Development of Multiphysics Numerical Methods to Study Coupled Flow, Radiation, and Ablation Phenomena for Planetary Entry Vehicles

James B. Scoggins

Aeronautics and Aerospace Department, von Karman Institute for Fluid Dynamics, Belgium, james.scoggins@vki.ac.be

Supervisor and University Supervisor: Thierry Magin

Assistant Professor, Aeronautics and Aerospace Department, von Karman Institute for Fluid Dynamics, Belgium, magin@vki.ac.be
EM2C Laboratory, École Centrale Paris, France

Abstract

This report briefly outlines the proposed research of developing numerical methods for the coupling of fluid flow, radiation, and ablation physics surrounding planetary entry vehicles.

Keywords: multiphysics coupling, numerical methods, hypersonics, radiation, ablation, planetary entry

1. Introduction and Motivation

Space exploration is one of the boldest and most exciting endeavors that humanity has undertaken, and it holds enormous promise for the future. After the successful manned missions to the Moon and many probe entries in the atmospheres of our outer planets, our next challenges for spatial conquest include bringing back samples to Earth by means of robotic missions and continued manned exploration, which aims at sending human beings to Mars and returning them safely home.

Of the many design challenges associated with these goals is the exceptionally difficult task of accurately predicting the heat-flux to the surface of the spacecraft thermal protection system (TPS) during planetary entry. An inaccurate prediction can be fatal for the crew or the success of robotic missions. Large safety factors are often added to vehicle TPS thicknesses to avoid such catastrophes at the expense of additional cost, weight, and reduced payload margins. Thus it is necessarily important to understand and accurately model the complex phenomena that affect the surface heat-flux such as the following potential "mission killers:" 1) Radiation of the plasma in the shock layer, and 2) Complex surface chemistry on the thermal protection system material (Fig. 1). However, current entry vehicle design paradigms largely decouple many of the physico-chemical processes due to numerical and modeling constraints, making it difficult to infer from current design tools the complex, coupled phenomena occurring for any given entry problem. Thus, our poor understanding of the coupled mechanisms of flow, radiation, and ablation leads to the difficulties in flux prediction.

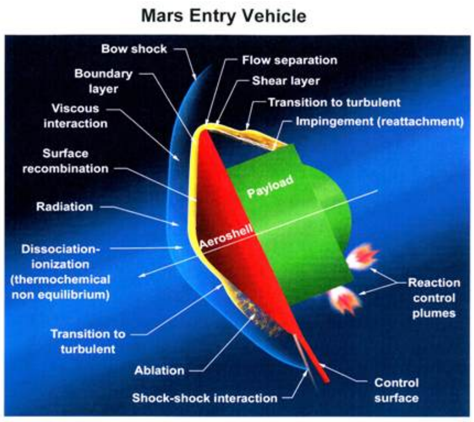

Figure 1: Diagram depicting physical phenomena surrounding a spacecraft during a Martian atmospheric entry. Credit: NASA Hypersonics Project [1]

2. Research Objectives

The AEROSPACEPHYS project is focused on improving our predictive capabilities by *"Integrating* *new advanced physico-chemical models and computational methods, based on a multidisciplinary approach developed together with physicists, chemists, and applied mathmaticians, to create a top-notch multiphysics and multiscale numerical platform for simulations of planetary atmosphere entries, crucial to the new challenges of the manned space exploration program. Experimental data will also be used for validation, following state-of-the-art uncertainty quantification methods.*" The proposed research project, aimed at developing a complete multiphysics tool which fully couples flow, radiation, and ablation models, will be an integral component of the overall objectives of the AEROSPACEPHYS project.

Currently, other researchers are working on state-of-the-art modeling capabilities for the various decoupled systems necessary for the accurate description of the flow physics associated with hypersonic flight [2]. These include the development of advanced collisional-radiative models for thermochemical nonequilibrium and radiation modeling via strong collaboration with the computational chemistry group at NASA Ames Research Center (ARC) [3; 4; 5], improved carbon-phenolic ablation models through Direct Simulation Monte Carlo methods [6], accurate and efficient modeling of atmospheric entry plasmas in the transition and continuum regimes, as well as a previously developed state-of-the-art treatment of transport properties for ionized plasmas [7; 8]. In addition to these advanced modeling efforts, an experimental investigation of various thermal protection materials is also under way with the use of the VKI Plasmatron facility [9; 10]. The next step in developing a complete multiphysics tool for studying hypersonic entries will be to couple these efforts, including contributions from outside VKI such as a new ablation code from NASA ARC (PATO [11]), into a comprehensive, 3-dimensional, multiphysics code which couples the various models being developed into a complete flow/radiation/ablation tool.

The development of this multiphysics framework will be completed through a series of important milestones during the research project at VKI. During the first phase, the Mutation library, which provides chemistry, transport, and equilibrium computations for ionized plasmas, will be upgraded to use C++ and incorporate improved algorithms and models for the transport and equilibrium calculations. The improved library will be designated Mutation++. Additionally, during the first phase of development, a 3-dimensional hypersonics CFD code will be implemented with the use of the OpenFOAM library. OpenFOAM is a natural choice because it offers extensive features to aid the development of a hypersonics solver including grid/mesh data structures, built-in parallel framework, and linear algebra routines. The flow solver will also make extensive use of Mutation++. Following this work, the task of coupling radiation into the flow solver will be completed alongside a detailed development of a general multiphysics framework for hypersonic problems. Next an ablation tool being developed by NASA ARC will be additionally coupled to the flow/radiation solver, finally allowing the computation of a fully coupled flow/radiation/ablation simulation.

Apart from improved simulation fidelity provided by the implementation of various physico-chemical models developed in the Aeronautics and Aerospace Department, the new multiphysics tool will finally allow a detailed study of the various coupled phenomena that have been largely overlooked due to lack of existing computational models. These include the coupled relationships between shock layer radiation and absorption by pyrolysis and ablation products in the boundary layer and gas-surface interactions and in-depth ablation due to boundary layer chemistry. The final goal of this research will be to study these effects as they pertain to specific experimental and flight test situations such as plasmatron simulations and post-flight analysis of the EXPERT mission (Fig. 2).

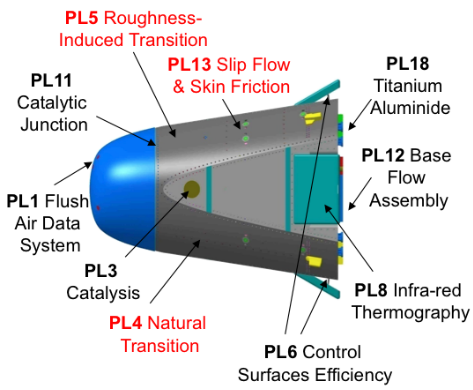

Figure 2: ESA Expert Vehicle & Payloads

3. Mutation++

As mentioned in Section 2, the first task in developing a complete multiphysics tool will be to update the Mutation library to a modern, object oriented library written in C++ which can be coupled to new or existing CFD tools. This effort is in fact already underway. The MUTATION library provides **mu**lticomponent **t**ransport **a**nd **t**hermodynamic properties/chemistry for **ion**ized plasmas.

MUTATION++ will incorporate all of the same features as its predecessor, however a number of algorithmic changes will be made to improve the library's robustness and performance. In particular, the equilibrium composition solver in MUTATION can fail for some mixtures and thermodynamic states for which the nonlinear set of equations to be solved becomes numerically stiff. Such conditions have been encountered in certain pyrolysis gas mixtures making it impossible to solve some boundary layer problems with ablation and pyrolysis species. MUTATION currently employees the Newton-Raphson iterative procedure to solve the set of equilibrium equations with the fast Schur complement method for the linear update. This algorithm has proven to be very fast, however it does not handle numerical stiffness well. MUTATION++ will instead implement a method known as the Gibbs function continuation (GFC) method developed by Pope [12; 13], which is guaranteed to find the equilibrium composition for all well posed problems regardless of the numerical stiffness of the mixture.

To help increase the performance of the MUTATION++ over its predecessor, specialized lookup tables will be incorporated for the calculation of expensive model parameters such as Arrhenius rates laws, equilibrium constants, collision integrals, etc. This lookup table feature has already been incorporated into the MUTATION++ library and can compute lookup tables at start-up given a function and desired accuracy (error tolerance) or can be loaded from precomputed tables. More testing is still required to determine the exact speedup generated by using such lookup tables but initial tests with randomly generated functions shows that an order of magnitude decrease in computational time can be achieved for some model parameter calculations.

Additional features will also be added in MUTATION++ which will enable coupling to implicit CFD solvers such as the calculation of the species production rate Jacobian matrix for finite-rate chemistry.

4. Concluding Remarks

The focus of this research will be to develop state-of-the-art numerical methods that allow the coupling of fluid flow, radiation, and ablation modeling for planetary entry simulations that is computationally competitive with current uncoupled methodologies. To this extent, the basic ground work has been laid through planning and collaboration internal to VKI and abroad. However, this research is still in the preliminary phases, leaving much work left to be completed.

Acknowledgments

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