Development of a Numerical Simulation Tool for the Aerothermal Flow through an Ablative Thermal Protection System for Atmospheric Entry

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1. Introduction

The challenge of atmospheric entry for a spacecraft has stimulated research on the aerothermal flow around the vehicle Thermal Protection System (TPS). During this phase, the spacecraft is strongly affected by aerodynamic heating due to the dissipation of its kinetic energy. Predicting an accurate heat-flux is a complex task, and especially modeling the following phenomena that are potential mission killers: the complex surface chemistry on the thermal protection material and the flow transition from laminar to turbulent. These difficulties are enhanced at higher entry velocities, typical of new missions to Mars or asteroids. To protect the payload or the astronauts onboard, engineers use safety factors to design the heat shield thickness leading to increased mass of the TPS.

The experimental investigation of entry aerothermal problems is still an extremely difficult endeavor which makes numerical methods crucial in advancing our understanding of these phenomena and in developing predictive design tools.

2. Problem statement

Reusable and ablative materials are the two main types of TPS in use today. While reusable protection materials are designed for low heat flux trajectories, ablative TPS are best suited for high entry velocity [1]. Requirements concerning mass efficiency for missions with very high entry velocities have led to the development of a new class of light carbon composite ablators. The components of these materials are carbon fibers and a filler matrix of phenolic resin. During atmospheric entry, a part of the heat flux is transferred inside the heat shield, leading to a gradual temperature increase of the material and to its transformation. One can separate the TPS in different zones: the virgin material, the pyrolysis zone and the char layer (see Fig. 1).

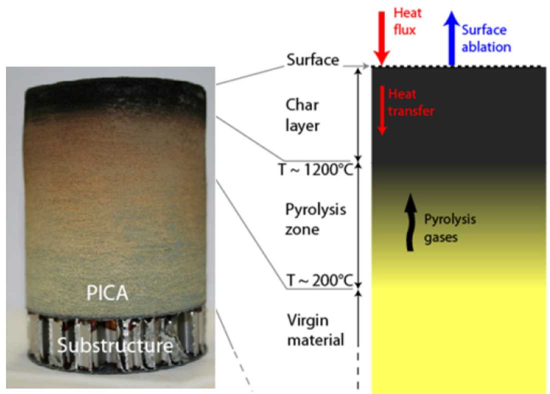

Figure 1: Picture of a core of Phenolic Impregnated Carbon Ablator (PICA) extracted from the TPS of Stardust [2] and schematic of the zones of degradation illustrating the material response to high-enthalpy flow

The virgin material is the unaltered part of the shield. In the pyrolysis zone, the phenolic resin is progressively carbonized producing pyrolysis gases which are transported out of the material by diffusion and convection through the pores. The third zone is composed of the fibrous carbon preform and of the carbonized phenolic resin and is destroyed by ablation [3].

The models implemented until recently are well suited for dense ablative materials but for this new class of material, new design tools need to be developed. Our poor understanding of the coupled mechanisms of ablation and flow transition leads to difficulties in heat-flux prediction. More specifically, pyrolysis and ablation generate a mass flow and a surface roughness that interact with the flow in the boundary layer. Such perturbations can trigger transition of the flow from laminar to turbulent, leading to a strong increase of the convective heat-flux. This interaction between the type of flow and the roughness is illustrated in Fig. 2.

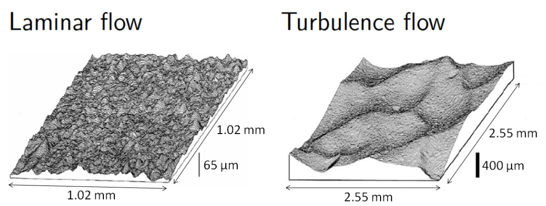

Figure 2: Surface topographies of polycrystalline graphite samples ablated under different flow regimes [4].

3. Method

The objective is to develop an integrated numerical tool for the high-fidelity prediction of the aerothermal performance of light carbon composite materials and their effects at the scale of the vehicle. This work focuses on the combined simulation and modeling of the flow and wall phenomena by means of a computational approach that can go seamlessly from a compressible flow to porous media and implements the most accurate physical models for non equilibrium flows and ablation. Accordingly, the goal is to capture the flow features away from the wall, the developing boundary layer, and the phenomena inside the TPS material. The challenges are many. Not only does one need to correctly resolve these two distinct media, the open flow and the wall but it is quite critical to capture their interactions and in particular the balance of the phenomena in the context of the transition of the boundary layer from laminar to turbulent regime.

The numerical tool will be implemented inside an existing code Argo developed in Cenaero. This platform is based on a Discontinuous Galerkin Method (DGM) which cumulates the advantages of finite volume and finite element discretization [5]. The approach will consider both the Direct Numerical Simulation (DNS) of the fluid flow equations for simplified geometry and their solution through modeling in a spatially filtered context (Large Eddy Simulation-LES). DGM is well suited for DNS and LES for complex geometry thanks to the use of unstructured meshes. Argo already possesses a formalism to solve convection-diffusion-reaction problem as well as an implicit temporal integration. This platform has already proven its capability to run DNS and LES computation in parallel for transitional flow at relatively high Reynolds number (60-100) [6].

The implementation strategy of the different models for the porous media follows the approach proposed by Lachaud to develop the Pyrolysis and Ablation Toolbox based on OpenFOAM (PATO) [7]. In a first step, we will consider the implementation of the model of Kendall et al [8] published in 1968 which has proved its validity for dense material. From the extremely complex phenomena occurring in a porous ablative material, they are only modeling Fourier's heat transfer and pyrolysis of the solid. Progressively more complex models will be introduced which take into account, for example, the identification of the species produced by pyrolysis, the transport and the chemical evolution of the pyrolysis gases inside or outside the material or the ablation as a volume phenomenon.

The verification and validation of the numerical tool developed will be gradual in its complexity and complementary by the different aspects tested. For instance, a milestone of the project is the comparison of the results with the work of Crocker and Dubief [9] which deals with a turbulent flow in a channel influenced by an eroding wall. Comparisons with simple geometry test cases studied at the Université catholique de Louvain in pyrolysis of the biomass and VKI experimental data will allow to validate the simulations inside the heat shield.

4. Ongoing work

Our current effort is twofold. On one hand, we focus on the implementation of diffusive and reaction terms in a one dimensional DG code. On the other hand, we investigate immersed interface techniques for moving boundaries in a DG context in order to capture recession of the material. The results of the current 1D code are compared with the Aerotherm Charring Material Ablation (CMA) program developed by Kendall et al [8].

5. Perspectives

The numerical methods currently being implemented will be useful to compare against the results of Crocker and Dubief [9] . In this context, we envisioned to use immersed interface technique to model surface ablation. According to the assumptions of Kendall et al [8], the flow of pyrolysis gas through the TPS is considered normal to the heated surface and the drop in pressure through the char is supposed negligible. The next step will be to drop this hypothesis and solve Darcy's equation which models the gas flow inside the porous medium. Afterwards, the idea is to evolve towards 2D and 3D versions of the code describing the in-depth thermal response of the material.

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