Notes on Pyrolysis Material Study

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August 26, 2025

1 Introduction

These notes intend to progressively introduce the reader to the physics commonly adopted to describe ablative materials for Thermal Protection Systems (TPSs) in the literature. Commonly used for very high speed reentry in aerospace industry, they are highly studied as the sizing of the TPSs is currently one of the bottleneck for increasing the payload for space exploration.

This class of material have to be distinguished from passive materials, that only store incoming energy and are used as heat sink, but can be re-used several times, and actively cooled materials, which benefits from local heat dissipation to mitigate the incoming heat flux. On the other hand, pyrolising TPS are employed for their high potential in limiting the transport of energy in depth of the space vehicle, at the expanse of self-degradation due to surface and in-depth heterogeneous reactions under high temperature, preventing their employ for future mission. This degradation process leads to an expel of energy due to out-gassing of hot products resulting from material ablation out of the vehicle. Eventually, the underlying surface blowing is increasing the thickness of the boundary layer, mitigating further convective heating in complex multi-physics processes. This will not be considered in these notes.

All the presented models derived thereafter are already implemented in the open source software PATO, and all the presented examples have been obtained using it. Starting from a simple heat transfer problem, the specificity of pyrolysing materials will be progressively introduced, and examples will provide an overview of the sensitivity of the results regarding the multiple physical processes at play within TPSs during atmospheric reentry. Finally, a note on ablation process and its effects on in-depths energy transport will close this note. The main literature sources used to write these notes are the following: [1], [2] and [3].

2 TPS Physical Modelling

In this section, the physics of ablative materials is described step by step by starting from a simple heat conduction problem that will serve as a reference as it is the behaviour of passive TPS. As the problem may be seen by some as artificial, the readers already familiar with the topic are encouraged to look directly at the main references used for these notes. Finally, for readers more interested by surface and mass balance between the TPS and the boundary layer, the topic is addressed in section 3.

2.1 A Simple Conduction Problem

Let's start by considering a material submitted to a time independent imposed temperature on one end, whereas the other is considered adiabatic (see Figure 1). The imposed temperature is chosen to be representative of temperature usually encountered over TPS surface such as it is expected it will trigger pyrolysis in the future If the material is assumed to be non porous

$$T_{\mathrm{imp}} = 2000K$$
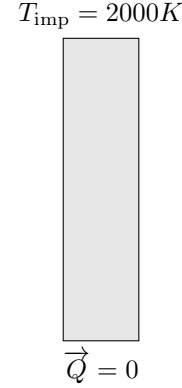
$$\overrightarrow{Q} = 0$$

Figure 1: Schematic of the configuration studied in the next section.

such as passive materials, the description of energy transport is generally assumes to follow the Fourier law which reads as :

$$\frac{\partial}{\partial t}\left(\rho^s c_p^s T^s\right) - \nabla\left(\lambda^s \nabla T^s\right) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\left(\rho^s\right) = 0 \qquad (2)$$

The upper script ^{s} denotes solid phase related properties. In the future, for porous material, the upper script ^{g} will be used for gas phase related variables. Additionally, it is assumed for now that the solid material is homogeneous, *i.e.* made of only one pure phase such as steel or carbon graphite. However, the reader should keep in mind that in the next parts, the composite nature of the TPS will be introduced, and the different solid phases will be indexed as $^{s_1}, ^{s_2}, ..., ^{s_n}$ following the notation in [2]. In equation (1), the assumption of solid material energy $e^s = c_p^s T^s$ has been made. Equation (2) translates the fact that for a non porous material, there is no variation of material density *a priori*. Any phase change or heterogeneous chemical reactions are happening at the boundary (the material being **non porous**, no volumetric chemistry is considered) and only surface ablation can be considered in such configuration (see section 3).

An example of simulation with this kind of material is shown on Figure **??**. In this example, for the sake of simplicity, the material properties c_p^s and λ^s has been

chosen constant and are reported on Table **??**. In that configuration, an analytical solution exists [4]

It can be noted that as previously said, this example is artificial in the sense that there are currently no dissipative processes occurring on the top boundary of the numerical domain. Consequently, surface temperature keeps increasing whereas in reality :

- Radiative cooling would **bound** the surface temperature, preventing it from reaching such a high value. This cooling is the most efficient one (as it scales with the fourth power of surface temperature, see section 3), but additional local dissipation processes would also intervene in reality (melting, sublimation...)

- The surface heat flux is directly provided by the thermal state of the boundary layer. The use of a **constant** non-homogeneous Neumann boundary conditions is physically irrelevant, as the effect of convective heating over the material is reduced as surface temperature rises (let's consider for example a simple Newton's approximation for boundary layer heat flux of the form $\overrightarrow{Q} = \alpha \left(T_e^g - T_s^s \right)$ with T_e^g the **gas phase** boundary layer edge temperature and T_s^s the **material** surface temperature. Ultimately, as material surface temperature becomes hotter than the boundary layer, the heat flux sign would reverse, and the fluid would cool down the surface.

3 Surface Balance for TPS

Now that the physics at play inside ablative material have been (more or less) uncovered, the attention of the reader is drawn on the surface specific processes whose consequences results in the self-degradation of ablative material as discussed in the previous section 2.

Bibliography

[1] J. Lachaud, J. Scoggins, T. Magin, M. Meyer, and N. Mansour, "A generic local thermal equilibrium model for porous reactive materials submitted to high temperatures," *International Journal of Heat and Mass Transfer*, vol. 108, pp. 1406–1417, 2017.

[2] J. Marschall, M. MacLean, P. E. Norman, and T. E. Schwartzentruber, *Surface Chemistry in Non-Equilibrium Flows*, pp. 239–327.

[3] C. O. Johnston, "Study of aerothermodynamic modeling issues relevant to high-speed sample return vehicles," 2014.

[4] D. W. Hahn and M. N. Ozisik, *Separation of Variables in the Rectangular Coordinate System*, ch. 3, pp. 75–127. John Wiley and Sons, Ltd, 2012.