Affected depth and effective reactivity in porous thermal protection materials for atmospheric re-entry

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Keywords : thermal protection materials, ablation, effective reactivity, image analysis

1 Introduction

The entry into a planetary atmosphere is one of the most critical phases of space missions. During this phase the vehicle needs to be protected in order to be able to sustain the severe heat load due to the harsh post-shock environment. For spacecraft entering at considerably high velocity (higher than 10 km/s), engineers have always been compelled to use ablative materials to build efficient heat shields. Carbon-based ablative materials are subject of numerous studies, as they represent the most performing subclass of ablative TPS materials; here, we will consider lightweight ablators, made of carbon fiber preform consolidated with a few percent of phenolic resin, considered for moderately sever re-entry scenarios.

An important characteristic of lightweight ablators is the possibility to ablate in-depth, due to their high porosity. Therefore, the gaseous species coming from the outer flow field do not just diffuse inside the boundary layer but also through the porous material. Hence, in the experiment, the heterogeneous gas-solid reactions are not taking place entirely at the surface but rather on a finite thickness of material. The depth of this region is directly related to the competition between reactant diffusion through the fibers and surface reactivity of the fibers in the porous material. State-of-the-art CFD codes do not take into account the in-depth diffusion of reactants and hence are limited to a macroscopic description of the surface reactivity. Differently, numerical methods like Monte-Carlo Random Walks, capable of taking into account the reactant diffusion through the fibers and the reaction with the fibers, allows for a microscopic approach of the in-depth diffusion/reaction process [1]. Here, we will introduce a simple analytical method relating the depth of the affected zone to the intrinsic reactivity of the constituents and to the test conditions; application of the method to foresee the values of the effective reaction rates will be described then, on the basis of tests performed on the Plasmatron facility [2], followed by X-ray tomographic investigation and image analysis. Experimental observations and post-test analysis will be used together to extract information on the carbon fiber reactivity from the tests.

2 A simple analytical model

Let us assume a diffusion-reaction equation, written in 1D through the thickness of the porous medium, coupled to a porosity variation due to chemical ablation:

$$\begin{cases} \dfrac{\partial C}{\partial t} + \nabla.\left(-D_p \nabla C\right) = -\sigma_v k_{het} C \\ \dfrac{\partial \varepsilon}{\partial t} = \Omega_s \sigma_v k_{het} C \end{cases} \tag{1}$$

where Ω_s is the solid molar volume, and where the effective diffusivity D_p in the porous medium and the internal surface area σ_v relate to the porosity ε through the initial fibre radius r_f by:

$$D_p = \varepsilon^2 D_{\text{gas}} \qquad \sigma_v = \frac{2(1-\varepsilon)}{r_f} \tag{2}$$

These relations are correct in the present case of diluted, quasi-isolated and non-overlapping cylindrical fibres. Seeking steady solutions with respect to a coordinate frame moving at the recession velocity v_r and

using a boundary-layer approximation technique, one obtains the following expressions for the boundary layer thickness δ_a:

$$\begin{cases} \delta_a = \dfrac{3}{2}\dfrac{D_{\text{gas}} C_b \Omega_s}{v_r\left(C_b\Omega_s + 1 - \varepsilon_0\right)} \\ \delta_a = \dfrac{15}{4}\dfrac{r_f v_r}{\Omega_s C_b k_{\text{het}}} \end{cases} \tag{3}$$

where C_b is the gas concentration at the porous medium boundary. The model may be used to identify C_b and the solid reactivity from the measured recession velocity and ablation depth, by inverting these relations, giving in the current case:

$$k_{\text{het}} \approx \frac{45}{8}\frac{r_f D_{\text{gas}}}{\left(1-\varepsilon_0\right)\delta_a^2} \tag{4}$$

3 Application example

As eq. (5) shows, the heterogeneous reaction rate may be recovered from images as soon as the affected depth is known, the remaining parameters being identifiable from the test conditions. A procedure allowing retrieving this quantity from X-ray CT scans has been designed: for each transverse slice of the material, the ellipses resulting from the fibres intersections with the slice plane are identified and their small axis found; then, the slice-average of this quantity is plotted against depth, as illustrated in Figure 1.

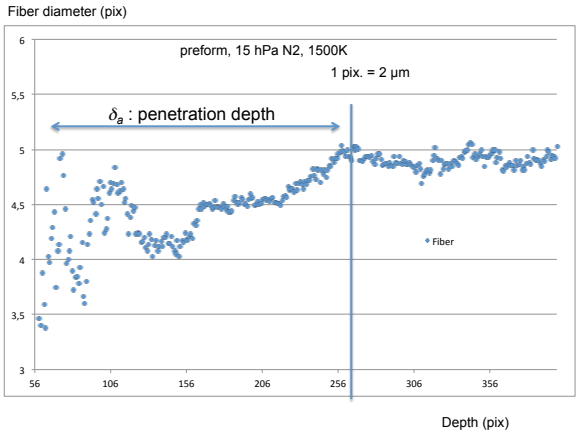

Figure 1: Fiber diameter profile against depth in a fibrous preform ablated under 15 hPa of N_2 at 1500K in the Plasmatron facility, as obtained from X-ray CT and image analysis. 1 pixel = 2 µm.

In the investigated case of ablation by an air plasma at 2000 K, the value found for the heterogeneous reaction rate is of the order of 200 $m.s^{-1}$, giving a sticking coefficient around 10^{-3}, in agreement with literature.

These very encouraging results will be strengthened by detailed MC/RW simulations, and extended to the case of catalytic recombination reactions.

References

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