Numerical investigation of three-dimensional effects within a charring ablator

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Introduction and Motivation

Atmospheric entry/exit of vehicle takes place in the hypersonic flow regime where flow field is extremely complex. High temperature gradients occurring in the shock-layer region ionizes and dissociates the air. Even if a large portion of heat generated during this process is convected away in the surrounding air, a fraction of it is still transferred to the vehicle. Therefore, efficient design of the Thermal Protection System (TPS) is necessary in order to reduce the heat conducted into the body surface, optimize the heat shield and avoid structural failure of the vehicle.

In the case of using ablative material, which has been proven an efficient way to reduce the rate of heat transfer into the vehicle, ablation modeling is a challenging task, as it involves simulating complex processes of mass loss and energy absorption through complex chemical reactions. Moreover, in case of decomposing (charring) ablators, inner pyrolysis takes place. This results in the formation of porous material as well as inner gas, further increasing the complexity of the numerical model. Available literature indicates that most of the past investigations either do not consider the actual physical processes occurred during ablation, or are limited to one and two-dimensional models.

In present investigation an attempt has been made to simulate the actual physics of thermal ablation phenomenon by considering anisotropic, multilayer, variable material properties model in three-dimensions. The newly developed model is verified using closed form analytical solutions and validated with the available data. This effort consists of the first steps of an ongoing project to develop a comprehensive multiscale, multi-physics and multi-dimensional material response code aimed at modeling charring and surface ablation. Preliminary results will show the successful development of a numerical model for simulating the multidimensional heat transfer phenomena that occurred in a typical ablative TPS.

FreeCFD [1]

- Second order finite volume approach for spatial variables and uses a fully implicit first-order backward Euler time integration.
- Performs three-dimensional simulation of a typical problem, uses the popular CGNS format for computational grids and takes advantage of parallel computing through domain decomposition (ParMetis) and MPI.
- Linked to the PETSc library, which provides efficient methods for solving large and sparse linear systems.
- Convective fluxes are solved by a variety of available methods, which allows the code to solve problems ranging from Mach 0.001 to more than Mach 10.

Governing Fluid Dynamics Equations

The conserved variables, source terms, and primitive variables are given by

\[ \rho, \mathbf{u}, e \]

where \( \rho \) is the density, \( \mathbf{u} \) is the velocity, and \( e \) is the total energy.

Governing Equations for Material Response Code

The governing equations for the proposed material response model include energy, momentum and mass conservation equations for solid and gas medium. The conservative variables, source terms, and primitive variables are given by

\[ \rho, \mathbf{u}, e, \mathbf{Q}, \mathbf{F}, \mathbf{S} \]

where \( \mathbf{Q} \) represent the porosity of the material, and subscript \( j \) and \( k \) are the gas and solid phases, respectively. As for the parameters \( \mu \) and \( \lambda \), used to define flow through a porous media, they are respectively the viscosity and the permeability, and they are used to integrate Darcy’s Law in the momentum equation. The solid material model includes multiple species. Then total density of the material is therefore computed with

\[ \rho = \rho_g + \sum_j \rho_{g,j} \]

Material Response: 3D carbon-phenolic cube

- The carbon-phenolic properties (non-charring) defined in Ref.[2] are used.
- Total heat flux is externally computed and is applied at the vehicle surface; whereas, insulated wall boundary conditions have been imposed at the remaining boundaries.
- Test condition, computational grid and heat flux distribution are shown as following. Figure (a) illustrates the computed temperature distribution for the IRV/2 vehicle after 4 seconds of constant exposure. As expected, maximum levels of temperature is observed at the blunt nose section of the body. A gradual decrease in temperature values is also apparent as one move towards the base section. Figure (b) to (c) illustrates the same results while using different values of an anisotropic thermal conductivity. As can be seen, the results are significantly different.

Future Plans

- Spallation prediction capability
- Integrated coupling with the fluid part of the code
- Internal chemical decomposition modeling
- Spalled particle tracking
- Surface chemistry

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References


Conclusion

The first steps of an anisotropic multi-layer and multidimensional material response code for charring ablators have been presented. The code, part of an integrated CFD framework that allows the simulation of hypersonic flow, allows to model the complex physical processes that occur during a typical atmospheric re-entry. Preliminary results have been presented, both from the flow solver and the material response modules. Those results are encouraging, and shows that the integrated solvers is an efficient and robust method to solve this class of problems. The final version of this work will include an extensive set of verifications and validations, and results will be compared to existing numerical and experimental data.