

Modeling instrumented test articles for Plasmatron X aerothermal environment

2023 AIAA Aviation Forum

12 May 2023

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Outline

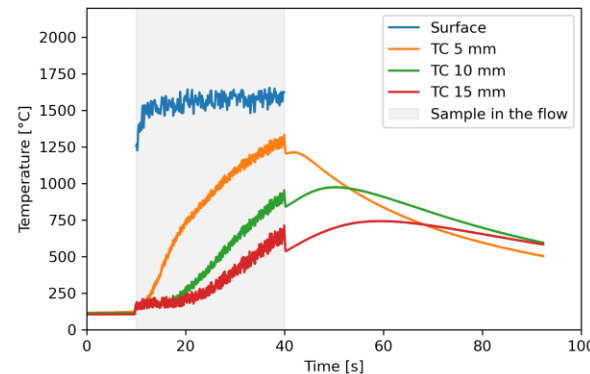
- Introduction
- TPS Material Testing Overview
- Motivation & Approach
- Aerothermal Environment for Plasmatron X
- Material Response Simulations
- Results
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Introduction

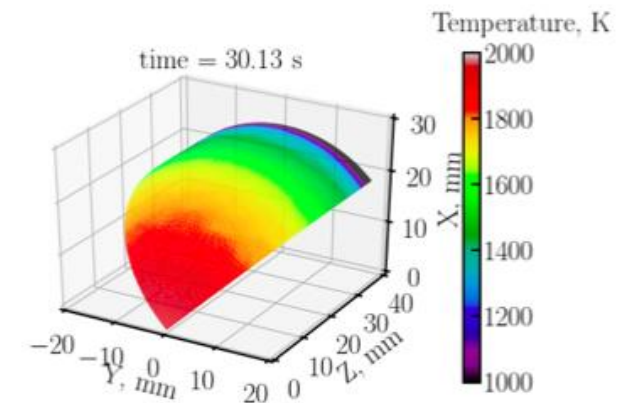
- High-enthalpy ground testing is widely used for evaluating performance of Thermal Protection System (TPS) materials.
 - Arcjets and inductively coupled plasma (ICP) torches commonly used.
 - Allows for replicating test-relevant stagnation heat fluxes and pressures.
- To test TPS materials, samples are exposed to high-temperature plasma flows and their ablative response is observed.
 - Non-intrusive and intrusive measurements can be made.



FiberForm assembly exposed to N₂ plasma in CHESS Plasmatron X ICP[1].



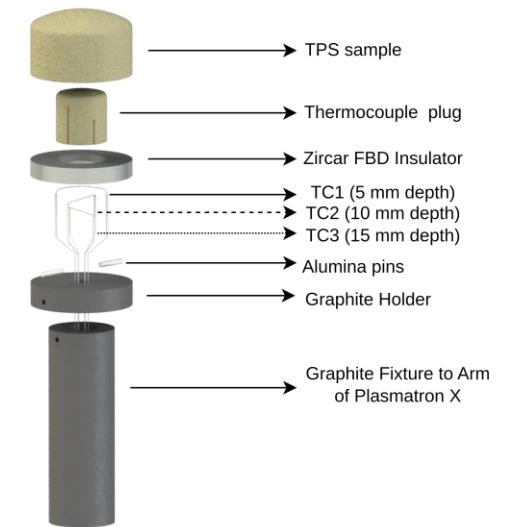
In-depth Temperature from embedded thermocouples[2].



Surface temperature of TPS through IR imaging[2].

TPS Material Testing Overview

- TPS samples are attached to a water-cooled arm using components such as:
 - Assembly holder (to attach to arm).
 - Insulators (to reduce heat conduction between sample and arm).
 - Embedded thermocouples (TCs), for in-depth temperature measurements.
- Presence of assembly components highly varies the material response of the TPS sample, leading to altered results.
- Importance of TC readings:
 - Evaluation of TPS materials in different conditions.
 - Validation for material modeling.
 - Serves as inputs for inverse analysis.



Assembly components used for testing with 3 embedded TCs.

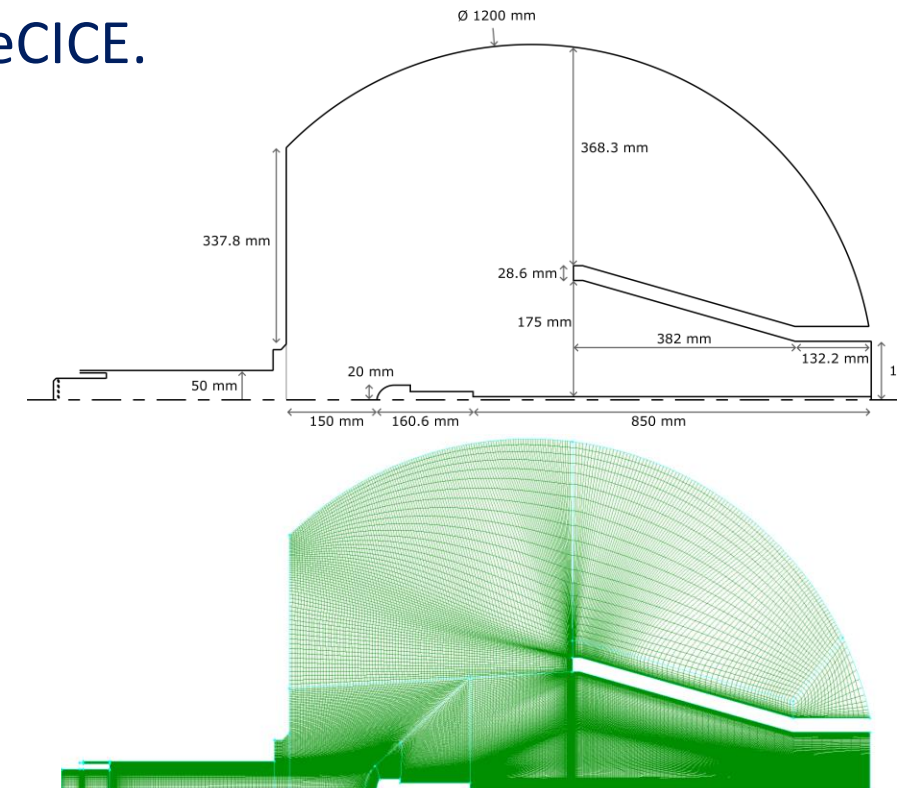
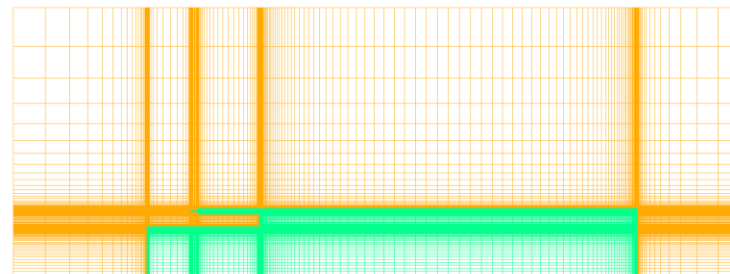
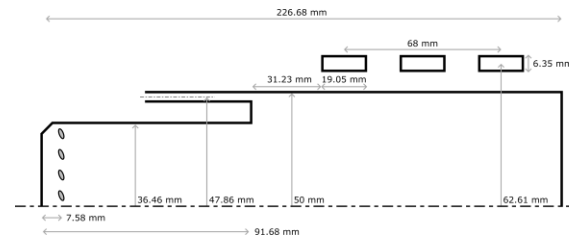
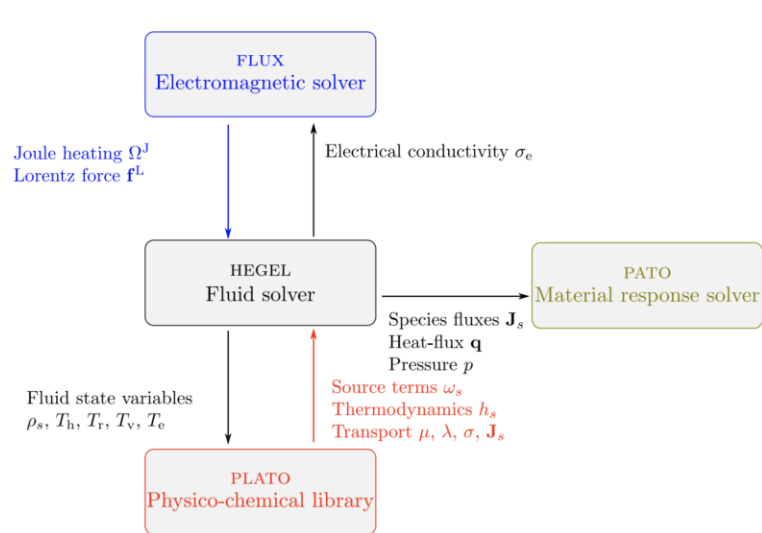
Motivation & Approach

- Goal is to simulate material response of various thermocouple configurations for TPS samples tested in the Plasmatron X facility.
- An isoQ geometry is chosen for the TPS material along with all the secondary components used for instrumenting and assembling the sample.
- **Approach:**
 - Simulate aerothermal environment for Plasmatron X using the coupled-framework developed at UIUC[1].
 - Inputs of operating power, chamber pressure and mass flow rate were provided.
 - Obtain boundary conditions for material response simulations from aerothermal environment.
 - Perform material response simulations in PATO for various sample assemblies.



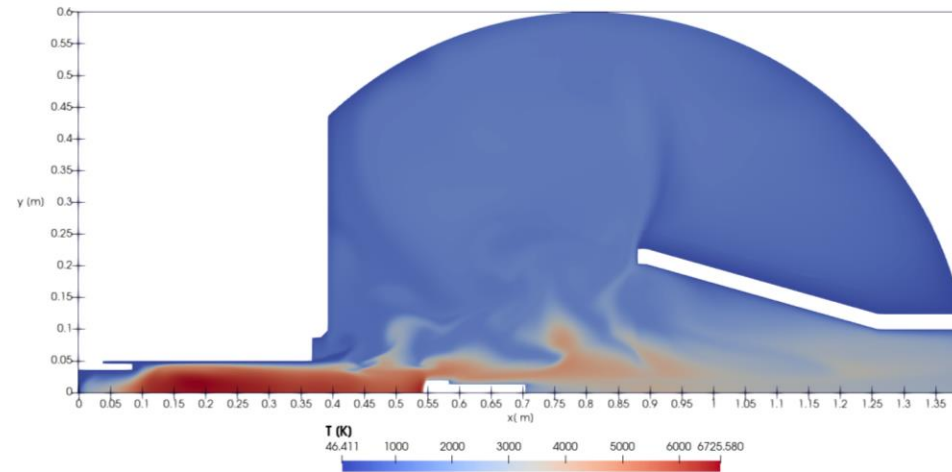
Aerothermal Environment of Plasmatron X

- Inductively coupled plasma in the plasmatron X facility is simulated using overlapping domains of
 - Flow domain simulation using HEGEL
 - MHD domain including coils using FLUX.
- HEGEL[1] and FLUX[2] are explicitly coupled using preCICE.



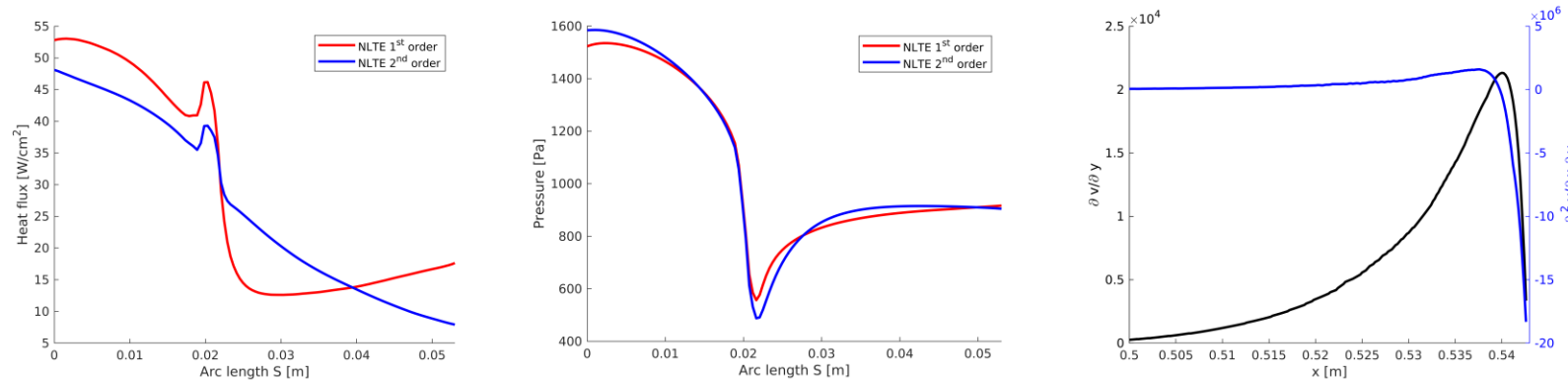
Aerothermal Environment Simulations

- Non-local thermodynamic equilibrium (NLTE) simulations were performed using Air 11 and Park 2-Temperature model.
- Inputs to simulations were:
 - Operating power of 100kW,
 - Back-pressure of 1000Pa,
 - Mass flow-rate of 8g/s.
- Hot-wall boundary conditions of 2300K is assumed at the stagnation surface of the sample.
- Explicit RK4 time integrator with second-order MUSCL reconstruction is performed.



Boundary Conditions for Material Response

- From HEGEL, the heat flux and stagnation pressure are computed along the stagnation surface.
- Boundary layer edge along the stagnation line is identified, and the edge properties of enthalpy, density and velocity are computed.

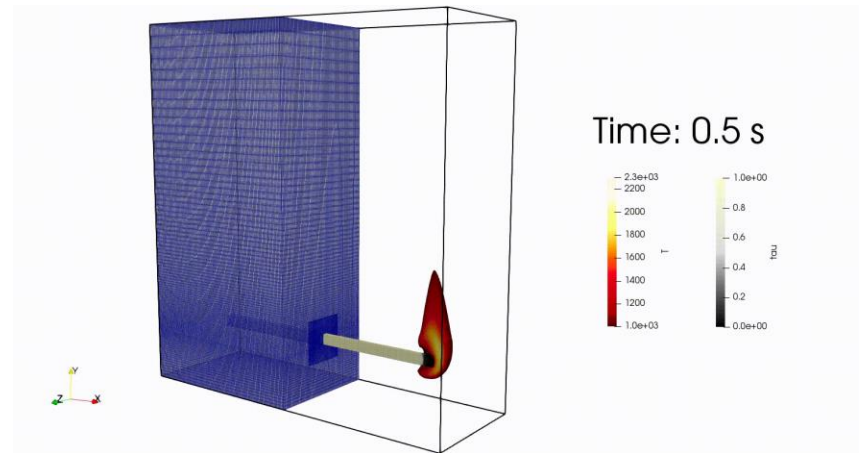


- Film coefficient is obtained using stagnation point heat flux and edge enthalpy as,

$$\rho_e u_e C_{H_0} = \frac{q^{flow}}{(h_r - h_w)}$$

Computational Modeling in PATO

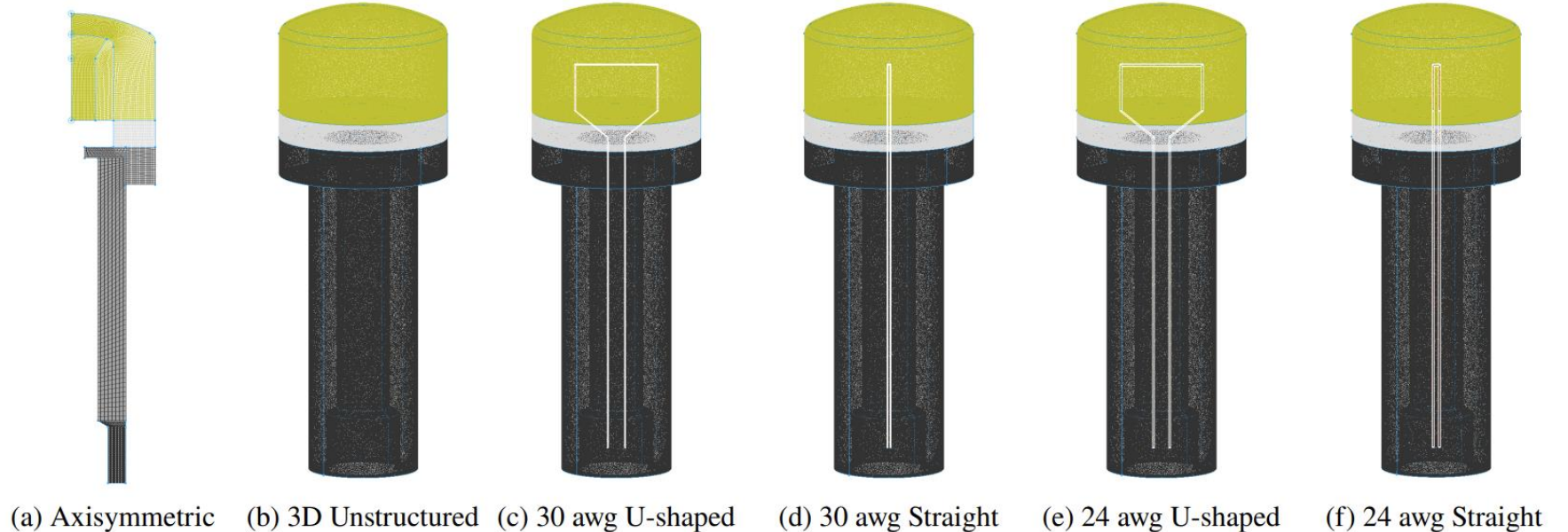
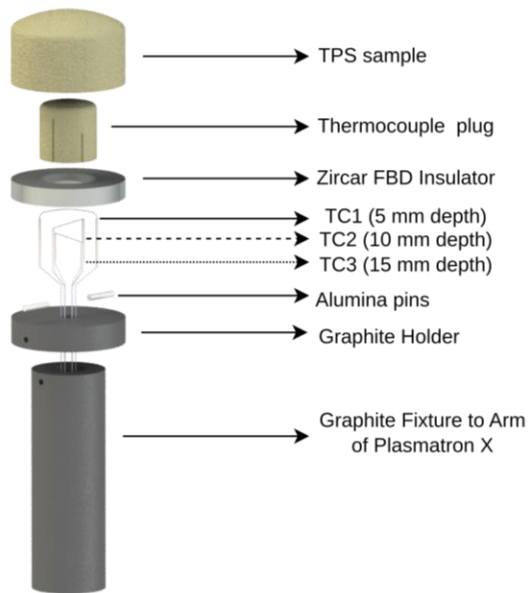
- Porous Material Analysis Toolbox based on OpenFOAM (PATO):
 - 3D Finite-volume solver developed using OpenFOAM^[1].
 - Can simulate material response for wide range of materials with pyrolysis, ablation, mechanical erosion, etc.
 - Assumes Darcy Law for momentum and solves mass and energy conservation.
 - Can simulate multiple materials that are in perfect contact at interface with each other.



Simulation of a burning match in PATO[2].

Meshing for Material Response

- Meshing was done in Pointwise, and simulated in PATO for the following cases:
 1. 2D-Axisymmetric simulations of stack-up w/o TC.
 2. Unstructured 3D simulation w/o TC, based on spacing from 2D-Axi simulations.
 3. Unstructured 3D simulation for stack-up with TC at 15mm depth.



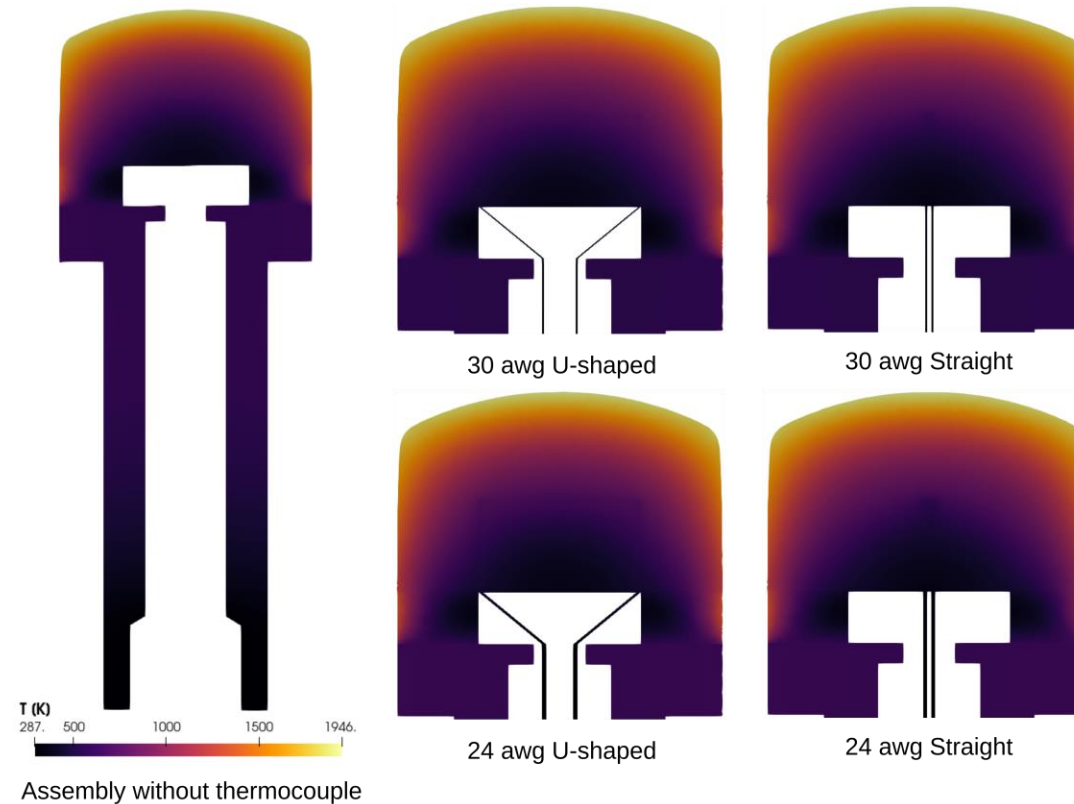
Material Response Simulation Setup

- The stack-up is initially at 14°C and 1000Pa.
- In the simulations, the stack-up is exposed to the plasma and heated for 30seconds and cooled for 45seconds.
- For stagnation surface, a B' boundary condition was used, with heat flux and pressure taken from aerothermal environment with a flux factor map.
- At the bottom of the stack-up a constant temperature of 14°C is imposed.



Material Response Simulations

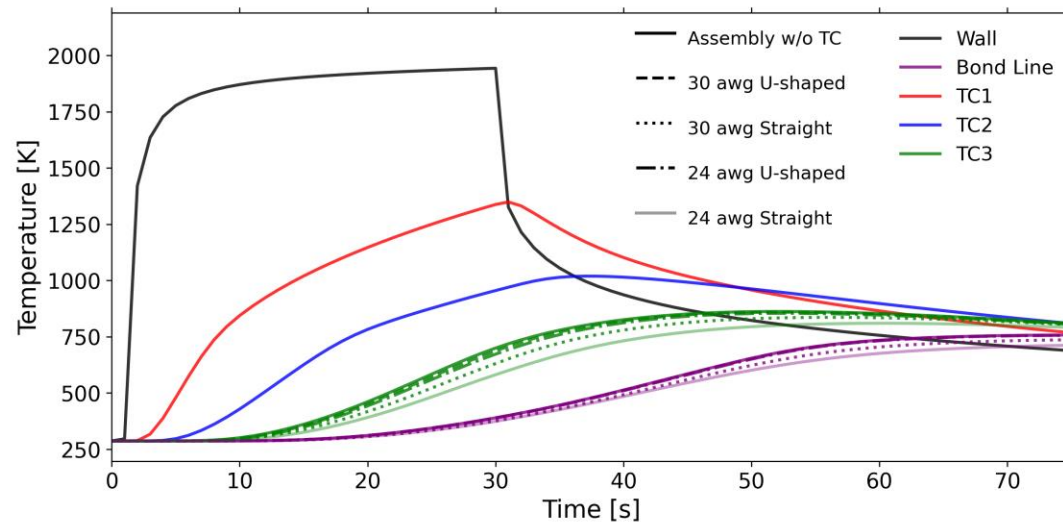
- Simulation contours for temperature shown below:
 - Shows that temperature profile is similar in all cases throughout the sample
 - Temperature near TCs gets lower, especially for 24awg straight TC case.



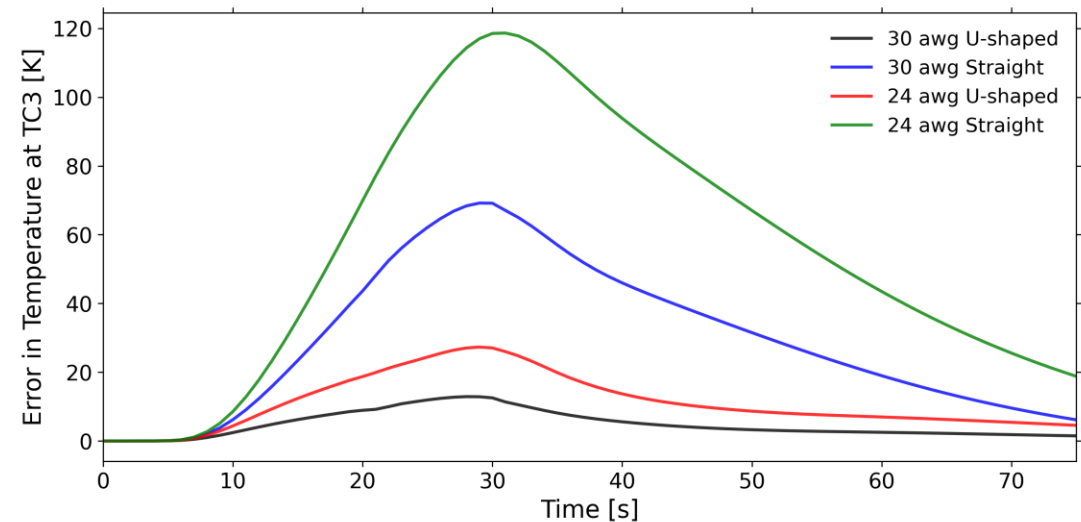
Temperature contour along slice at maximum heating, at $t = 30\text{sec}$.

Temperature Profiles

- Temperature profiles at top surface, 5, 10, 15mm depth, and bond line of the sample are compared.
- Temperature profiles showed that physical presence of thermocouple affects the temperature locally at 15mm depth.
 - 30awg thermocouple has lower error compared to 24awg.
 - U-shaped thermocouple for both gauges performs significantly better than the straight thermocouple.



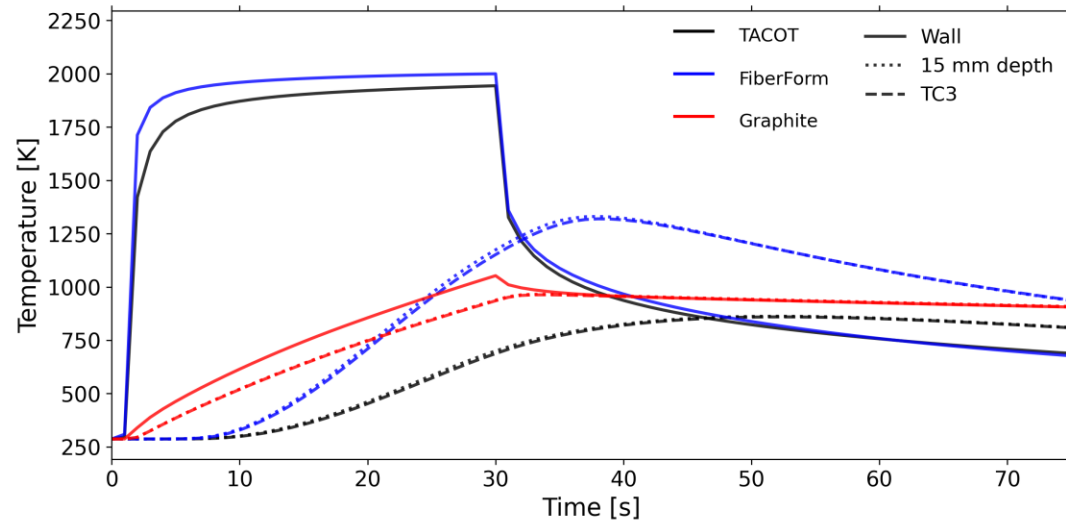
Temperature profile in the TACOT sample for different TC configurations.



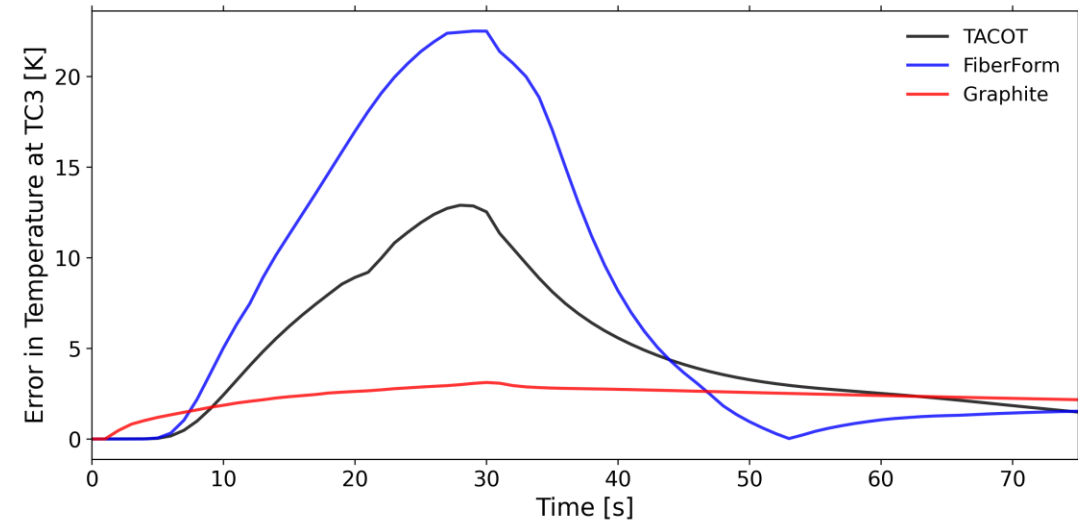
Error in temperature at 15mm depth w/ and w/o a TC.

Variation of error with TPS Material

- For the 30 awg U-shaped TC, different TPS materials, namely TACOT, FiberForm and Graphite, were considered.
- The error at 15mm depth was:
 - 22.5°C (1.98%) for FiberForm,
 - 12.9°C (1.96%) for TACOT,
 - 3.1°C (0.33%) for Graphite.
- Material properties clearly have an influence on the error.



Temperature profile in different TPS samples for 30awg U-shaped TC.

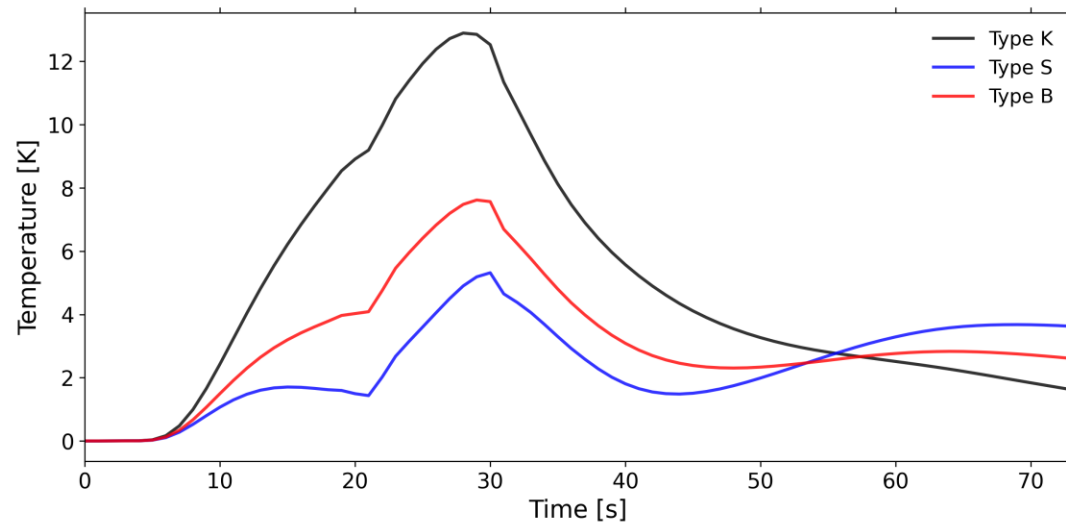


Error in temperature at 15mm depth w/ and w/o a TC.

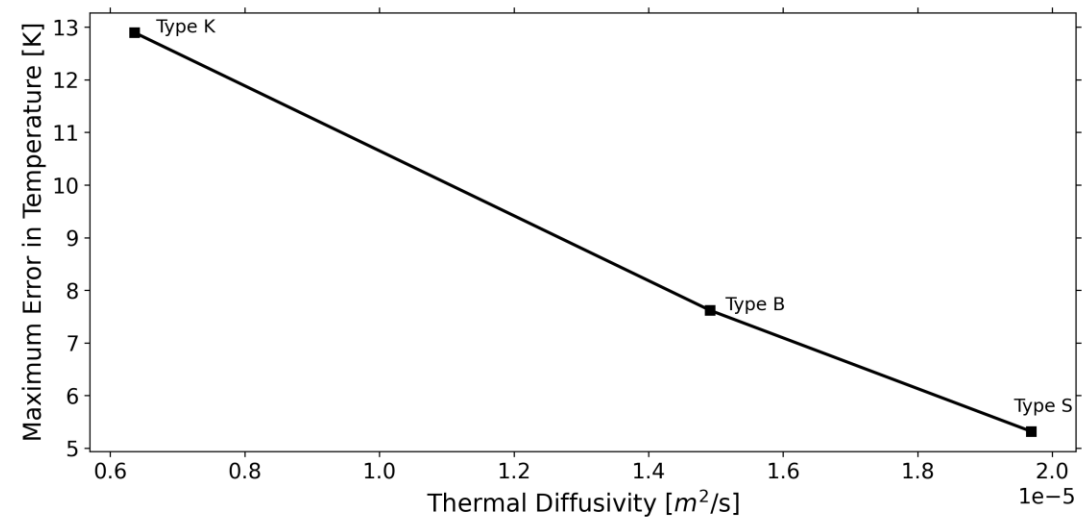


Variation of error with TC type

- For TACOT, the TC type was varied for the 30 awg U-shaped TC at 15mm depth.
- The different types studied were Type K, S and B:
 - To vary TC type, the density, thermal conductivity and heat capacity were varied in the simulation.
- Relative material properties clearly have an influence on the error.



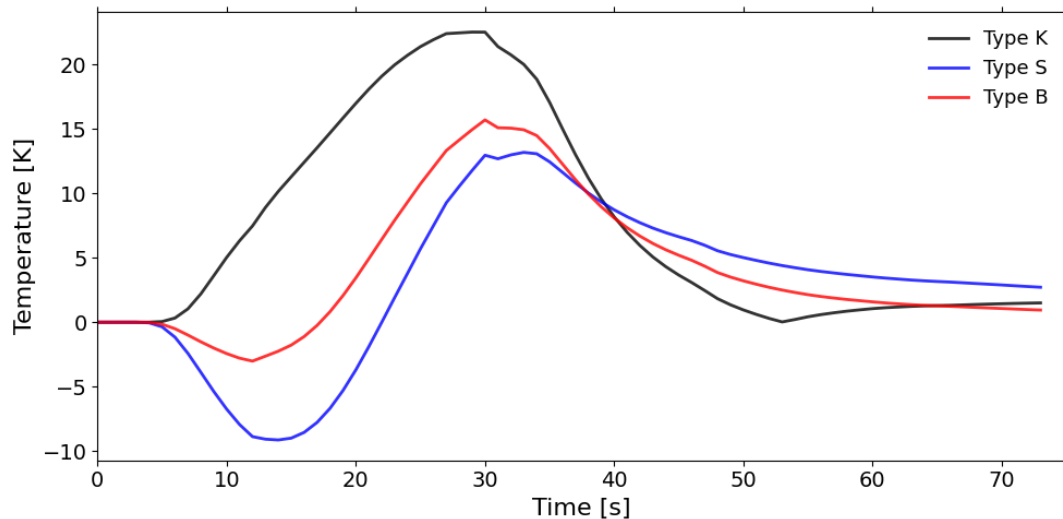
Temperature profile in TACOT sample for 30awg U-shaped TC of different types.



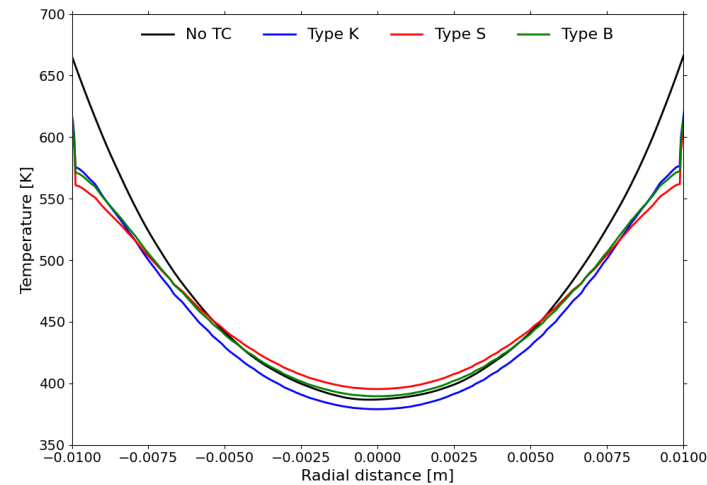
Error in temperature at 15mm depth w/ and w/o a TC for different TC types.

Side Heating due to TC presence

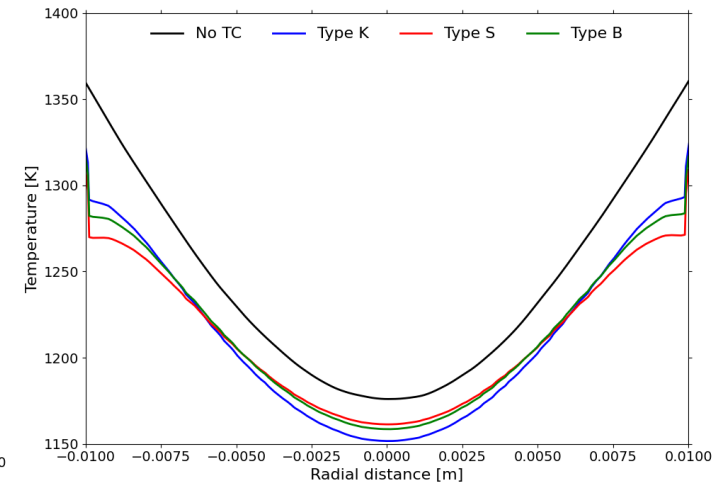
- For the U-shaped TCs, heat could transfer from the sides of the TC to the junction increasing the temperature at the junction.
- Could occur if:
 - TC lead wires are too close to the side walls of the sample.
 - Sample is preferentially oriented and has higher conductivity in the side-wise direction.
- Need to consider while choosing TC plug diameter.



Error in temperature at 15mm depth in FiberForm for different TC types.



Temperature profile along TC at $t = 12\text{sec}$.



Temperature profile along TC at $t = 30\text{sec}$.

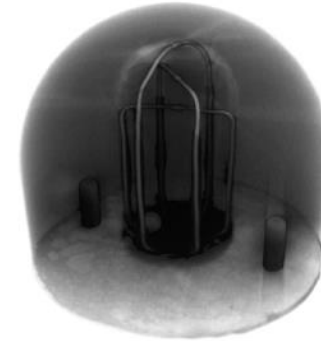
Final Remarks

- To accurately capture in-depth behavior of TPS materials, intrusive thermocouple measurements are needed.
- Presence of different components alters the ablative response of the TPS material, which affects the temperature measured by thermocouples.
- Physical presence of the thermocouple can also have significant impact on the local temperature field.
 - U-shaped TCs are better for TACOT than Straight-TCs.
 - TCs with smaller thickness have lesser impact on the TPS material's temperature.



Future Work

- Include thermocouple plug, implement non-perfect contact in PATO.
- Couple TC temperature field to an electrostatic solver, obtain voltage-difference across TC and find TC reading.
- Simulating samples with more materials such as gap-fillers, TC insulators, etc.
- Experimentation!



(a) Graphite sample embedded with TCs[2],
(b) PICA assembly with RTV cylinder.



[1] Munafò, Alessandro, et al. "A Multi-Physics Modeling Framework for Inductively Coupled Plasma Wind Tunnels." *AIAA SCITECH 2022 Forum*. 2022.

[2] Ringel, Benjamin M., et al. "Ablation of carbon thermal protection system materials in high enthalpy air plasma." *AIAA AVIATION 2022 Forum*. 2022.

Acknowledgements

- This work was supported by a NASA Space Technology Graduate Research Opportunities Award.
- I would like to thank:
 - Jeremie Meurisse and PMM group, AMA Inc. at NASA Ames,
 - Benjamin Ringel and CHES colleagues,
 - CHES, Grainger College of Engineering,
 - Jeff Engerer, Sandia National Laboratories,
 - NASA NSTGRO.

Thank you! Any questions or suggestions?

