Verification of the Icarus Material Response Tool

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Motivation

As TPS materials grow in complexity so do the models required to simulate the accurate thermal response. For simulating

- Complex geometries
- Gas transport
- Highly orthotropic thermal properties
- Thermoelastic response

flexible and easily extensible simulation tools are needed.

For design, material response codes should be efficient and extensively verified and validated.

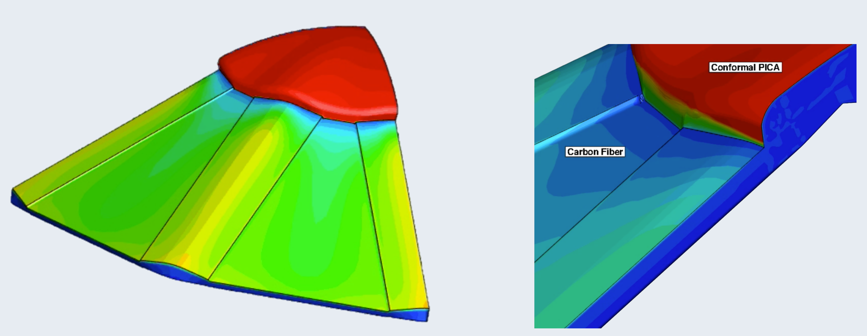


Figure 1: Simulation of ADEPT with Icarus

Introduction

Due to the complex physics encountered during re-entry, material response solvers are used for two main purposes: improve the understanding of the physical phenomena; and design and size thermal protection systems (TPS). Icarus [1], is a three-dimensional, unstructured material response tool that is intended to be used for design while maintaining the flexibility to easily implement physical models as needed. Because TPS selection and sizing is critical, it is of the utmost importance that the design tools be extensively verified and validated before their use. Verification tests aim at insuring that the numerical schemes and equations are implemented correctly by comparison to analytical solutions and grid convergence tests.

Physical Boundary Conditions

At the surface of the material domain, Icarus solves a mass and energy balance [2]. These account for the exchange of mass and energy between the material and the aerothermodynamic environment. If mass loss at the wall is given to be negative, the mass balance at the wall can be given by:

$$\underbrace{\dot{m}_w}_{\text{Wall mass flux}} = \underbrace{\dot{m}_c}_{\text{Solid char flux}} + \underbrace{\dot{m}_{g_s}}_{\text{Gas flux from pyrolysis}}$$

Here, subscript w denotes the wall while subscripts c and g are for solid char and gaseous species, respectively. The energy balance at the wall is determined by adding the contributions of heat fluxes and solving for the heat conduction into the material.

$$\underbrace{\dot{q}_{cond_s}}_{\text{Conduction}} = \underbrace{-\rho_e u_e C_H (h_r - h_w)}_{\text{Convective heating}} - \underbrace{\alpha \dot{q}_{rad}}_{\text{Radiative heating}} + \underbrace{\sigma\epsilon(T_w^4 - T_\infty^4)}_{\text{Re-Radiation}} + \underbrace{\dot{m}_w h_w - \dot{m}_c h_c - \dot{m}_{g_s} h_g}_{\text{Energy flux due to mass flux}}$$

Here, the aerothermal convection term is often given by a CFD simulation. For decoupled CFD-MR simulations, a correction factor can be applied to account for the change in heat transfer coefficient due to mass loss into the boundary layer. The surface-energy balance with the blowing correction[3] is formulated as:

$$\dot{q}_{cond} = -\rho u_e Ch_0 \left(\frac{Ch}{Ch_0}\right) (h_r - (1 + B_c' + B_g')hw)) - \alpha \dot{q}_{rad} + \epsilon\sigma(T^4 - T_\infty^4) - \dot{m}_c h_c - \dot{m}_{g_s} h_g$$

When using the blowing correction, the temperature of the material domain is decreased, and is decreased more-so near the surface, as shown by the Figure 2, which shows time-traces of material temperature at various depths.

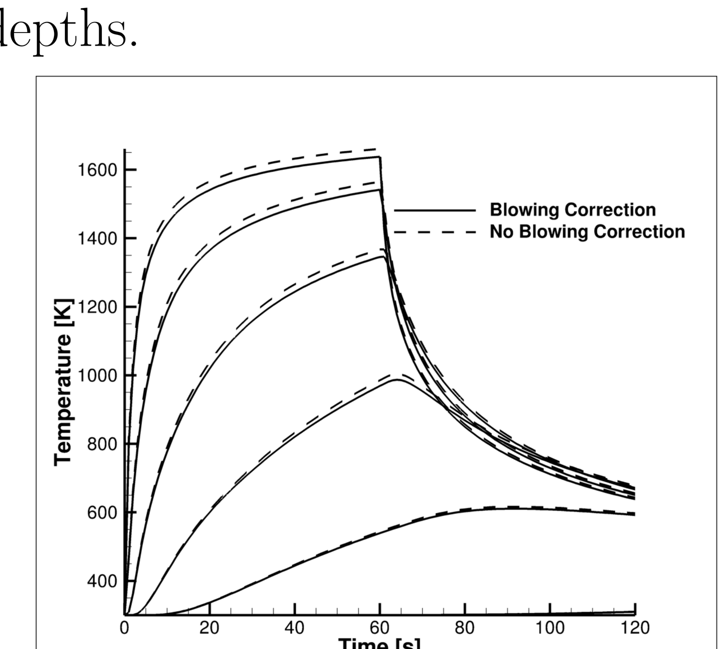
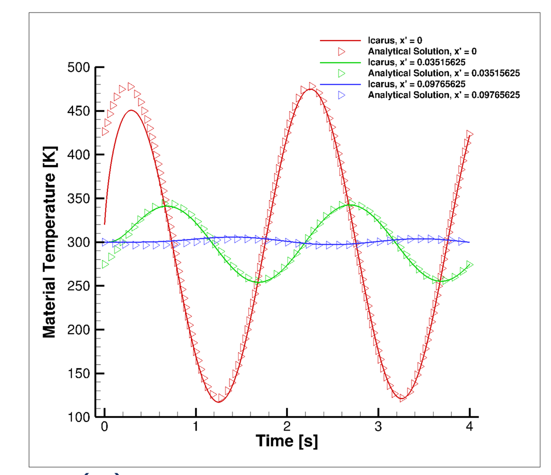
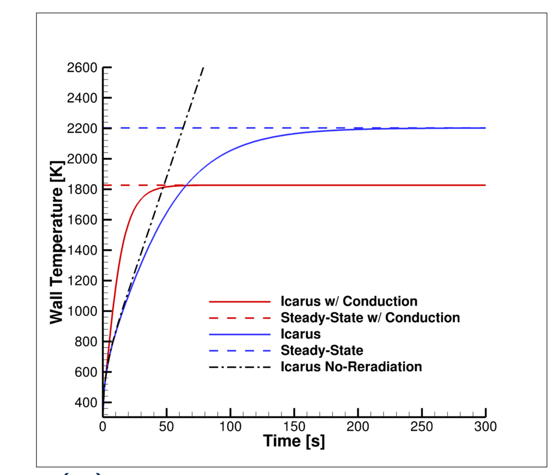


Figure 2: Blowing Correction

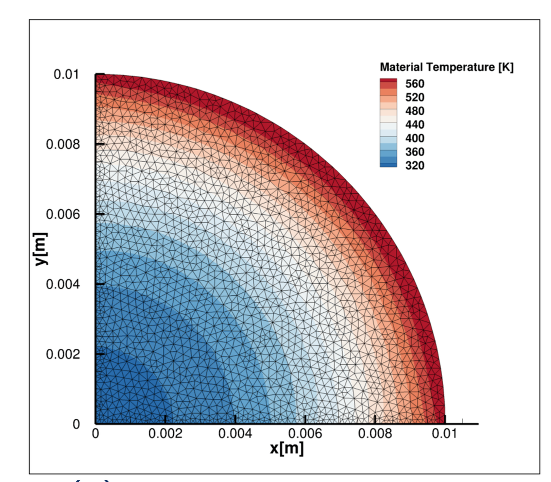
Results



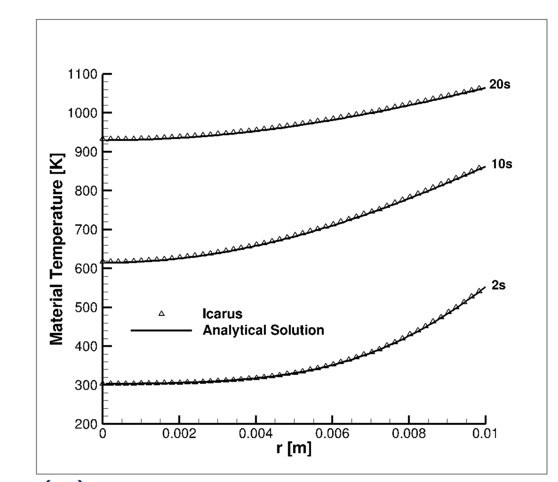
(a) Time-varying heat flux



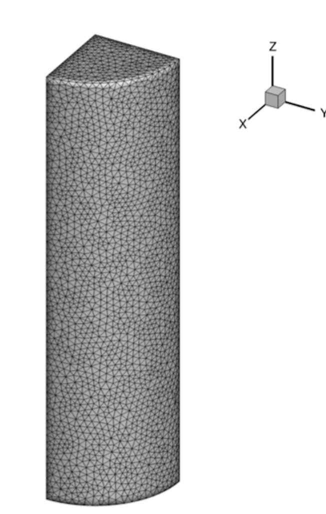
(b) Verification of re-radiation



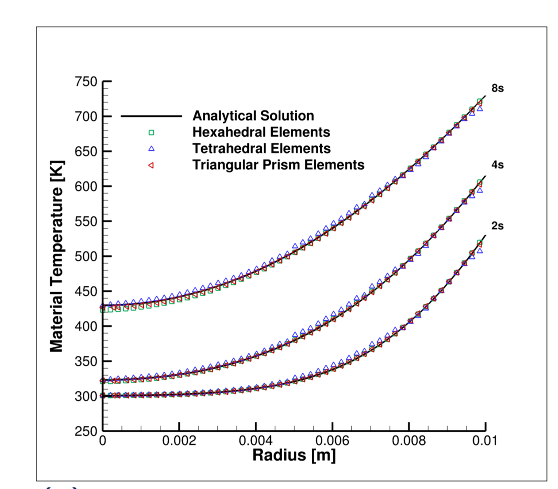
(c) 2D axisymmetric sphere



(d) Perfect gas convection on a sphere



(e) 3D quarter cylinder



(f) Perfect gas convection on a cylinder

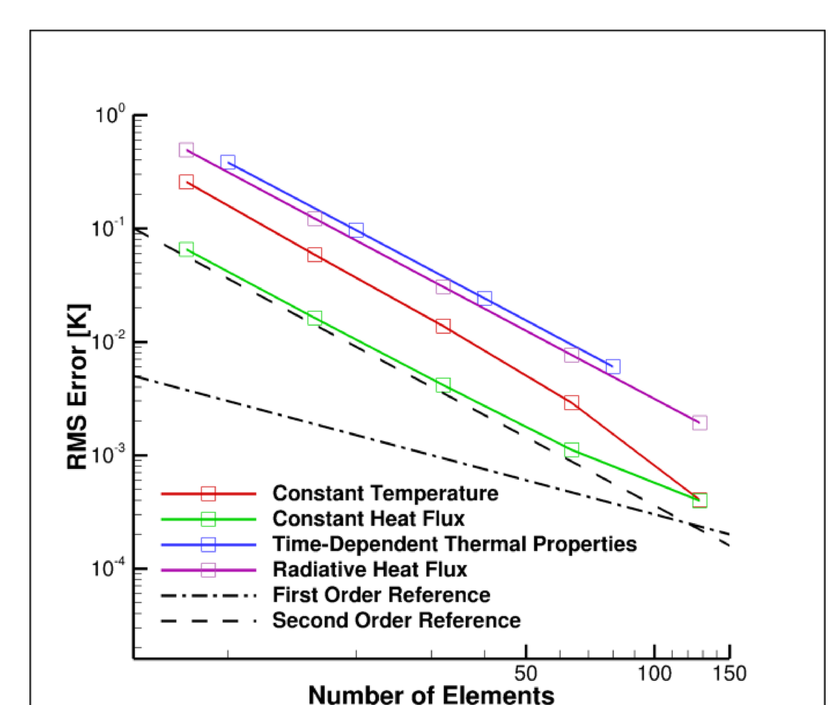


Figure 3: Verification of the radiative heat flux, constant specified heat flux, isothermal boundary conditions.

Conclusion

Verification tests for the Icarus material response tool are shown. Due to the complexity in nature of ablation problems, a modular approach to the verification is used. In this work, each of the boundary conditions is verified independently. Other aspects of the code are also tested such as the multidimensionality, the use of various grid elements types, time-varying boundary conditions and variable thermal property materials. The code shows good agreement with all analytical solutions and achieves second order convergence in error.

References

[1] Schulz, J. C., Stern, E. C., Muppidi, S., Palmer, G. E., Schroeder, O., and Martin, A., "Icarus: a three-dimensional, unstructured material response design tool," *55th AIAA Aerospace Sciences Meeting*, No. 0667 in AIAA SciTech Forum, Grapevine, TX, June 9-13 2017.

[2] Moyer, C. B. and Rindal, R. A., "An Analysis of the Coupled Chemically Reacting Boundary Layer and Charring Ablator, Part II: Finite Difference Solution for the In-Depth Response of Charring Materials Considering Surface Chemical and Energy Balances." Technical report 66-7 part ii, Aerotherm, March 1967.

[3] Kays, W., Crawford, M., and Weigand, B., *Convective Heat and Mass Transfer*, McGraw-Hill, 4th ed., 2005.

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