Towards a Numerical Model of Ablative Thermal Protection Systems in Hypersonic Vehicles

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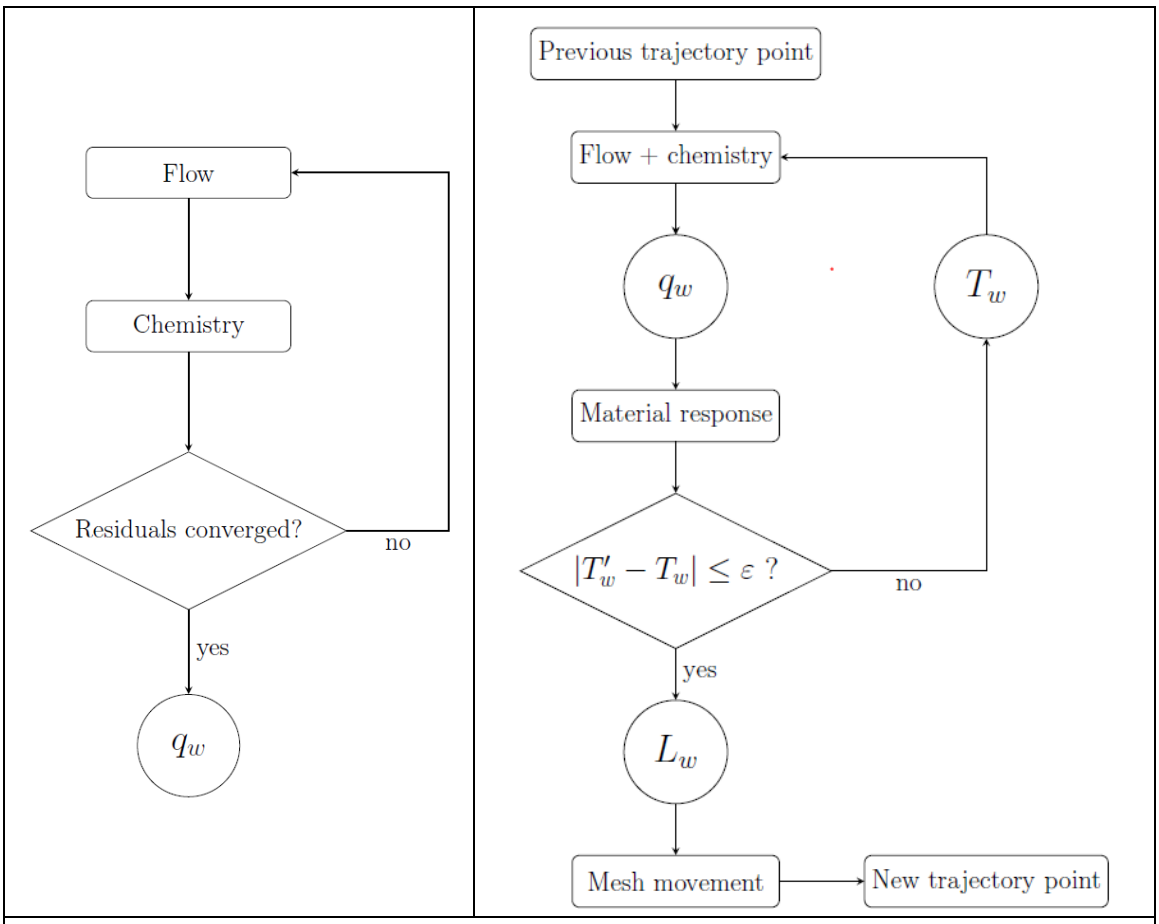
A design challenge in hypersonic flight is the accurate assessment of the ablation of thermal protection systems (TPS). The rapid increase in temperature behind shock waves results in conditions of local thermo-chemical non-equilibrium and large heat fluxes on the vehicle's windward surface, promoting reactions between the scorching gas flow and the ablative outer layer of the TPS [1]. The physical times associated with the heat conduction in the TPS and the surface recession mechanisms are orders-of-magnitude greater than those of flow advection and gas-surface chemistry [2]. Hence, the numerical modeling of ablation generally consists of solving the steady-state flow field for a series of design points along the craft's anticipated trajectory, while the material response is, by contrast, assumed to be transient [3].

This paper introduces a coupling methodology for modeling surface ablation in the edge-based finite element all-Mach solver HALO3D (High Altitude Low Orbit 3D) [4]. A loosely-coupled approach is adopted to make the code computationally tractable, while maintaining accurate flow and material predictions. It can be summarized in five stages:

1. Flow and chemistry (comprising both volume and finite-rate surface chemistry) solvers are sequentially executed to calculate wall heat fluxes q_w (Figure 1a);
2. Heat conduction through the material is then calculated, ensuring energy conservation at the gas-solid interface, that is treated as a Neumann boundary condition;
3. 1. and 2. are repeated until the maximum difference in wall temperatures , $T'_w - T_w$, falls below a tolerance threshold ε (Figure 1b);
4. The surface recession rate, $\dot{r}$, is then derived, and a new interface location computed using a wall displacement given by
$$L_w = \dot{r}\,\Delta t_{\mathrm{traj}},$$
where Δt_{traj} is the physical time separating two successive trajectory points;
5. The mesh is finally updated using an ALE (Arbitrary Lagrangian Eulerian) methodology to morph the grid to account for the material loss [5].



(a) Coupling algorithm between flow and chemistry solvers

(b) Coupling algorithm between flow solver and material response code

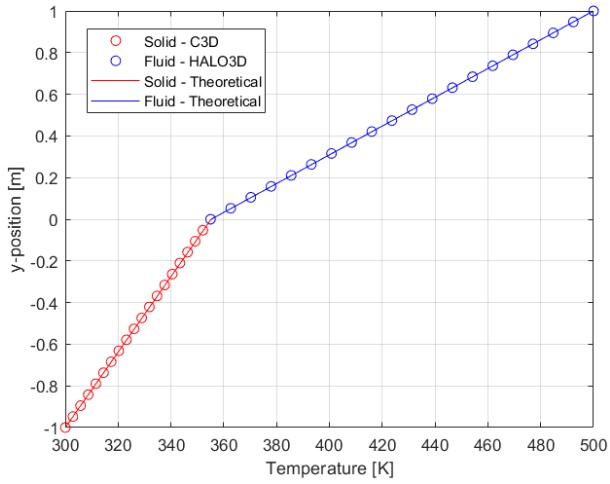
Figure 1. Loosely-coupled approach adopted in HALO3D to model surface ablation

In this paper, a preliminary verification of the coupling algorithm has been conducted. The interaction between flow field and material response is first investigated for a one-dimensional canonical conduction problem involving two stacked 1 m^3 cubes, each representing the flow and solid domains, respectively. They are uniformly discretized along the *y*-axis using 20 nodes and the temperature on the bottom-most and top-most boundaries are imposed as 300 K and 500 K, respectively. The air is at rest to eliminate convection heat transfer and the interface is treated as a Dirichlet boundary condition on the flow side and as a Neumann boundary condition on the solid side. The temperature profile along the *y*-axis is plotted in Figure 2a and the coupling between flow and material is shown to give results in excellent agreement with the analytical solution, with a predicted interface temperature only 0.07% off the theoretical value.

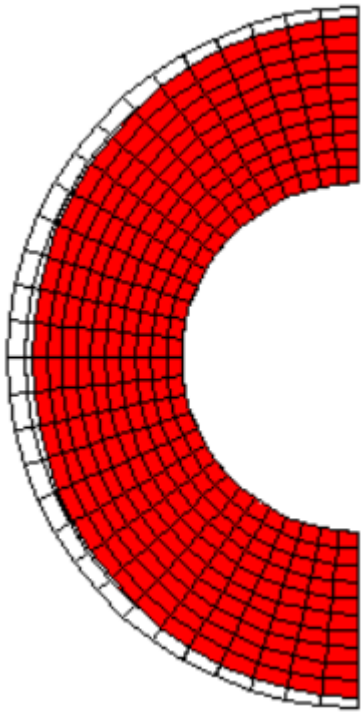
Subsequently, the loosely-coupled algorithm is tested for a half cylinder of radius $R = 0.0254$ m whose surface is receding following the Vieille's law [6] recalled in Eq. 2

$$\dot{r} = a \times p^n \tag{2}$$

where p is the gas pressure, and a and n are constants taken equal to 1.58 and 0.48, respectively [7]. The material region is discretized using 12 nodes and has an initial thickness of $\frac{R}{2}$ and temperature of 800 K. In the flow solver, a Mach 6.3 reacting Nitrogen flow simulation is conducted with inflow pressure, temperature, and velocity set to 2813 Pa, 1833 K, and 5594 m/s, respectively. In addition, the first layer height is equal to 6.3×10^{-5} m in order to respect Y+ limitations. Results shown in Figure 2b indicate that surface recession is, as anticipated, maximum at the stagnation point and amounts $0.05 \times R$ after an arbitrary elapsed time of 2 seconds. Furthermore, the gradual decrease in material loss along the circumference is verified to be symmetric with respect to the x-axis.



(a) Temperature profile along the y-axis for the 1-D conduction problem



(b) Surface recession for the hypersonic flow over a half cylinder with the initial grid (black lines) and the morphed domain (red)

Figure 2. Canonical verification cases for the proposed coupling approach

Future work includes validation of the HALO3D ablation framework using Vieille's law and the finite-rate surface chemistry module for 3D geometries, and its application to 3D cases of interest.

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Acknowledgements

The CFD Lab extends its thanks to the Lockheed Martin Corporation, Ansys Canada and MITACS for the MITACS Accelerate grant supporting the current work.