along the trajectory. In the present work, the thermal response model is weakly coupled to the flow solver by intermittently exchanging the data after every few seconds.

Pyrolysis Model and Transpiration Cooling

As is explained above, the ablative TPS material is a composite material with organic resin used as a binder. Pyrolysis occurs when the local temperature increases beyond a certain limit [1]. After the limit is reached, the

material starts decomposing due to the endothermic processes of depolymerization and ablation. These processes result in material loss and the eventual formation of porous char with considerably lower density as compared to the virgin material. The heat removed per unit mass loss of virgin material due to pyrolysis is referred to as the heat of pyrolysis, H_P, and is given in units of J/kg.

In the present work, an estimate of the heat of pyrolysis, H_P, is obtained from the experimental work of Williams and Donald [1]. The value of heat of pyrolysis is 418680.0 kJ/kg for the chosen material AVCO 5026-H/CG. The rate of heat absorbtion due to pyrolysis per unit volume, represented by $\dot{Q}_P$, is given as follows:

$$\dot{Q}_P = H_P \dot{\rho} \tag{6}$$

where $\dot{\rho}$ is the rate of change of material density due to pyrolysis in the given time interval.

Transpiration cooling occurs when the relatively cold pyrolysis gas, produced from the sub-surface TPS layers, removes a finite amount of heat from the hot porous char while percolating to the heated surface. The specific heat capacity of the gas, C_{pg}, is obtained from Ref. [1] and is 2093.4 J/kg-K. The rate of heat absorbed per unit volume in the process of transpiration cooling, $\dot{Q}_T$, is given as follows:

$$\dot{Q}_T = \dot{\rho} \cdot C_{pg} \cdot (T - T_g) \tag{7}$$

where T_g is the temperature of the gas absorbing heat from the porous char at a temperature T, and $\dot{\rho}$ is the rate of change of material density due to pyrolysis.

RESULTS AND DISCUSSION

The model was discretized and solved for the AVCOAT based TPS exposed to the reentry flow conditions at high and moderate altitudes The impinging heat flux values were obtained from the DSMC solutions at three altitudes. After each of the DSMC runs the production of the pyrolysis gases was computed and the blowing rate values at the TPS surface were updated for the next DSMC run, thus making the flow and the material response solutions a loosely coupled technique. The heat flux is obtained from the point of reentry ($\sim$120 km) to an altitude of 81 km over a time span of $\sim$120 s with three DSMC solutions. Figure 2 shows a comparison of the flow solutions over the Crew Exploration Vehicle (CEV) shaped module at altitudes 95 and 81 km. As can be seen in parts C and D of the figure, where the temperature and X component velocity comparisons are presented, the flow configuration changes significantly with shock layer sharpening as the vehicle descents into the higher density atmosphere. The value of the heat flux at 120 km is assumed to be zero, while the computed values are: 1.5×10^4 W/m^2 at an altitude of 95 km, 3.95×10^4 W/m^2 at 85 km and 4.75×10^4 W/m^2 at 81 km respectively. Figure 3 (A) shows the front and back end temperature variation with time for the ablative AVCO 5026-H/CG material. The temperature distribution across the ablative TPS material is shown in Fig. 3 (B). It can be seen that there exists a large temperature gradient across the TPS varying from $\sim$1047 K at the front end to 273 K at the back end of the material.

One more objective of this work was to estimate the effectiveness of the active protection mechanisms such as pyrolysis regarding the reduction of the heat flux into the TPS. Pyrolysis gases effect the surface heat flux in two ways. First, the pyrolysis gases remove heat from the porous char layer by transpiration cooling. Second, they reduce the heating by decreasing the boundary layer temperature. Pyrolysis gases also alter the chemical ablation rates by blocking the active atomic species such as oxygen and nitrogen from reaching the wall.

Fig. 4 (A) presents computational results for the pyrolysis gas mass flow rate $\dot{m}$, along the vehicle trajectory. The computation of the rate is based on the rate of change of material density by the following equation.

$$\dot{m} = \sum_{i=0}^{N} \delta V_i \dot{\rho}_i \tag{8}$$

where δV_i is the volume of the ith layer, which for the one dimensional calculations is the same as the layer thickness δy_i for unit surface area and N is the number of layers (50 in these calculations). Hence mass flow rate is given in units of kg/m^2/s. It is worth mentioning that the maximum flow blowing rate reaches a value of 0.013 kg/m^2/s which is of the same order as given in the Ref. [5].

Since the pyrolysis process depends on the material temperature it is instructive to compare, the variation of pyrolysis gas flow rate with the surface temperature, as shown in Fig. 4 (B). It can be seen that until a surface

temperature of 588.88 K is reached, pyrolysis does not take place. Subsequently, the pyrolysis gas flow rate rises to the maximum magnitude of 0.013 kg/m²/s. Figure 5 (A) shows the rate of transpiration cooling brought about by the pyrolysis gases as they percolate to the heated TPS surface. The presented instantaneous rate of transpiration cooling is obtained at the topmost layer of the modeled TPS. It changes with altitude along with the pyrolysis gases flow rate, therefore the transpiration cooling rate and pyrolysis flow rate can be related as presented in Figure 5 (A). The rate is presented in units of W/m² by multiplying $\dot{Q}_T$ (rate of transpiration cooling per unit volume) with the layer thickness δy to give the rate the same units as the units of convective flux at the TPS surface.

Finally we solved an additional case at an altitude of 81 km assuming that there was no pyrolysis and heat transfer to the TPS, however chemical ablation was allowed. The heat flux into the TPS at the stagnation point in this case was $7.46x10^5$ as compared to $5.28x10^5 \frac{J}{m^2 s}$ with the full 1D TPS material model applied. The heat flux comparison along the vehicle for the cases with and without pyrolysis is presented in Figure 5 (B). Chemical ablation was considered in both simulations. A significant reduction in the heat flux level at 81 km shows the degree of effectiveness of the sacrificial ablation process.

ACKNOWLEDGMENTS

REFERENCES

1. S. Williams, and M. Donald, *Technical Report NASA RP-1289, NASA, Washington DC, USA* (1992).
2. R. Kumar, E. Titov, and D. Levin, *accepted by the AIAA Journal for publication* (2010).
3. M. Ladacki, J. Hamilton, and S. Cohz, *AIAA Journal* **4**, 1798–1802 (1966).
4. *NASA Ames Thermal Protective Materials and System Branch, TPSX, http://tpsx.arc.nasa.gov* (2005).
5. C. O. Jhonston, P. A. Gnoffo, and A. Mazaheri, *AIAA-2009-4318, 41st AIAA Thermophysics Conference 22-25 June 2009, San Antonio, Texas* (2009).
6. P. Subrahmanyam, *International Journal of Aerospace Engineering* pp. 1–21 (2009).
7. E. Kaya, *Department of The Air Force Air University, Air Force Institute of Technology* (2008).
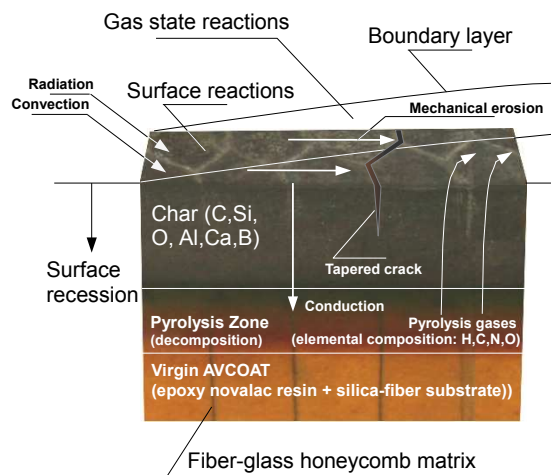
FIGURE 1. Illustration of various processes taking place in the shown zones in the ablative TPS material AVCO 5026-H/CG.
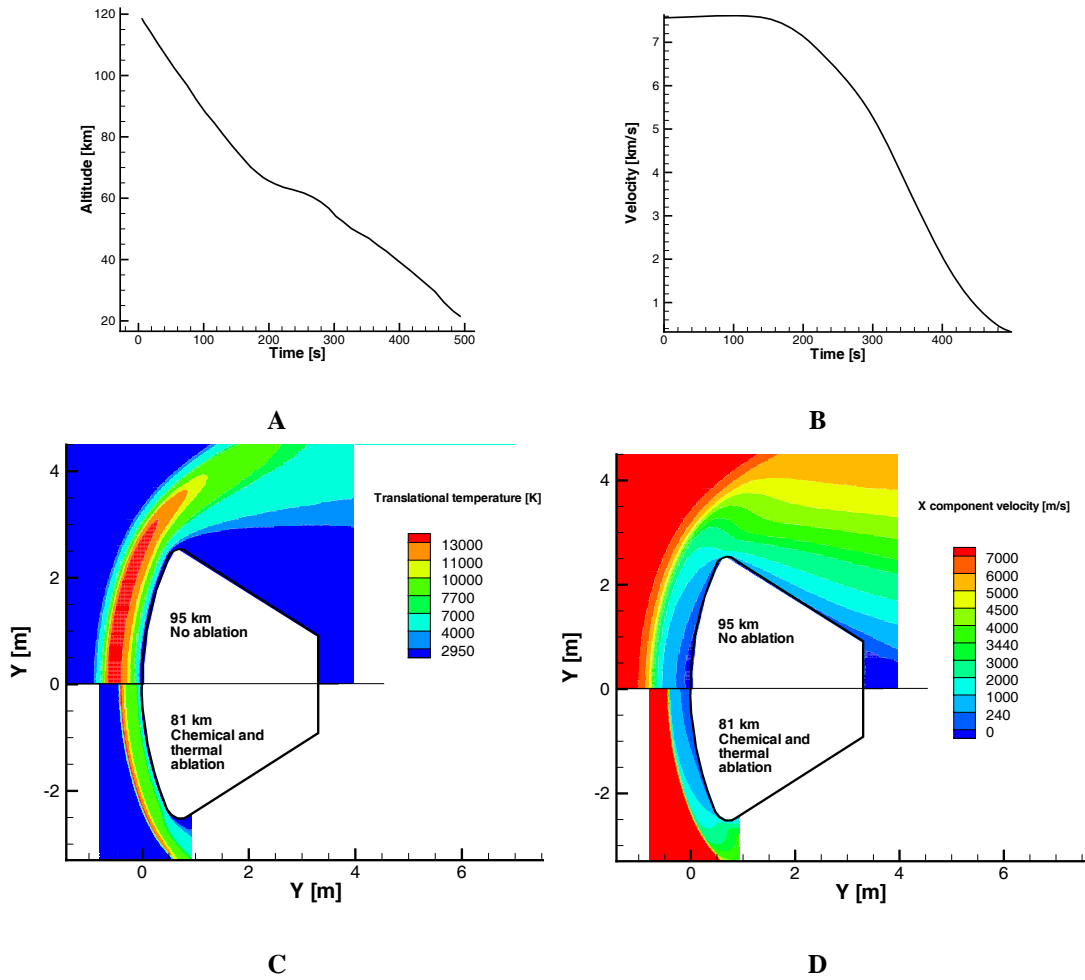
FIGURE 2. A: Altitude vs time trajectory data for Atmospheric Reentry Vehicle (ARV), B: Velocity vs time trajectory data for Atmospheric Reentry Vehicle (ARV). Flow parameters at 95 and 81 km C: Translational temperature contours, D: X component velocity contours
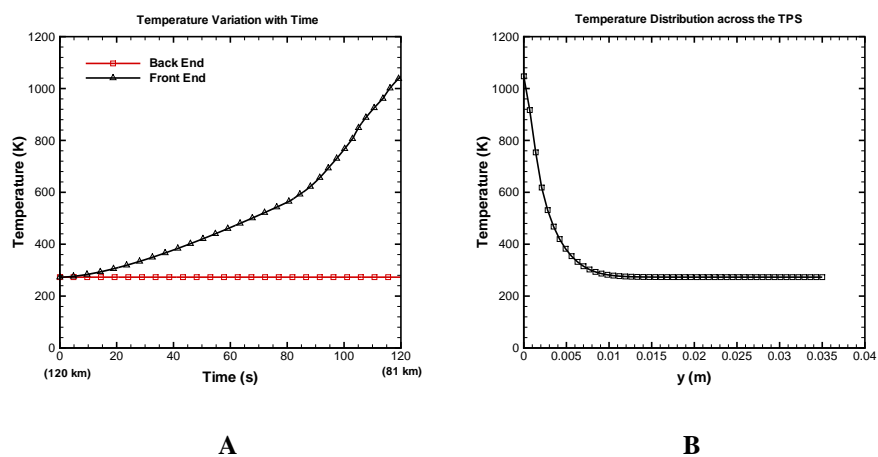
FIGURE 3. A: Thermal response of the ablative TPS material, AVCO 5026-H/CG, along the trajectory. Temperature values at the front (exposed) and back end of the TPS is shown, B: Temperature distribution across the ablative TPS material, AVCO 5026-H/CG.
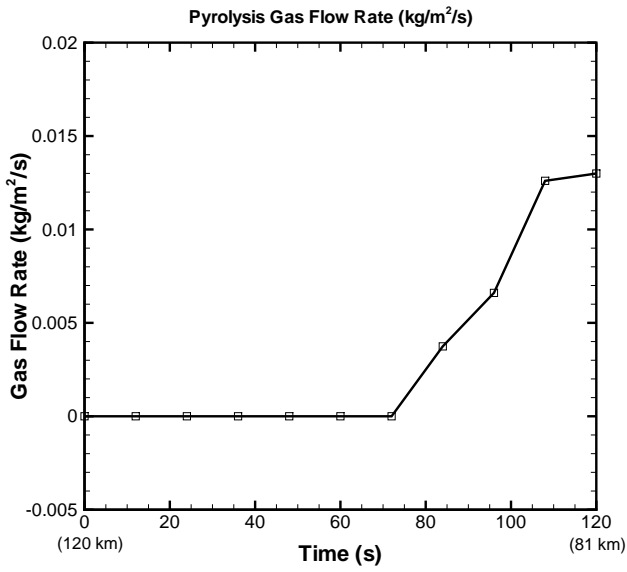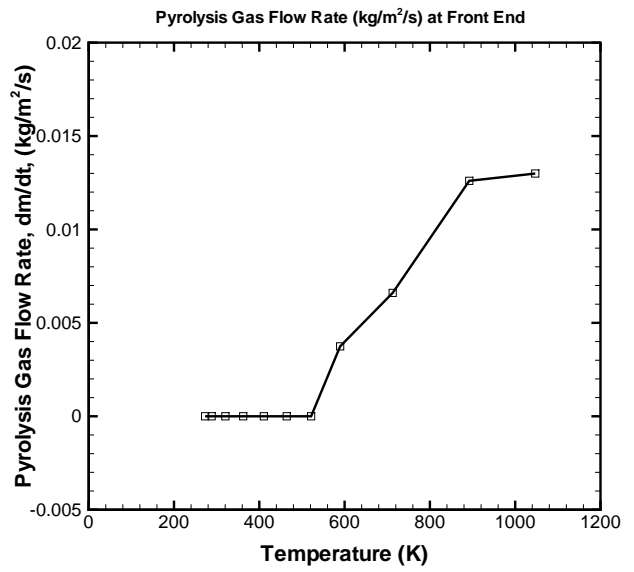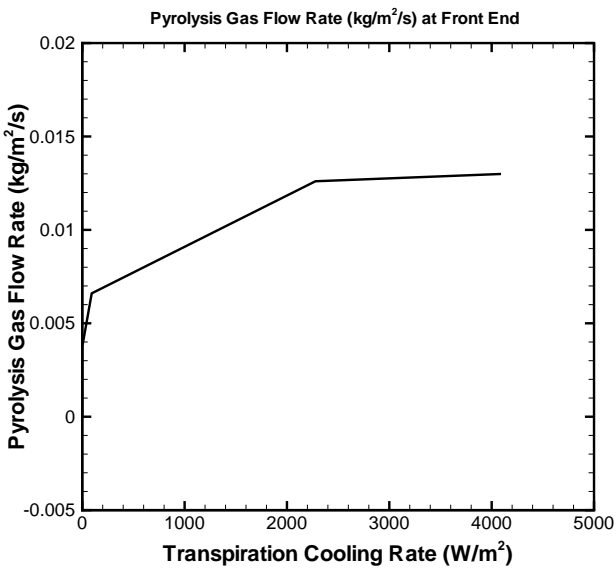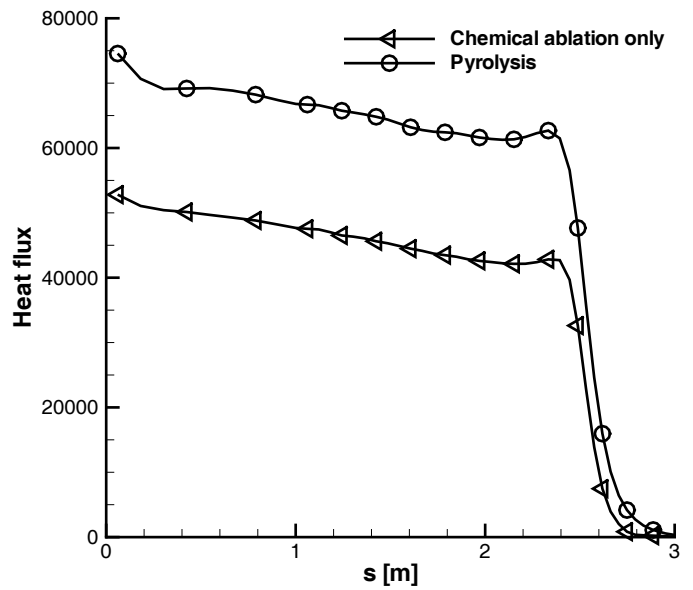
FIGURE 4. A: Overall pyrolysis gas flow rate, $\dot{m}$, B: Overall pyrolysis gas flow rate, $\dot{m}$, vs the front end surface temperature.

FIGURE 5. A: Overall pyrolysis gas flow rate, $\dot{m}$, vs the transpiration cooling flux, $\dot{Q}_T \times \delta y$., B: Heat flux into the TPS at 81 km [$\frac{J}{m^2 s}$]. Cases with and without pyrolysis.