Influence of Gas Surface Interactions Modeling on Radiative Heat Transfer for Hypersonic Atmospheric Entry

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Workshop topic: Ablative-Radiative TPS and Meteors

Background of the study

During high-speed atmospheric entry the shock-heated gas emits and absorbs strongly, and radiative heating becomes a significant, and at the highest speeds dominant, contribution to the heat load on the vehicle's thermal protection system (TPS). At lunar-return velocities (around 11 km/s) the radiative flux is already comparable to convective heating near peak heating, and for sample-return and interplanetary trajectories in the 12–20 km/s range it becomes the leading term. Reliable prediction of this radiative environment is therefore central to the design and sizing of entry heat shields [1, 2].

Most modern heat shields use carbon-fiber/phenolic ablators, the Phenolic Impregnated Carbon Ablator (PICA) being the most representative. These materials protect the vehicle by ablating. Oxidation, nitridation and sublimation of the carbon fibers, together with pyrolysis of the phenolic matrix, inject CO, atomic carbon, CN and hydrogen-bearing species into the boundary layer [3, 4]. There, these products reduce convective heating, but they also introduce strong additional radiating systems and modify both the emission and the absorption of the shock layer [5]. The radiative and the ablative environments are thus two-way coupled: shock-layer radiation drives the wall temperature and hence the ablation rate, while the ablation products reshape the radiative field that reaches the wall. Predicting the radiative heat flux on an ablating heat shield therefore requires simulations that couple the flowfield, the surface chemistry and the radiative transport in a self-consistent way. The objective of this study is to quantify this coupling between ablative gas–surface chemistry and radiation across a range of high-speed Earth-entry conditions.

Methodology

The study relies on a high-fidelity framework coupling three computational tools. The finite-volume CFD solver HEGEL [6] integrates the two-temperature, thermochemical-nonequilibrium Navier–Stokes equations for an air–carbon–phenolic mixture on an axisymmetric body; the thermochemical library PLATO [7] supplies the closure models, namely chemical kinetics, transport properties and gas–surface fluxes; and the radiation transport solver MURP [8] integrates the radiative transfer equation for a non-gray, absorbing and emitting medium, returning both the volumetric radiative source term fed back to the flow energy balance and the wall-incident radiative flux. HEGEL and MURP are coupled explicitly and advanced until a steady-state coupled solution is reached.

Gas–surface interactions are described with a zero-dimensional surface model that evaluates all surface processes from the local wall state, adopted here as an intermediate-fidelity step toward fully coupled material simulations. The model combines state-of-the-art finite-rate air–carbon chemistry, carbon sublimation, and a steady-state pyrolysis closure that injects the hydrogen-bearing pyrolysis gas into the boundary layer; a spatially resolved surface recession rate follows directly from the surface mass balance. Radiation is computed line-by-line from quasi-steady-state electronic populations, accounting for bound–bound, bound–free and free–free transitions of N, O and C and for the principal diatomic systems (N_2, O_2, NO, CN, CO, C_2, N_2^+); the radiating systems of the pyrolysis-gas species are also included when ablation is active. A reduced-order spectral grouping strategy reproduces the line-by-line solution to within about 5% using only 100 spectral groups, making the coupled simulations affordable [9].

The framework is applied to a 60° sphere-cone capsule entering Earth's atmosphere. To isolate the role of the surface chemistry on the radiative environment, three wall treatments are compared: a fully catalytic, ablation-free wall used as a bounding reference; the baseline air–carbon ablation model; and an extended ablation model that adds carbon sublimation and phenolic-matrix pyrolysis.

Results

A coupled CFD–radiation simulation at an entry velocity of 10 km/s establishes the baseline. Relative to the catalytic wall, surface ablation injects CO, atomic carbon and minor amounts of CN into the boundary layer and softens the near-wall temperature gradient, lowering the stagnation-point convective heat flux ($\sim$1500 to 1300 W/cm^2) and the radiative-equilibrium wall temperature ($\sim$4200 to 3800 K). Despite this cooler boundary layer, the wall-incident radiative flux is consistently *higher* for the ablating wall: it rises from 112 to 143 W/cm^2 at the stagnation point (+27%), with the ablative-to-catalytic ratio reaching about 1.7 further downstream. This increase is driven by strong emission from carbon-bearing species, namely atomic carbon and the CN Violet system, combined with reduced boundary-layer absorption from the weaker N_2/O_2 recombination at the ablating surface.

These results show that the choice of surface chemistry model has a first-order, counterintuitive effect on the radiative heating: a treatment that lowers convective heating can simultaneously raise the radiative flux. They also indicate that the coupling should strengthen with entry velocity, since the hotter walls reached at higher speeds intensify carbon sublimation and pyrolysis-gas injection.

Conclusion

The baseline results establish that ablative gas–surface chemistry and shock-layer radiation are tightly two-way coupled in high-speed Earth entry, and that the fidelity of the surface chemistry model is a first-order driver of the predicted radiative heating rather than a second-order correction. The full contribution will extend the analysis to entry velocities of 12, 15 and 20 km/s, representative of sample-return and interplanetary conditions, and present a systematic three-way comparison of the catalytic, baseline air–carbon, and extended ablation walls, quantifying how carbon sublimation and pyrolysis-gas injection reshape the boundary-layer radiation and the wall heat-flux and recession-rate distributions.

Beyond the present study, the zero-dimensional surface closure is intended as a stepping stone toward fully coupled CFD–radiation–material simulations, in which in-depth conduction, pyrolysis-gas transport and the resulting heat-shield shape change are resolved. Extending the framework along representative entry trajectories would then enable time-accurate predictions of the radiative environment of ablating heat shields, with direct relevance to TPS design and to the modelling of meteoric entry.

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