12th Ablation Workshop

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Posters

Overview and welcome

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Overview of Ablation Modeling at NASA

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Abstract

The ambitious scientific payload and crew delivery goals of imminent and future NASA missions are associated with challenging and complex vehicle entries. Advanced ablative Thermal Protection System (TPS) materials will be required for such missions, and, as such, a robust ablation modeling capability is critical to assessing performance by bridging the wide gap between ground testing and entry conditions. The traditional ablation modeling toolset - continuum thermal/materials response analysis - has grown recently to include high-fidelity, multi-scale, and multi-physics techniques that provide a more complete description of the rich physics and chemistry of ablation to better drive down risks related to extreme entries. The present talk provides a snapshot of ongoing NASA activities in ablation modeling, including a review of the current technical capabilities and tools at play within the Agency, the important role academia plays in supporting technical area advancements, and how such internal and external investments intersect with upcoming missions to drive down risks.

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Overview of AFOSR ablation activities

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Overview of ArianeGroup and the European Space Agency ablation activities

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Abstract

ArianeGroup ablation activities during the latest years played around the HEARTED ESA project [1]. European background is limited to velocities not exceeding the 8km/s typical of a Low Earth Orbit re-entry. The main objective of Hyper-velocity EArth Re-entry TEchnology Demonstrator (HEARTED) is to fill such a knowledge gap by demonstrating Europe's capability of safely and successfully flying a Earth Re-entry Capsule (ERC) with an entry velocity ~ 11km/s and to prepare for future science/exploration missions. Such a mission aims at speeding-up the maturation of several identified critical technologies with lack of knowledge/experience. One of the main technology development focused on the Thermal Protection System maturation combining not only thermal but also thermo-structural capabilities. For this purpose a Naxeco© Resin monolithic heatshield have been manufactured with a new robotized process and this pieces will equipped the SCX01, the first experimental Space Case (a reentry capsule demonstrator) that will be launch on Ariane6 maiden flight [2]. In order to improve fidelity of the thermal and ablative response simulations of such TPS, AGS is supporting VKI by improving thermo-physical characterization technics of ablative and charring material [3] as well as producing the European ablative test case based on representative plasma test campaign [4].

Keywords: Thermal Protection System, Naxeco, High Speed Reentry, Hearted, Space Case, AblaNTIS, ReChar TPS

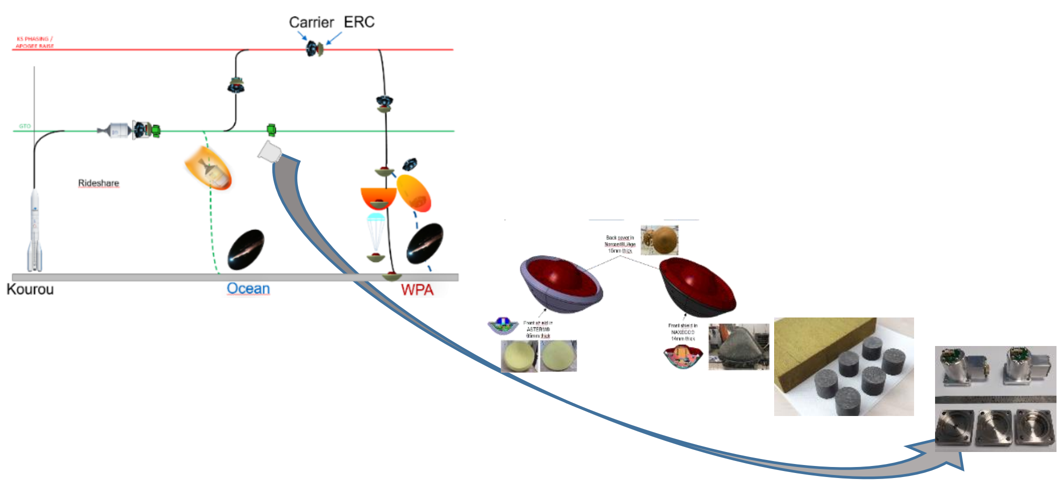

Figure 1: From Mission, Earth Entry Capsule and technologies development roadmap at ArianeGroup

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[2] Spacecase: development of a commercial test plateform for reentry experiments. J. Bertrand, M. Régnier, G. Pinaud, P. Tran, Heilbronn, DE, 19–23 June 2022

[3] ReChar: Assessment of reliable material characterisation methods for charring ablators, B. Helber, F. Torres-Herrador, A. Turchi, T. E. Magin, O. Chazot, A. Denis, Heilbronn, DE, 19–23 June 2022

[4] Ablative material numerical test case series (AblaNTIS)—From experimental tests to numerical results, A. Turchi, B. Helber, F. Torres-Herrador, A. Fagnani, T. Magin, F. Pascon, L. Chipperfield, H. Ritter, FAR2022, Heilbronn, DE, 19–23 June 2022

Overview of Ablation Research at Sandia National Laboratories

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Abstract

The past few years have brought about an increased interest in increasing our fundamental understanding the ablative performance of heat shields for Earth atmospheric reentry, largely due to an invigorated interest in redesigning ballistic and hypersonic weapon systems. Over this time period, Sandia has significantly increased its investments in ablation research, including work in fundamental materials manufacturing and characterization, multi-scale multi-physics modeling for prediction material properties and performance, vehicle-scale coupled aerodynamics and material thermal response modeling, diverse ground testing, and lower-cost flight tests. This work largely focuses on woven composites for thermal protection systems, including carbon-phenolic and carbon-carbon materials, among others. In this talk, we overview the broad scope of fundamental and applied research Sandia is conducting, and how it impacts the greater ablation research community.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Keywords: woven composites, thermal protection systems, ablation, manufacturing, modeling, ground testing, flight testing

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An overview of VKI activities related to ablation research

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Abstract

This talk will provide an overview of ablation relevant activities carried out at the von Karman Institute for Fluid Dynamics (VKI). Our main efforts focus currently, beside the material characterization and simulation of carbon-phenolic materials (other talk), on the detailed experimental and numerical characterization of demise processes of common space debris materials. Those are mostly silicates (such as quartz, which represents an interesting material for the study of surface energy and mass balances of melt flows with evaporation), alloys (mostly titanium, which is problematic because of its low oxidation resistance), and Carbon-Fiber-Overwrapped-Vessels (COPV), which inherently behave like an ablator as they are composed of woven carbon fibers and epoxy resin. We will present experiments and simulations of those materials in different temperature regimes [1]. The experimental setup has been further improved for a more detailed investigation of the surface emissivity at different wavelength bands, adapted to each material [2].

New supersonic nozzles, including a semi-ellipse, have been designed and commissioned at VKI for the purpose of extending the testing regimes and the operational envelope of the Plasmatron facility [3]. Higher shear stresses can be reached in stagnation point but also flat plate configuration for a wider range of future material characterization tests.

Beside our experimental work in the high-enthalpy Plasmatron facility, we also performed low-temperature ablation experiments in the low-enthalpy hypersonic wind tunnel H3 at the VKI using camphor. The goal of this activity was to study the effect of the shape change on the aerodynamic coefficients of the ESA Phoebus capsule in hypersonic conditions [4]. In a parallel activity, spin-off results on cross-hatching have been obtained.

Keywords: Ground-testing, simulations, demise, radiometry, gas-surface interaction

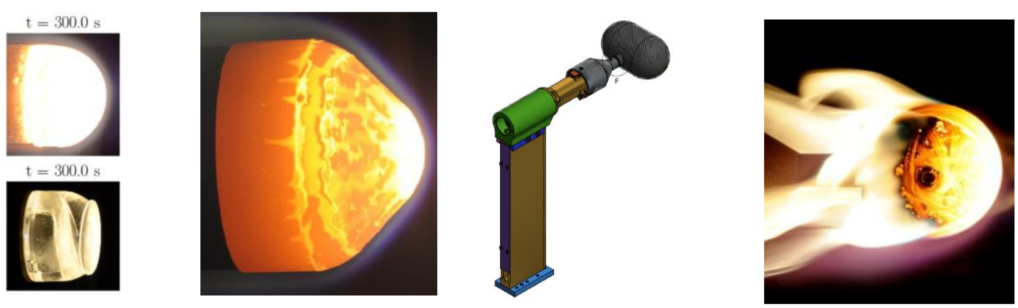

Figure 1: Subsonic (upper) and supersonic (lower) quartz ablation (left), titanium oxidation (middle-left), and ablation test of a miniaturized COPV tank with titanium liner (both right).

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A perspective on ablative TPS needs by emerging commercial space and NASA's role

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Mesoscale Ablation Modeling

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Abstract

The development of next generation materials for thermal protection systems will rely more heavily on simulation than ground testing, in contrast with historical development practices. High-fidelity image-based simulation using as-manufactured materials builds the relation between material mesostructure and ablative performance, fostering rapid development and progress in material design. Addressing the ablation problem at the mesoscale helps characterize the role of material heterogeneities and defects and can inform volume-averaged material response models that are typically calibrated to a specific material.

In this talk, we present a pyrolysis and ablation model of a woven composite at the mesoscale. Each phase is treated as a porous material where gas and solid phase species are tracked using a mass balance equation allowing for changing density, chemical reactions, dynamic material properties, and pyrolysis gas flow. Pyrolysis is modeled through simple Arrhenius reaction mechanisms in the matrix and weave phase, where an inert fiber background is present in the latter. Temperature evolution is captured through an enthalpy-based porous energy equation accounting for the species present in each phase. Surface ablation and recession is tracked using the Conformal Decomposition Finite Element Method. We demonstrate the variability in mass loss, recession, and surface roughness as a function of material geometry and properties.

Keywords: woven composites, thermal protection systems, pyrolysis, ablation, mesoscale

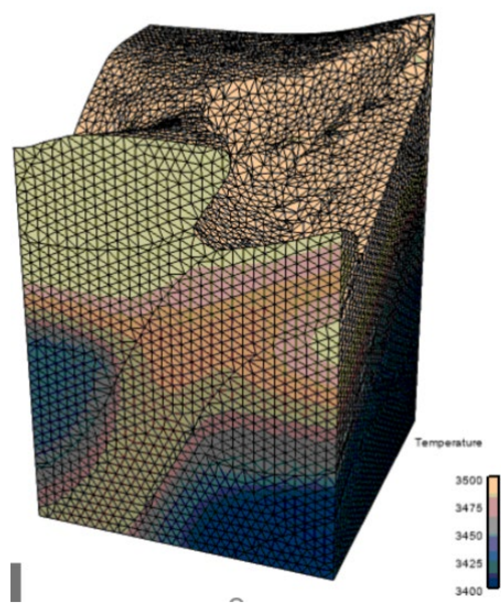

Figure 1: Volume rendering of a transient mesoscale simulation of ablation of a woven composite, colored by temperature and showing the uneven recession of the top surface.

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Supervised learning model for permeability of TPS materials

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Abstract

Generating an exhaustive material property database for ablating thermal protection systems (TPS) materials is a challenging task because the properties must be quantified as a function of temperature, pressure, degree of char, degree of oxidation, and composition of decomposing gases. Typically, properties are quantified in the virgin and char state (or a few states in between) and interpolated between these two limits, which introduces errors in material response simulations. More importantly, for a multi-dimensional input space of temperature, pressure, degree of char, oxidation, and other parameters, the approach taken for interpolation itself is an open problem. We demonstrate that supervised machine learning models can be used to overcome this issue by building models for material properties that can be incorporated into material response codes in a straightforward manner. The model can be trained on a limited set of data, and more importantly, the model maps the multi-dimensional complex space to an analytical function that is both continuous and differentiable. The development of the supervised learning model is illustrated using material permeability, where a model is developed for permeability as a function of temperature, pressure, porosity, degree of char, size of the microstructural volume, and the type of gaseous species flowing through the material.

Keywords: Supervised machine learning, material property database

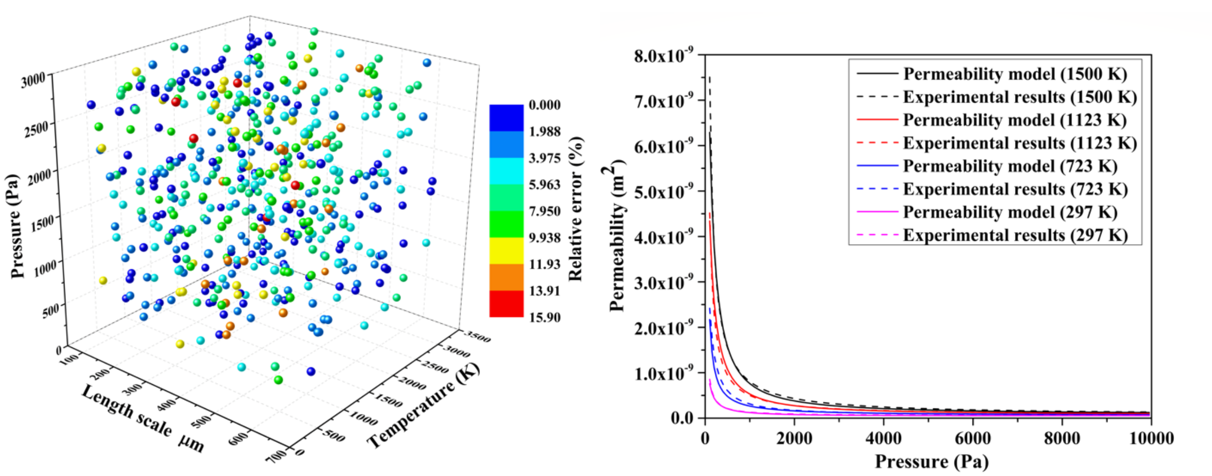

Figure 1: Training of a supervised learning model and comparison to experiments

Characterizing Char Rate and Extent in Fiber-Reinforced Plastics Using X-ray Computed Tomography

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Abstract

Orbital debris is a growing problem for the space industry and the world in general, and an important component of the problem is what happens when that debris reenters the Earth's atmosphere. With more spacecraft opting for fiber-reinforced polymer (FRP) components, we need to understand the thermal destruction process of these materials during an atmospheric reentry and how much of the material can survive to impact the ground. The NASA Orbital Debris Program Office (ODPO) has developed a new charring model for FRP components to be integrated into the latest version of the Object Reentry Survival Analysis Tool (ORSAT). To validate this new model, the ODPO performed several test series using the Inductively Coupled Plasma (ICP) Torch facility at UT Austin. To measure the extent of charred material at different conditions, some of the test samples were scanned using x-ray computed tomography (CT) by the Astromaterials Curation Lab at Johnson Space Center. 3D image analysis was then used to calculate the volume and density of the char in each test sample. This paper presents the image analysis methodology, an assessment of the accuracy of the data analysis, and a comparison with calculations using the ORSAT charring model.

Keywords: Heat Transfer, Pyrolysis, X-ray Computed Tomography, Carbon Fiber, 1D Heat Transfer

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High temperature morphology of phenolic resin pyrolysis

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Abstract

This study utilizes synchrotron x-ray micro-computed tomography (micro-CT) to resolve the morphological and mass evolution of SC-1008 phenolic resin through its pyrolysis regime. The resin samples are heated in an inert environment and scanned *in-situ*, acquiring time-resolved tomographic datasets over a range of heating rates to observe its influence on porosity and volume change [1]. In-situ micro-CT improves on legacy studies [2, 3] of phenolic resin by observing the complete morphological evolution through pyrolysis by capturing porosity (open and closed), pore shape distributions, shrinking and swelling, and changes in local material density. Quantitative inner morphology changes are tracked and visualized in-situ for multiple heating rates up to 1000°C. Attenuation results can be used to approximate effective density, which agree well with heritage ex-situ measurements on charred phenolic. It is observed that the resin undergoes a period of volumetric swelling at temperatures below 350°C before a 45% decrease in bulk volume. Heating rate is found to clearly influence on the amount of closed porosity that accounts for 6% of total porosity. Future work aims at resolving the micro-morphology evolution in the presence of a weave reinforcement.

Acknowledgement: SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Keywords: Resin, Tomography, Pyrolysis, Morphology, Porosity, Synchrotron

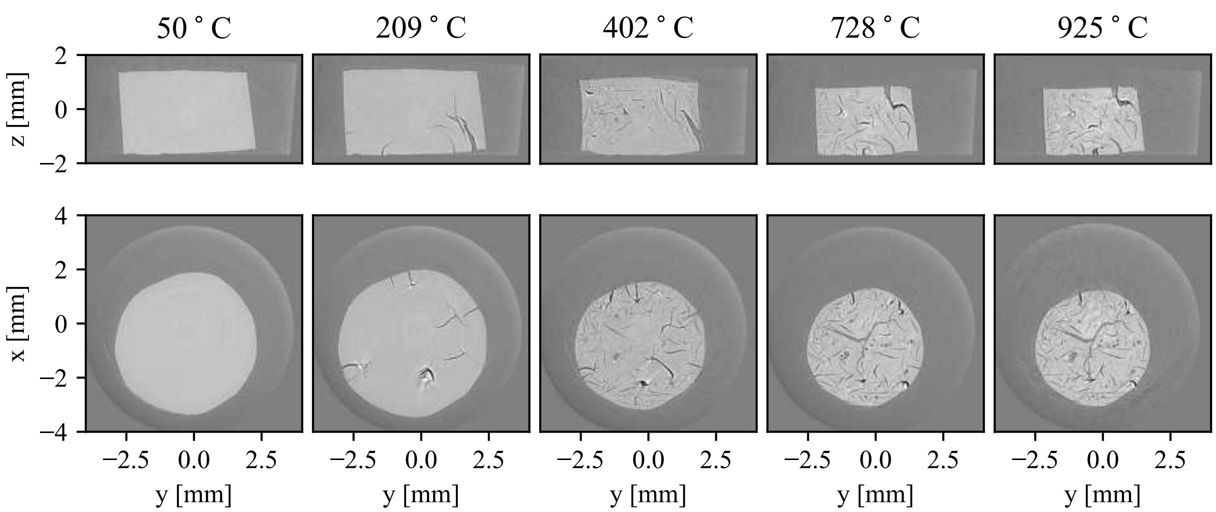

Figure 1: Pyrolysis and mesoscale morphological evolution of SC-1008 resin.

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Overview and Recent Developments of Icarus

Eric C. Stern[a,*], Joseph C. Schulz[b], Georgios Bellas-Chatzigeorgis[b], Olivia M. Schroeder[c], Grant E. Palmer[b], Prakash Shrestha[b]

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Abstract

Icarus is a three-dimensional, unstructured, finite-volume material response solver developed at NASA Ames Research Center and has been verified against other NASA material response tools like FIAT, which have a long history of successfully designing thermal protection systems (TPS). Icarus solves a set of conservation equations for mass and energy and uses Darcy's Law in place of momentum conservation. A toolkit of TPS analysis utilities has been built around a general-purposed Icarus library that in addition to the typical material response analysis also supports TPS sizing (1-D and multi-dimensional), uncertainty quantification, and has been successfully integrated into a multi-physics architecture built around the US3D flow solver. In this presentation, a brief overview of Icarus and its capabilities will be presented via a discussion of a variety of Icarus simulations that have been conducted in support of on-going NASA missions, e.g., Dragonfly, Mars Sample Return, etc. Lastly, the on-going efforts to develop a multi-physics architecture built around US3D and Icarus, called Ares, will be presented with a focus on the future direction of Ares and the types of NASA applications for which Ares is needed.

Keywords: Ablation, Material Response, Thermal Protection Systems

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Comparison of Material Response Models

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Abstract

The objective of this study is to investigate the differences and similarities between two commonly used material response (MR) models: 1dFIAT (Fully Implicit Ablation and Thermal response program) and ITRAC (Insulation Thermal Response and Ablation Code) [1, 2]. Models of an OTB (Oxy-Acetylene Test Bed) are compared to each other and to experimental results to find the strengths, weaknesses, and limitations of each MR model [3]. Two different surface thermochemistry programs were tested to create B' tables for the models [4]. PICA (Phenolic Impregnated Carbon Ablator) was used as a model ablative material and was evaluated at 3 different heat fluxes (250, 500, and 750 W/cm^2) for 60 seconds. Machine learning was used to generate and predict boundary conditions. The ideal applications for each program and challenges associated with material response modeling are also discussed.

Keywords: Material Response Model, Machine Learning, Boundary Conditions, Surface Thermochemistry, B', 1dFIAT, ITRAC.

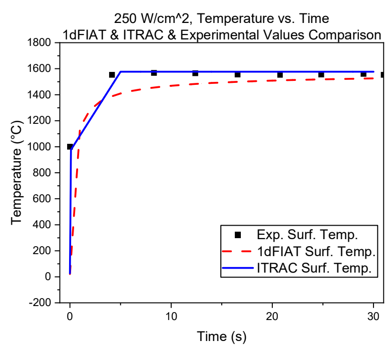

Figure 1: Surface Temperature Comparison at 250 W/cm^2, 60s.

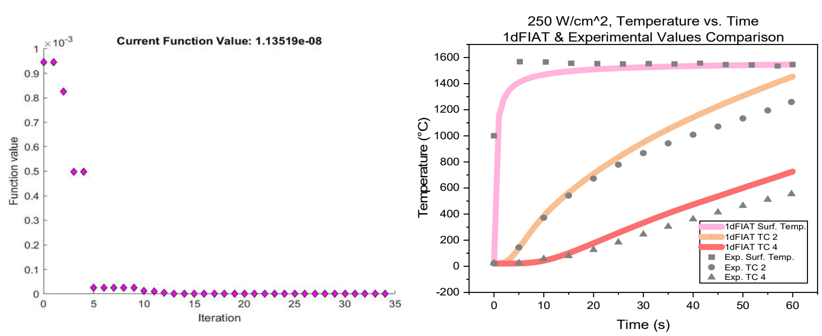

Figure 2: Machine Learning to Find Boundary Conditions and Refine Model

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Numerical reconstruction of spalled particle trajectories in an arc-jet environment

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Abstract

Spallation is a form of ablation, where the material loses mass in the form of particle ejections when exposed to high heat rates. The spalled particles are typically disconnected fibers or chunks of material. The presence of these particles in the flow field tends to change the surface heating rates due to their chemical interactions, and their ejections tend to accelerate the material recession.

Estimating the mass loss due to spallation is essential to evaluate its effect on ablative materials. In order to achieve this, a Lagrangian particle trajectory code [1] is used to reconstruct trajectories that match the experimental data for all kinematic parameters. A data-driven adaptive methodology [2] is used with the particle trajectory code that adapts the ejection parameters until the numerical trajectory matches the experimental one. The results from spallation experiments [3] conducted at the NASA HYMETS facility are considered. Since the chunks of material ejected from the material are not spherical, a non-sphericity model is developed and added to the reconstruction methodology. A back-tracking method is also added to simulate the particle's complete path.

Keywords: Spallation, Ablation, Particle-laden flows, Thermal Protection System

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Material Response Simulations of Dragonfly Capsule using Icarus

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Abstract

Icarus is a three-dimensional, unstructured, finite-volume material response solver developed at NASA Ames Research Center and has been recently used to analyze the material response of the Dragonfly capsule for a variety of problems. In this presentation, three topic areas will be discussed. First, the Dragonfly capsule has a unique forebody-shoulder geometry consisting of a ”tooth” intended to reduce the radiation exposure to the backshell surface material. The ”tooth” is subject to a three-dimensional convective heating profile, and the material response within that region can not be investigated using traditional one-dimensional design tools. Icarus simulations are used to investigate the multi-dimensional material response in the shoulder region of the Dragonfly capsule. Secondly, since the Dragonfly capsule will be instrumented in a similar manner to the Mars 2020 and MSL capsules, there are a variety of decisions with regards to sensor placement and design still under review. In the second topic of this presentation, Monte-Carlo simulations using Icarus will be used to assess the ideal thermocouple types and depths needed to best reconstruct the aerothermal environments. Lastly, a US3D-Icarus coupling tool called Ares is used to analyze the two-dimensional material response of the backshell. Radiometers on the backshell will be used to reconstruct the freestream Methane concentration, and it is intended to use fully-coupled fluid-material-radiation simulations to evaluate the uncertainties and sensitivities of the reconstruction process. Key results of the initial US3D-Icarus simulations are introduced to motivate future simulations of the fully-coupled problem.

Keywords: Ablation, Material Response, Thermal Protection Systems

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Overview of post-flight analyses and airborne observation of Hayabusa2 SRC ablative heatshield

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Abstract

The Hayabusa2 sample return capsule (SRC) entered the earth atmosphere directly from an interplanetary-transfer orbit at about 12km and was safely recovered on the ground [1), 2)]. During the reentry flight, airborne observation campaign was carried out under a collaborative research work between NASA and JAXA[3)]. As one of the analytical results of the airborne spectroscopic data, maximum surface temperature of the forebody heatshield was estimated to be about 2,600 K, which was low compared to the measured data in Hayabusa1 SRC reentry. Three-dimensional laser scanning was carried for measuring surface displacement of the forebody heatshield and it showed 0.37 mm recession at maximum (Fig. 2), which was within design criteria. In addition, internal aspects of the forebody ablator were inspected though theX-ray CT scanning for checking damages and the degree of thermal decomposition etc. As a result, no severe damages or deficits were found on the X-CT preliminary images [2)]. The reentry flight environment measurement module (REMM) onboard SRC successfully measured accelerations, attitude rates, and internal temperature profiles insides SRC for 420 sec during the reentry before touchdown.

Keywords: Hayabusa2, Sample Return Capsule, Heatshield, Ablator, X-ray CT scanning, Airborne Observation

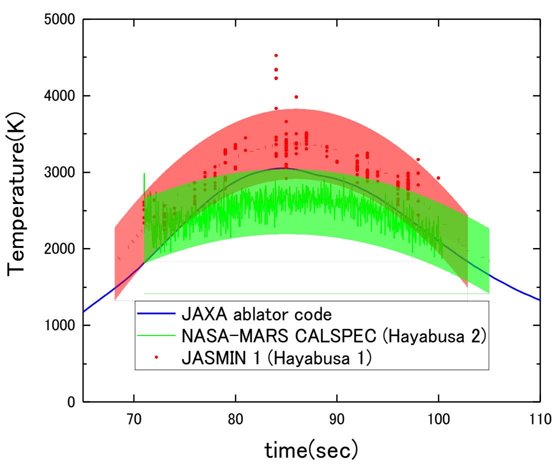

Fig. 1: Comparison of surface temperatures Hayabusa 1 (Red) and Hayabusa 2 (Green). JAXA ablation analysis was plotted as a solid line. (taken from Ref. [4])

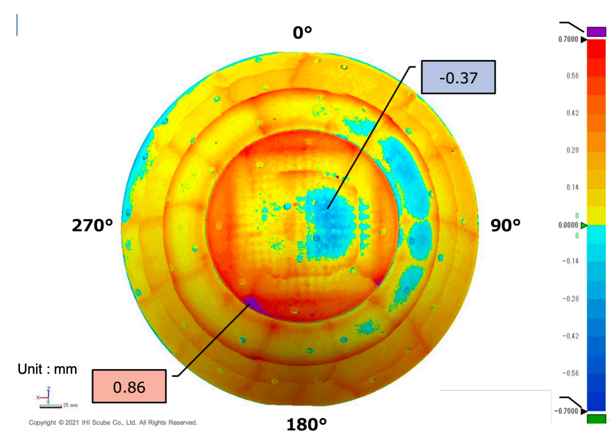

Fig. 2 : A result of 3D laser scanning of the Hayabusa2 forebody heatshield viewed from the nose tip. (taken from Ref. 2])

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KREPE: The First Orbital Entry Mission of the KRUPS capsule

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Abstract

The Kentucky Re-entry Universal Payload System (KRUPS) is a capsule developed to conduct atmospheric entry experiments quickly and inexpensively. KRUPS is designed to test multiple types of thermal protection systems (TPS) and data acquisition instruments. In 2021, three KRUPS capsules were sent up to the International Space Station (ISS) via the NG-16 Cygnus resupply vehicle. After the completion of the resupply mission, the Cygnus vehicle de-orbited with the capsules inside. Cygnus then broke up into the atmosphere in order to burn up stored trash. The three KRUPS capsules were released during this breakup event and re-entered the atmosphere of Earth at hypersonic velocities. Each capsule was outfitted with a heat shield which protected the internal electronics and allowed the capsule to survive the entry. The capsules were able to measure the temperature of the TPS during re-entry and transmit the data via the Iridium satellite network. This was the first high-speed re-entry experiment completed by a university and it was also the first re-entry of a vehicle outfitted with a 3D printed heat shield. The success of this mission demonstrated that KRUPS is a viable testbed for re-entry experiments.

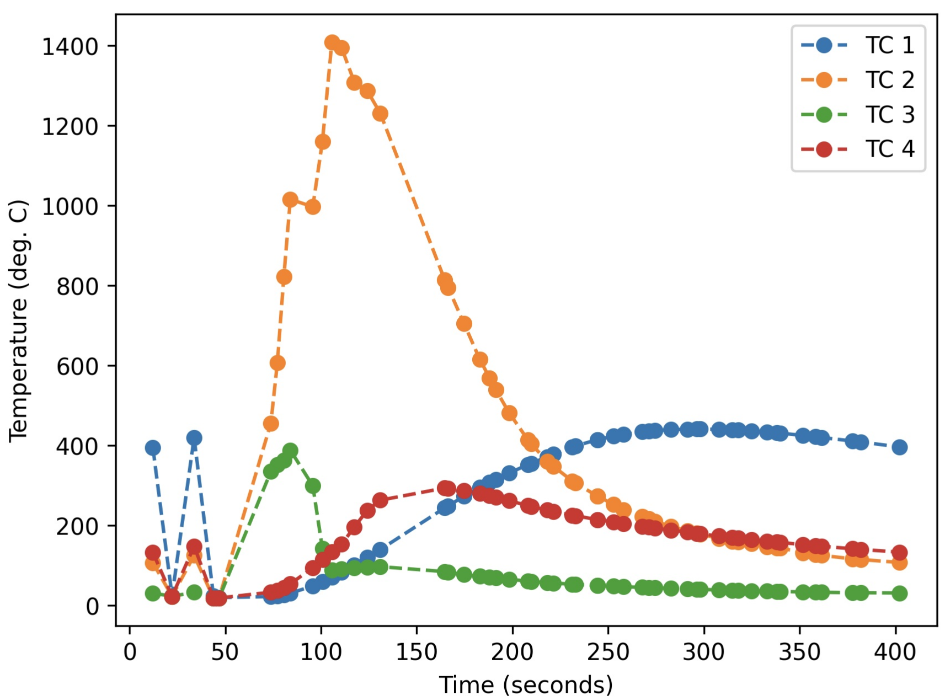

Figure 1: Thermocouple data obtained during KRUPS-002 re-entry

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NASA's envisioned future and where we fit

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Ares: A Multi-Physics Modeling Framework for Entry Systems

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Abstract

Recent developments in modeling capabilities for entry systems have enabled deeper understanding of relevant physics through high fidelity modeling. However, this fine-grained information can become stunted by the assumptions used at locations where the physics are highly coupled. An example of this is the uncoupled approach commonly used in ablation modeling, where the shared wall boundaries between fluid and solid domains are treated independently. In practice this implies that the total heat flux applied to a material response configuration is determined at an inconsistent wall temperature, the gas-phase kinetics associated with carbonaceous ablation products are entirely neglected in the flow, and boundary layer thickening due to blowing is accounted for only through a correction factor in the film coefficient. Furthermore, it is often assumed that shape change has no effect on the flow dynamics and resultant heating, which may hold true for shapes conducive to uniform heating distributions but breaks-down with the introduction of geometric features, material interfaces, or damage sites. Other examples of uncoupled methodologies include the treatment of radiative heat transfer and particle laden flows, both of which contribute terms in the surface energy balance.

In order to provide an alternative analysis approach, a new software is being developed, Ares [5], with the intent of providing a general platform to integrate specialized software kernels in a unified framework for multi-physics problems. To date, the focus of Ares development has been primarily on providing a fluid-solid coupling tool between US3D [1] and Icarus [4]. The software has been designed as an application programming interface (API) for the Icarus solver, using principles of object-oriented programming, where classes of the Icarus library are instantiated and manipulated from the coupling API.

At the interface, parallel data exchange algorithms for shared boundaries of distinct solvers are developed, allowing for decisions about the solid solver load balancing to be made independently of the partitioning of the flow solver.

To model the physics at the ablating wall, Ares solves the coupled surface energy and mass balance equations where the production rate of species at the wall is computed from a 20-reaction, finite-rate chemistry model developed at the University of Minnesota [3].

Finally, a radial basis function interpolation method is implemented for moving the fluid and solid meshes [2] to account for the ablation induced shape change.

In this presentation, an overview will be given of the development effort to date, ongoing applications of the software will be highlighted including validation efforts with arc-jet test campaigns, and finally, insights into the future development directions will be discussed.

Keywords: multi-physics, coupling, ablation, mesh motion, gas surface interaction

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Numerical Modeling of Ceramics Leading Edge Oxidation in Inductively Coupled Plasma Facility

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Abstract

Inductively coupled plasma experimental facilities (ICP) are ideal to test leading edge materials in hypersonic relevant environment. They represent a high-fidelity target for both hypersonic flow solvers and material response codes to match numerical predictions with experimental observations. In this talk, we present ongoing efforts to develop a numerical platform able to account for the multiphysic of material response in high enthalpy flow. The numerical framework is composed of a solid solver (namely PATO [1]) that simulates the multi-material probe used experimentally. The latter is composed of several parts: the ceramic sample being tested, graphite and the insulation; each component having its own physic model. A detailed overview of the coupling strategy within the probe is provided, and the material solver is coupled to the numerical framework developed for ICP simulations [2]. Oxidation of ultra-high temperature ceramic is presented for different regimes. A discussion on the results obtained and ways of improvement will close this presentation.

Keywords: Heat Transfer, Mass Transfer, UHTC, Porous Media, Carbon Graphite

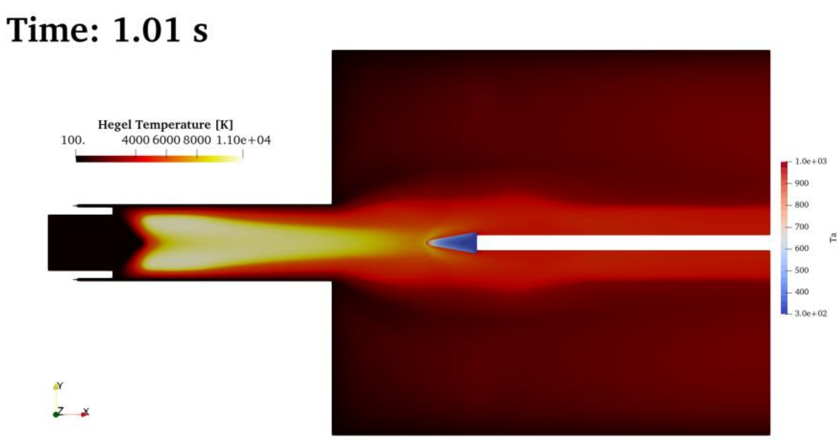

Figure 1: Zirconium Carbide Ceramics Response Simulation in an ICP flow

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Key aspects of a finite-rate air-carbon surface chemistry model

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Abstract

Recently molecular-beam experiments were performed [1] of high-velocity atomic oxygen (O) and atomic nitrogen (N) impacting carbon material at high temperature using a continuous molecular beam with lower velocity (2000 m/s) and approximately 500-times-higher beam flux than previous pulsed beam experiments [2]. These data were interpreted to construct a new air–carbon ablation model for use in modeling carbon heat shield ablation [3]. The new model comprises 20 reaction mechanisms describing reactions between impinging O, N, and O_2 species with carbon and producing scattered products including desorbed O and N; O_2 and N_2 formed by surface-catalyzed recombination; as well as CO, CO_2, and CN. For example, Fig. 1a shows probabilities for surface reaction product formation across a wide temperature range. The air-carbon ablation model includes surface-coverage-dependent reactions (surface coverage is shown in Fig. 1b) and exhibits a non-Arrhenius reaction probability in agreement with experimental observations. In this presentation, key aspects of the model that differentiate it from other models in the literature will be discussed. The dominant reaction mechanisms and rate coefficients will be described, and the rationale behind model choices will be discussed along with experimental evidence. Furthermore, key model aspects such as pressure dependence, oxidation in the presence of N-atom surface coverage, and avenues for future research, will be discussed.

Keywords: Nonequilibrium, Ablation, Computational fluid dynamics, Molecular beam scattering

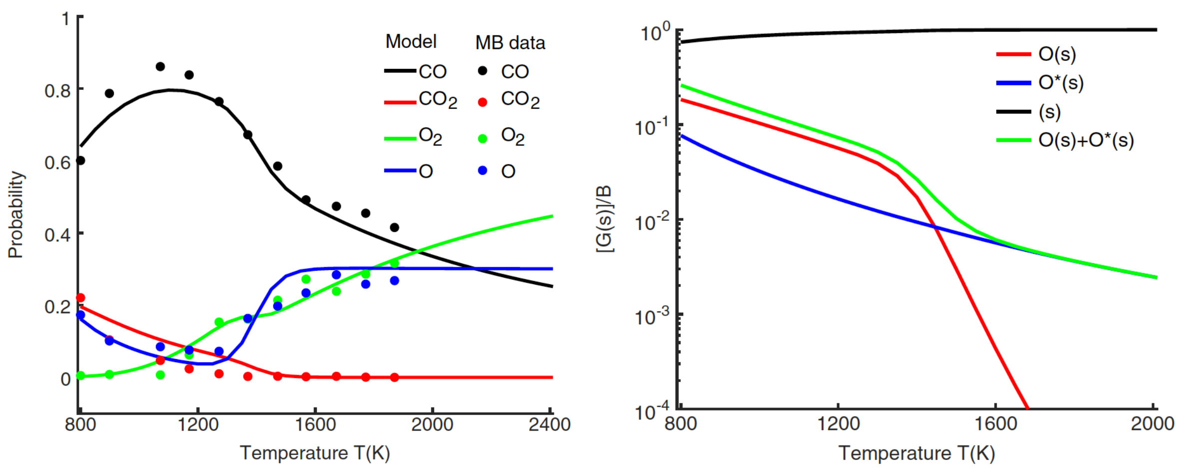

Figure 1: (a) Probabilities of reaction product formation according to the air-carbon ablation model and molecular beam measurements. (b) Surface coverage trends, for two types of adsorbed oxygen, predicted by the air-carbon ablation model. (Images taken from Ref. [3]).

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Detailed characterization and plasma-testing of carbon-phenolic ablators: towards an open-source datatabase for code validation

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Abstract

The sizing of ablative thermal protection systems for atmospheric (re)entry strongly relies on numerical modelling. Due to the complexity of the involved physicochemical processes, the development of accurate numerical models has been an ongoing task since decades. Still, significant uncertainties are attributed to the knowledge of the material response and its numerical rebuilding.

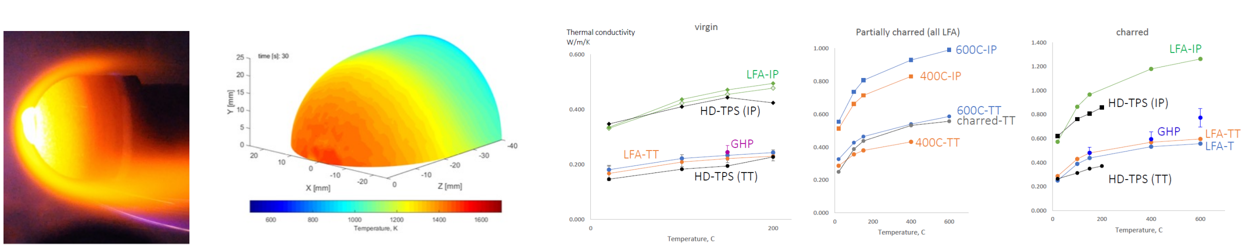
The generation of systematic test cases for the validation of ablative-material response tools is often hindered by restrictions typically present on the distribution of the material properties and test data. The creation of a validation dataset derived directly from plasma wind tunnel testing, and its compilation into a numerical test-case booklet for unlimited distribution, was a primary goal of the European Space Agency (ESA) GSTP project AblaNTIS led by the von Karman Institute (VKI). Therefore, the project was intentionally built around a material not subject to any confidentiality restrictions, the ZURAM® ablator developed by the German Aerospace Center (DLR).

A successful plasma wind-tunnel testing campaign was carried out in the VKI Plasmatron facility on both ZURAM and its "baseline" carbon-fiber preform. Tests were performed in sub- and supersonic high-enthalpy flows with cold-wall heat fluxes ranging from 300 kW/m^2 to 4.5 MW/m^2. The material samples were instrumented with up to 12 thermocouples to record the temperature evolution at different locations. Non-intrusive optical measurements were employed to measure the stagnation-point surface recession and temperature, and to reconstruct a quantitative 3D map of the temperature distribution over the sample surface.

A material characterization effort was paired with the plasma testing activity of AblaNTIS. This characterization began within AblaNTIS, to allow obtaining a first complete version of the ZURAM database, and was extended through the dedicated ESA TDE project ReChar, also led by VKI. ReChar, still ongoing, aims at establishing detailed and standardized material characterization techniques, applied to ZURAM, through the execution of several test phases in different, independent laboratories. This shall define standard measurement methods and procedures, which allow reliable and repeatable extraction of main material properties intrinsic to ablative materials such as the specific heat capacity and thermal conductivity.

The proposed contribution will describe the main outcomes of AblaNTIS and ReChar to prepare the future deployment of the numerical test cases and material databases built thorough these activities.

Keywords: Porous Ablators, ZURAM, Plasma Testing, Material Characterization, Material Response



(a) (b) (c)

Figure 1: (a) ZURAM sample tested in the VKI Plasmatron; (b) Reconstructed surface temperature mapping of ZURAM sample 30 s after injection in the plasma flow; (c) Comparison of thermal conductivity measurements for virgin (left), partially-charred (center), and charred (right) ZURAM using different measurement techniques.

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Ablation Test Cases: Validations for Modeling non-charring Ablators

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Abstract

Computational modeling of Thermal Protection Materials (TPM), used for aerospace applications, provides numerous advantages in preliminary selection and design of the heatshield material and shape for atmospheric entry vehicles. However, to serve as a reliable tool for prediction of the material thermal and ablative behavior, the modeling approach needs to be validated against real experimental and flight data, preferably at a range of conditions. The validation study is typically very complex as it requires reliable measurements not only for the material thermal response and surface recession, but also well characterized environmental conditions. The validation problem becomes even more complex when the material thermal response is dictated by the multi-physics effects such as solid conduction, in-depth thermal decomposition, pyrolysis gas flow and chemical reactions. The multi-physics effects complicate not only the modeling effort, but also the experimental measurement for validation of various aspects of the highly coupled problem.

In this study, a work was done to identify experimental data in the public domain that could serve as a validation source for material thermal response modeling tools. In addition, the studied test cases are aimed to serve as a guide for the planning of experiments for validation purposes in the future. To serve as a first step in a more complex validation study, the data presented here focuses only on non-charring ablators, where the material physics can be modeled with a single equation for the energy conduction and ablation is limited to the surface of the material. The scope of the presented test cases is limited to three materials: camphor, graphite and FiberForm®.

While there is no an ultimate test case that would validate every aspect of the material physics, the collection of the presented test cases provides a way for validation of the majority of important modeled parameters, such as surface and in-depth temperatures, surface recession and a shape change of the model. The numerical studies of the test cases are performed in an uncoupled mode, where the flow boundary conditions are predicted by the Data-Parallel Line Relaxation (DPLR) code [1] and the material thermal response is simulated with Kentucky Aerothermodynamics and Thermal Response System (KATS-MR) [2].

Sample results from the performed numerical studies are shown below. Figure 1 shows distribution of the surface heat flux and pressure on a hemi-cylinder model made of FiberForm® and tested in the HyMETS arc-jet facility. The results are shown for the high pressure condition among the two tests. The flow simulation was performed on a quarter of the original geometry. In the figure, for illustration purposes, the quarter shape is mirrored across the zx and xy planes. Figure 2 shows the material simulation results for the high pressure case (7500 Pa) and a comparison to the experimental data from the pyrometer and laser scan profile. The simulation was performed on a 2-D slice, extracted in the xy plane at the middle of the sample. Figure 3 shows the results from the second case for the lower pressure condition (3500 Pa).

Keywords: TPS ablation modeling, experimental validation

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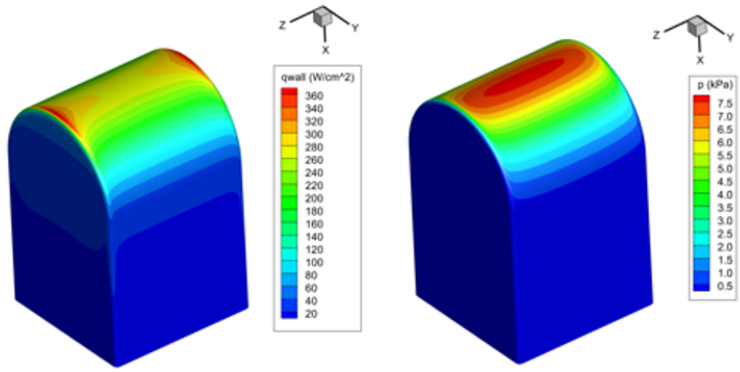
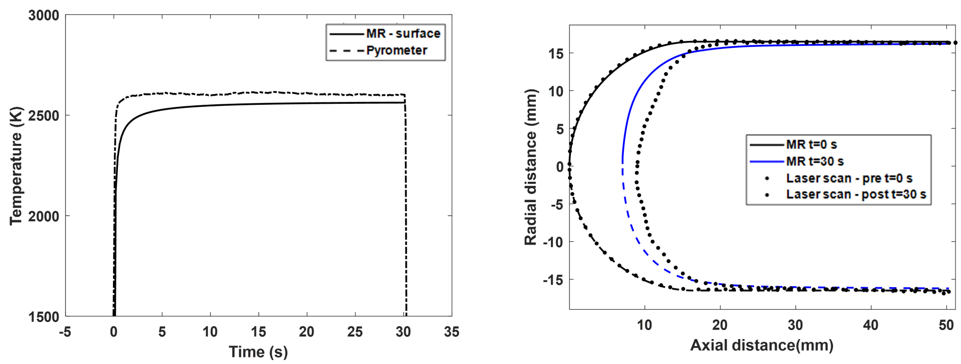


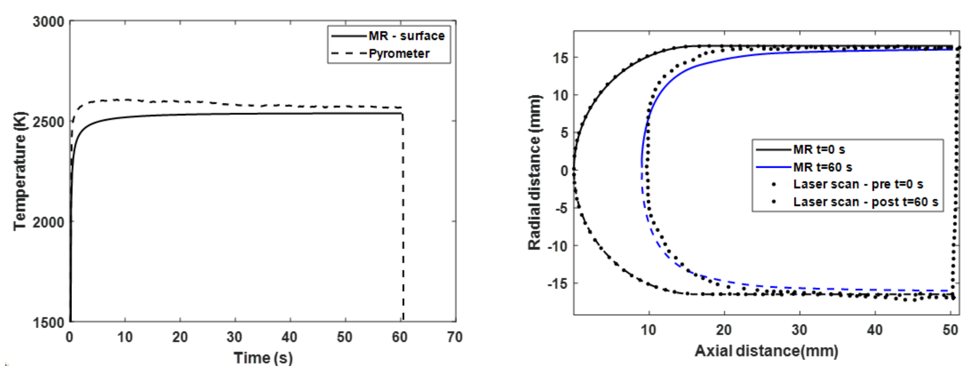
(a) Heat flux. (b) Pressure.

Figure 1: High pressure case. Simulated flow boundary conditions on a hemi-cylinder model. Quarter shape was mirrored across zx and xy planes.



(a) Surface temperature. (b) Shape change.

Figure 2: FiberForm® - high pressure case (7500 Pa). Comparison of simulated material response and experimental data.



(a) Surface temperature. (b) Shape change.

Figure 3: FiberForm® - low pressure case (3500 Pa). Comparison of simulated material response and experimental data.

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Implementation of active sites to capture pitting of oxidizing carbon materials in DSMC.

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Abstract

In this work we demonstrate a newly developed capability to capture pitting of carbon fibers in DSMC simulations, specifically using the Stochastic PArallel Rarefied-gas Time-accurate Analyzer (SPARTA) code [1]. State-of-the-art reactive surface models in DSMC compute collision dependent carbon consumption rates (usually through desorption of CO) based on a set of surface reactions that has been derived from molecular beam experiments [2]. The reactivity on each carbon surface element is constant in those models, such that the carbon surface recedes uniformly as a result of ablation. However, it is well known that in reality the carbon surface has locally different reaction rates due to the presence of defects at the atomic scale [3]. These defective sites have a much higher reactivity than the average sites (2-3 orders of magnitude) and are first to react during ablation leading to its removal. This causes all the neighboring atoms to be defective and increase their reactivity, thus leading to the localized carbon removal around these "active" sites (as shown in Fig. 1). In this manner, these highly reactive defective sites serve as nucleation sites for the formation and growth of etch pits with potentially detrimental effects on the structural integrity. Recently a detailed surface chemistry framework was developed in SPARTA, capable of incorporating various reaction mechanisms such as adsorption, desorption, Eley-Rideal (ER) and Langmuir-Hinshelwood (LH) mechanisms [4]. Within this framework, we have implemented the capability of a single surface having multiple site sets with different reactivities. Using this feature, we can simulate the presence of active sites on carbon surfaces, whose reactivity is much greater than an average site as a result of defects. We have implemented the active site fraction as a property of surface elements within SPARTA, which is directly proportional to the local reactivity of each surface element. By introducing an initial distribution of the active site fraction across the carbon surface, and propagating it in a manner that mimics the evolution of real reacting carbon surfaces, we are able to capture the formation and growth of etch pits as a result of surface consumption reactions such as oxidation.

Keywords: DSMC, carbon, oxidation, pitting, active sites

Acknowledgements

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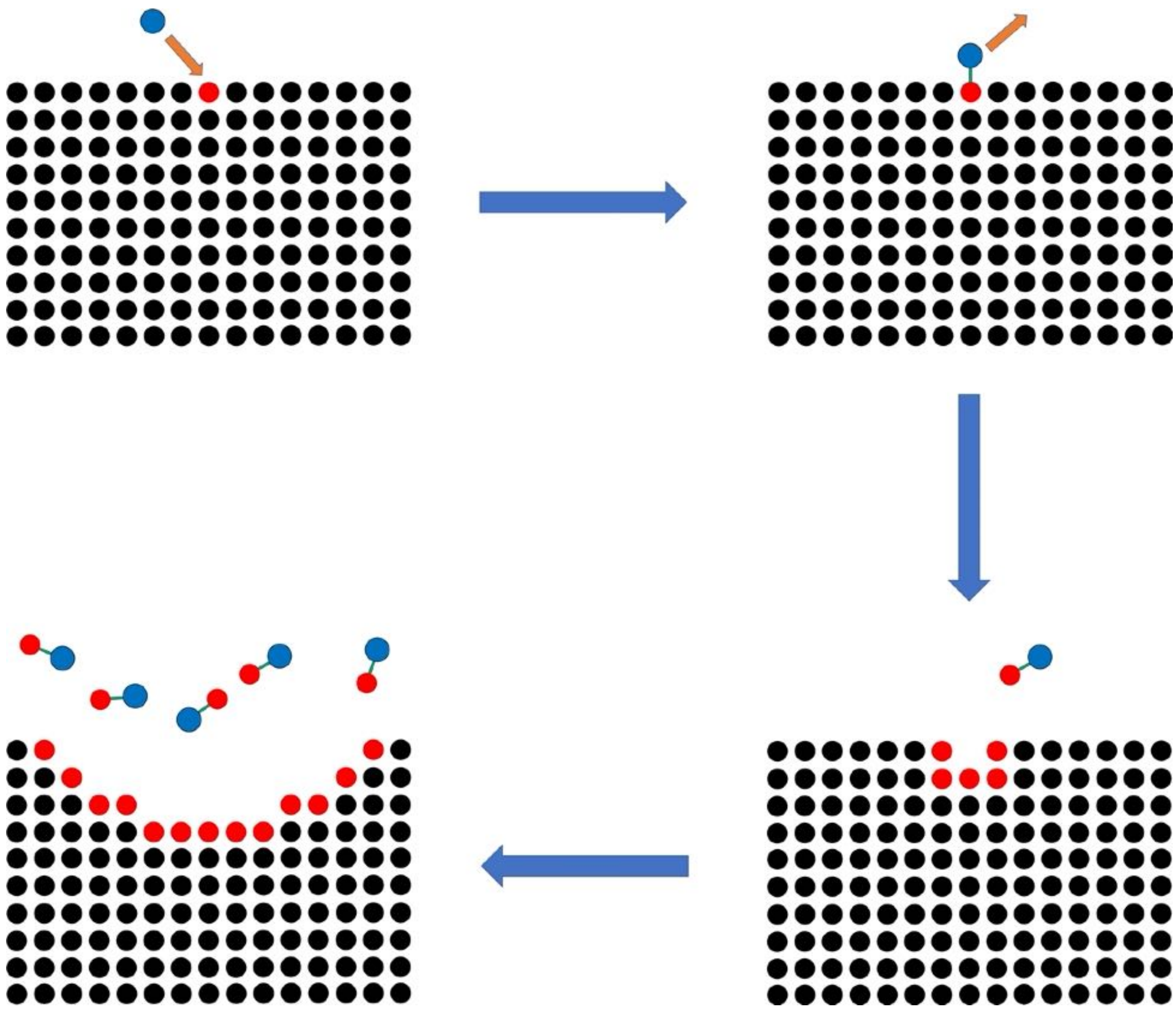

Figure 1: Schematic of an etch pit formation due to active sites.

Chemical Kinetics and Thermal Properties of Ablator Pyrolysis Products during Atmospheric Entry

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Abstract

Legacy and modern-day ablation codes typically assume equilibrium pyrolysis-gas chemistry. Yet recent experimental data suggest speciation from resin decomposition is far from equilibrium. A thermal and chemical kinetic study was performed on pyrolysis gas advection through a porous char. The finite-element tool Aria [1] simulated ablation of TACOT under the standard 1D Ablation Workshop Test Cases [2-3]. Temperature and phenolic decomposition rates generated using Sandia's finite element code SIERRA/Aria were used as inputs to a simulated network of continuously stirred tank reactors (CSTR) in the chemical solver Cantera. Utilizing a detailed finite-rate chemistry model [4] encompassing major PICA pyrolysis products from experimental results [5], the CSTR network used pyrolysis gas kinetics to determine composition and thermal properties. Results show a highly chemically reactive zone exists in the ablator between 1350–2500K, where generated pyrolysis gases transition in composition from a chemically frozen state to chemical equilibrium. Compared to the legacy experimental data and assumption of equilibrium kinetics employed by TACOT, the finite rate results demonstrate a significant departure in computed pyrolysis gas properties. In the low-temperature regime, total thermal advection due to decomposition and pyrolysis-gas pick up (transpiration cooling) decreased by as much as 50% relative to the standard TACOT values. These results suggest finite rate pyrolysis gas kinetics play an important role in the energy balance for ablative systems.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Keywords: Heat Transfer, Mass Transfer, Pyrolysis, Chemical Kinetics, Fluid, Non-equilibrium

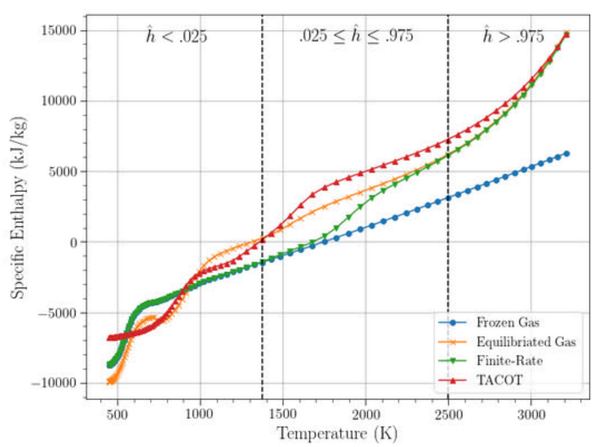

Figure 1: Pyrolysis Gas Enthalpy of Bessire-derived decomposition species computed via a finite-rate model, compared to expected equilibrium and frozen compositions (TACOT values from Ref. [2]).

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Ablation response of high enthalpy instrumented test article assembly

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Abstract

To study aerothermal response during atmospheric entry, ground testing of thermal protection system (TPS) materials is performed in high enthalpy facilities such as arcjets and inductively coupled plasma torches. TPS samples that are tested in these facilities are assembled using numerous components such as insulators and fixtures, made of different materials than the samples themselves. Additionally, the samples are instrumented with thermocouples at various heights to study the thermal behavior of the TPS during the tests. Because of contact with water-cooled surfaces and because involved thermal capacities and masses might be large, the presence of such assembly components and thermocouples may have substantial effects on the overall material response of the sample and the measurements taken by the thermocouples. Therefore, to accurately understand the effects of fixtures and instrumentation to the overall aerothermal response of a TPS material, this study focuses on a test article assembly designed for the Plasmatron X facility of the Center for Hypersonics and Entry System Study (CHESS). We model all the secondary components used in the assembly to mount and instrument the TPS material samples of reference ablators. The conditions of test case 3 from the Ablation test cases series[1] are applied to a scaled iso-Q shape for the Plasmatron X and compared to the material response of a sole TPS sample. Simulations are performed using the Porous Material Analysis Toolbox based on OpenFOAM (PATO)[2]. Different TPS materials including pyrolyzing and non-pyrolyzing, porous and dense ablators, and characteristic sizes of thermocouples used in actual test configurations are considered. The influence on the overall material response is discussed, along with recommendations for test article design.

Keywords: Material response modeling, thermocouples, arcjets, inductively coupled plasma, PATO

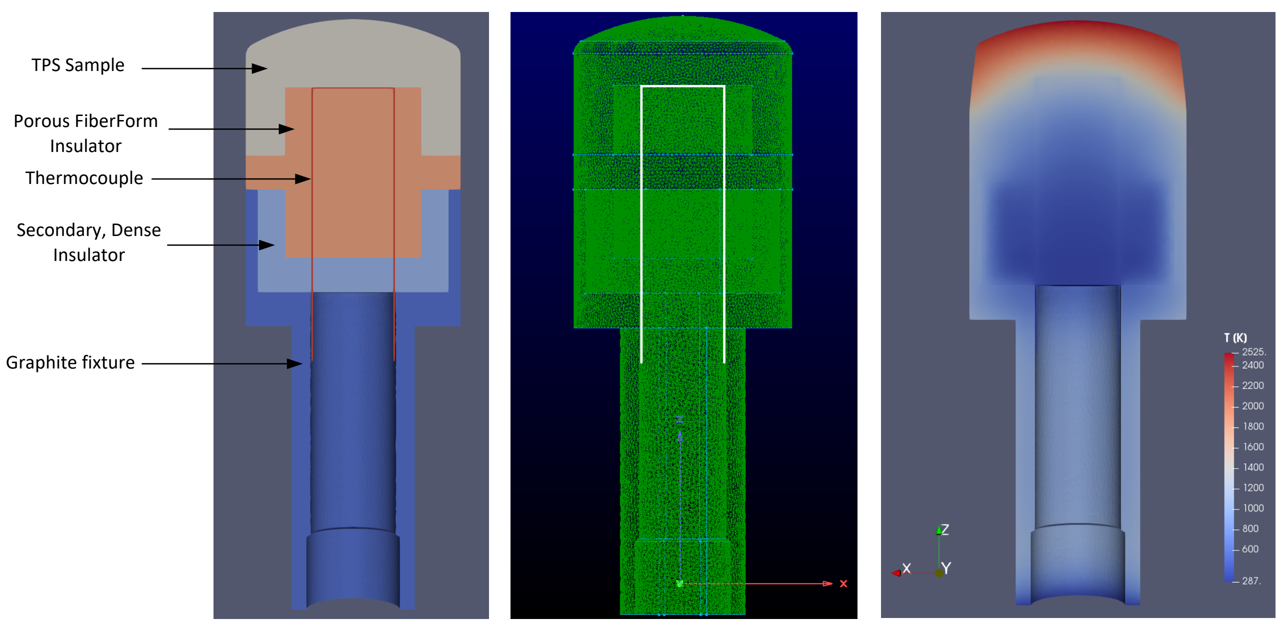

Figure 1: (a) Rendering in Paraview showing the stack-up used for simulations,

(b) Mesh of the various components from Pointwise, (c) Temperature profile in assembly from Paraview.

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Radiative transport through TPS materials

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Abstract

High entry speeds and exotic planetary gases can result in significant radiative heat loads on space capsules from the shock layer. The mechanism behind the transport of radiative heat is fundamentally different from the conductive mode of energy transport. Penetration of radiative emissions were either ignored or combined with convective heat flux because it was assumed that it would be absorbed within 1 mm of the TPS material. However, new experimental work shows that spectral radiation can penetrate the material and affect the material response over a significant depth, and radiative transport through TPS materials is an open problem. We use a multi-scale approach to solve this problem by computing effective radiative coefficients through an in-house code and then solving the radiative transport equation through the entire TPS material. The multi-scale analysis indicates that peak temperatures inside the material are higher when radiative transport is explicitly accounted for instead of combining it with the convective heat flux. Small variations in the absorption coefficient of the silica-based materials also affected the in-depth temperature profiles. Additionally, a broader temperature distribution is obtained inside the material with low absorption coefficient, and the charring density profiles are also influenced by the radiative heat flux. The initial study suggests that it could be important to include radiative transport in material response solvers.

Keywords: Radiative coefficients, radiative transport, material response

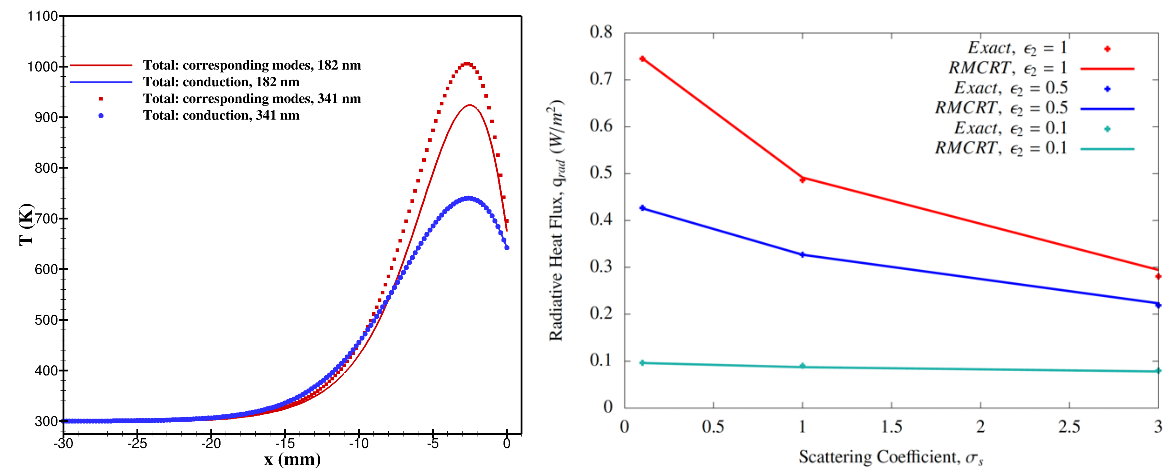

Figure 1: In-depth temperature profiles inside TPS material by explicitly accounting for radiative transport (left) and validation of a radiative Monte Carlo solver (right).

TPS Certification by Analysis: Model-driven Characterization of Properties and Failure in Woven Thermal Protection Systems

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Abstract

Woven, ablative thermal protection system (TPS) materials provide a robust option for aggressive (re)entries and thus have been baselined for the upcoming Mars Sample Return (MSR) mission's Earth Entry System (EES). The reliability requirements for MSR-EES necessitate understanding of material property variability, which could be significant given the complex structure and anisotropic nature of properties in TPS weaves, as well as the response to potential impact with micrometeoroids or orbital debris during the EES re-entry. The TPS Certification by Analysis effort within the Entry Systems Modeling project seeks to provide computational models and analyses that support the certification against such material-based risks. For the present talk, focus will be given to the characterization of baseline woven TPS material properties and mechanical failure limits, which entails (1) use of computational techniques (e.g., machine learning) to interpret computed tomography images of the weave to generate representative structural models and (2) application of multiscale material modeling approaches to characterize thermomechanical and failure properties.

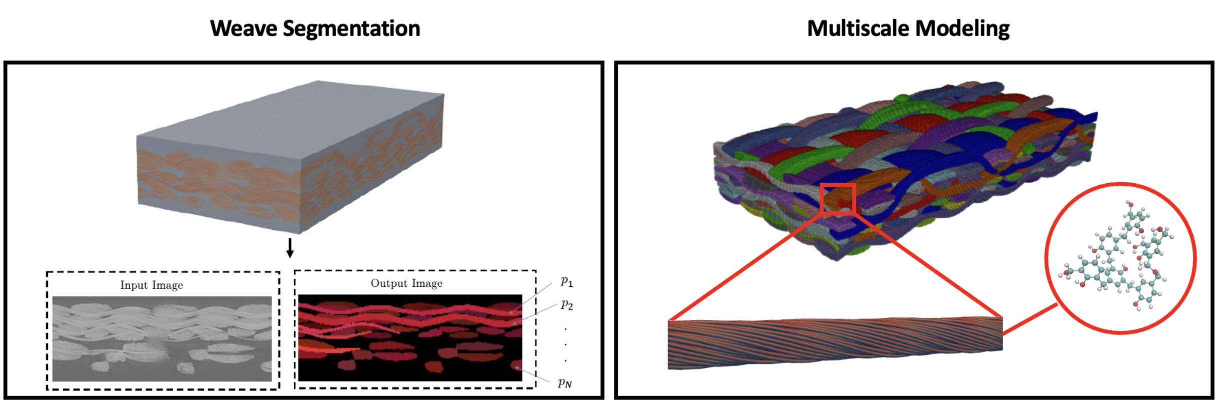

Figure 1: Segmentation of a weave (*left*) and multiscale property modeling (*right*).

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A Table-Top Shock Tunnel for Investigations of Hypersonic Ablation

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**Presenter*
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Abstract

The molecular beam technology used previously in beam-surface scattering experiments serves as the basis of a new "table-top shock tunnel (TTST)," which is intended to allow rapid and low-cost measurements of shock-layer chemistry and material response in well-characterized hypersonic flows. In addition to providing fundamental data for the development of models, the production of controlled shock layers above ablating and non-ablating surfaces and the measurement of their phenomenology provides a means to validate new models. Furthermore, material response can be tested in realistic environments and aid in the development of materials for hypersonics applications. Initial characterization of the TTST has been carried out by studying the ablation phenomenology of a Kapton polyimide surface exposed to a hypersonic O/O_2 beam at various distances from the nozzle throat and comparing the experimental observations with the results of DSMC calculations performed in the Schwartzentruber Group. Additional experiments with the TTST have characterized the temperature-dependent ablation phenomena of vitreous carbon at high temperatures.

Solar-Thermal Testing for Ablator Thermal-Model Validation

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Abstract

Aerothermal heating of decomposing ablators produces complex coupled physics, including aeroheating, surface reactions, recession, heat diffusion, resin decomposition, and gas transpiration. These mechanisms modulate surface heating in ground-testing facilities, such as arc jets and plasma torches. Experimental conditions are difficult to precisely measure [1, 2], require careful interpretation via models [3], and are complicated by ablator response [4].

Addressing these challenges, we have developed a unique ablator testing methodology at Sandia's National Solar Thermal Testing Facility. Solar-spectrum irradiation (up to 550 W/cm^2) heats the sample surface with precisely measured heat flux (±4.7%), insensitive to gas blowing and surface temperature. Convective heat transfer, char combustion, gas combustion, and recession are suppressed via testing in a vacuum chamber backfilled with inert gases. Suppression of competing mechanisms isolates pyrolysis and thermophysics within the ablator and characterizes these phenomena under a well-controlled environment.

Solar-thermal testing imposes no aerodynamic force and relieves sample geometry constraints (e.g., Iso-Q design). The figure below presents our newly implemented experimental hardware optimized for this environment. High aspect ratio (AR=100) thermocouple holes were drilled into samples with a newly developed laser machining technique. Fine-gauge bare-wire thermocouples were encased in 10-µm wall quartz tubes and embedded in the sample. A clamshell assembly constructed from space shuttle tile (LI-900) restricted radial dispersal of heat and pyrolysis gases. The entire assembly was mounted on a newly designed Radiant Heat Mass Balance, measuring sample mass-loss dynamically and sensitive to signals on the order of 10^0–10^3 mg. Two-dimensional simulations in SIERRA/Aria modeled this experimental setup and were compared to the experimental results. Model and experimental uncertainties were characterized and propagated in DAKOTA, enabling a validation assessment of our ablator thermal models for entry and fire applications.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Keywords: Solar Thermal, Decomposing Ablator, Ground Testing, Thermocouples, Mass Balance, Mass Loss

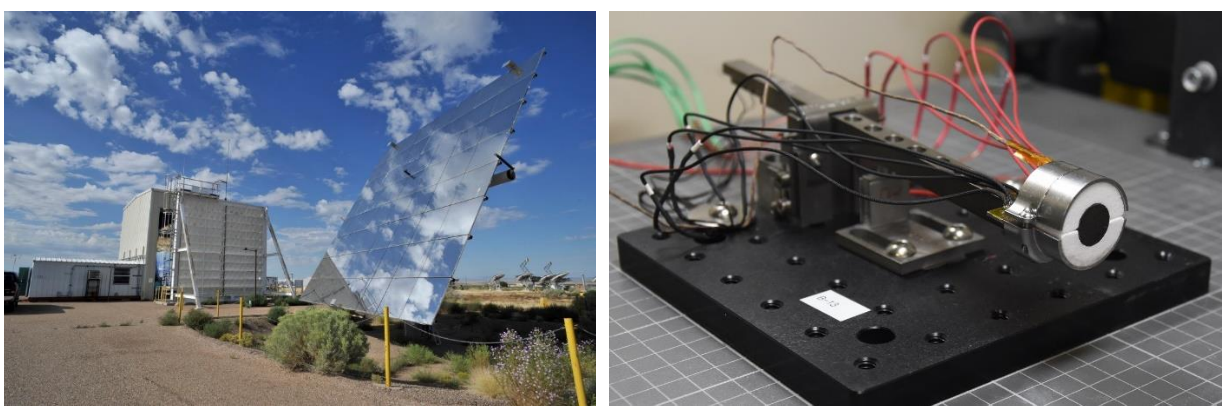

Figure 1: (left) Solar furnace at the National Solar Thermal Testing Facility. (right) Sample instrumented on the Radiant Heat Mass Balance.

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Assessment of Density Grading for the Carbon-Phenolic Ablator ZURAM

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Abstract

During atmospheric entry, spacecraft are exposed to extreme thermal loads due to their high entry velocity. Owing to their variable density and the effective energy dissipation through ablation and re-radiation, carbon-phenolic-based ablators are suitable as ablative thermal protection material (TPM) for thermally particularly demanding interplanetary return missions. In order to investigate and enhance this material class, the German Aerospace Center (DLR) developed in cooperation with the Institute of Space Systems (IRS, University of Stuttgart) the ablative carbon-phenolic thermal protection material ZURAM. An approach to enhance the performance of lightweight ablators is to increase their density. To avoid excessive mass increase of the thermal protection, an attempt was made to produce a material with a density gradient in the thickness direction. The grading of the ablative material was achieved by a near-surface re-infiltration with phenolic resin. In order to investigate the influence of the densification on the ablative properties, graded ZURAM samples were manufactured and tested in the arc heated facility L2K at the DLR department for Supersonic and Hypersonic Technology in Cologne (figure 1). The material performance was assessed in-situ by measuring the surface temperature as well as the temperature in depth direction with integrated subminiature thermocouples. Furthermore, the recession and the mass loss were determined during the analysis after the test. The data obtained from the arc heated facility tests were analyzed to determine the influence of the density gradient on the ablator performance during atmospheric entry. The presentation shows the results obtained so far from the investigations on graded ZURAM samples.

Keywords: Carbon-Phenolic, Ablation, Recession, Density Grading, Arc-Heated Wind Tunnel

Figure 1: *Density graded ZURAM sample before and after test in arc-heated wind tunnel facility L2K (DLR, Cologne)*.

Towards the Measurement of Ablation Products in Hypersonic Boundary Layers

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Abstract

Various surface kinetics models exist for estimating production rates of species generated from the interaction of shock-layer gases with the wall in a hypersonic boundary layer. While useful, collection of model validation data in ground test facilities has largely centered around the technique of optical emission spectroscopy (OES), which is limited in its ability to accurately provide speciation data in hypersonic boundary layers. These limitations necessitate additional data collection techniques for such environments. In this presentation, we will discuss the implementation of Laser Absorption Spectroscopy (LAS) to measure carbon monoxide (CO) within a realistic hypersonic boundary layer as generated from a blunt-nosed leading edge in Sandia's Hypersonics Shock Tunnel (HST). This data set will serve as an additional source of data with which to validate existing finite rate surface kinetics models in realistic hypersonic flows with high wall temperatures. First, an overview of the experimental facility and the conditions generated will be provided, followed by a discussion of the various optical diagnostic techniques utilized in the facility, and concluded with a presentation of preliminary results and discussion of data collected within the HST.

Keywords: Boundary layer, hypersonics, ablation, preheating, surface kinetics

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An Orthotropic Thermal Conductivity Measurement in Fibrous Insulation Materials

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Abstract

During re-entry into planetary atmospheres, vehicles experience large amounts of aerodynamic drag. This drag is the primary source of deceleration for these vehicles, whether they are entering or leaving these atmospheres. This aerodynamic drag is also responsible for inducing large heat fluxes on the re-entry vehicle. Thermal protection systems (TPS) play an integral role in protecting re-entry vehicles, primarily the payload, against these extreme heat fluxes. Without a proper TPS, these vehicles could be severely damaged and in many cases would burn up during re-entry. Fibrous materials such as PICA are commonly used to construct TPS due to their low effective thermal conductivity. Several studies have investigated the through-the-thickness thermal conductivity of different fibrous insulation materials. These studies looked at modeling the through-the-thickness thermal conductivity in terms of the three primary modes of heat transfer that are present in these TPS materials: radiation, solid conduction, and gaseous conduction. Radiation is emitted from each fiber that composes the TPS material. Solid conduction takes place between the fibers of the TPS material matrix where they come into contact with each other. Finally, gaseous conduction takes place within the fiber matrix and is dependent on the environmental gaseous composition. The contribution from these three modes can be isolated by modifying the measurement experimental conditions. Radiation can be neglected if the sample is brought down to a low enough temperature. If the sample is tested in a vacuum, the effects of gaseous conduction can be removed. Previous research has isolated these different modes and characterized the through-the-thickness thermal conductivity as a function of these modes. Little to no work has been done on characterizing the in-plane thermal conductivity of TPS materials, which is estimated to be 2-3 times higher than the through-the-thickness thermal conductivity. This work will focus on characterizing the in-plane thermal conductivity of these TPS materials as a function of the three different modes of heat transfer to predict how these materials will behave in different environments. An experimental apparatus is being developed, similar to that of the comparative cut-bar method that will be used to measure the in-plane thermal conductivity of the selected samples.

Keywords: Heat Transfer, Conductivity, Fibrous Insulation, Through-the-thickness, In-plane

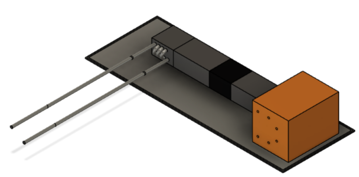

Figure 1: Fusion model of experimental set-up

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Experimental Characterization of Ablation and Spallation in the Plasma Wind Tunnel PWK1

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Abstract

Spallation, in the context of thermal protection system ablation, describes the phenomenon where solid particles are ejected or removed from the ablator surface. Open questions concerning spallation range from the mechanisms that lead to spallation to the effect that the spalled particles have on the flow field and eventually on the ablation performance. At the High Enthalpy Flow Diagnostics Group ablation is studied in plasma wind tunnel experiments and diagnostic methods for the characterization of the plasma and the ablation performance are developed. A comprehensive set of diagnostic methods was employed in several test campaigns at the plasma wind tunnel PWK1 with the objective to experimentally investigate the important aspects of spallation simultaneously.

The first set of instruments was aimed at the non-intrusive investigation of the ablation process on the ablator surface. The time resolved recession of the ablator surface was measured using photogrammetry. The surface temperature was tracked using pyrometry and thermography. In addition, the raw images from the photogrammetry were used for two-color ratio pyrometry, which provided temperature measurements with a very high spatial resolution. Another group of instruments was targeted at the investigation of the movement of spalled particles. The quantity of ejected particles was measured by means of high speed imaging. Light field imaging was employed to measure 3D trajectories of single particles. Lastly the effect of spallation and ablation on the flow field and the radiative environment was investigated using two spectrometers. This data allowed to study both the release of pyrolysis products from the ablator and the deposition of carbonaceous species into the flow.

The analysis of the data from single diagnostic methods or subsets of them has been a focus in the past. This work attempts to provide a comprehensive overview of the data from the entire suite of diagnostic methods.

Keywords: Spallation, Plasma Wind Tunnel, Photogrammetry, Spectroscopy, Material Testing

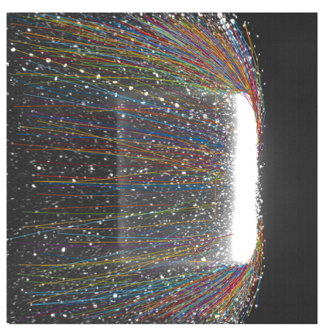

Figure 1: Trajectories of detected particles that were spalled from the surface of a FiberForm sample.

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Thermomechanical Response of Infrastructure Protective Materials to Direct Impingement by Rocket Exhaust

Jason R. Foley, W. Jacob Monzel, Malissa D. Lightfoot, et al.

Air Force Research Laboratory

Abstract

The development of materials capable of protecting permanent and temporary space lift infrastructure is a key activity in the Landing Surfaces IPT of AFRL's Rocket Cargo Vanguard. The Rocket Cargo Vanguard program will be introduced, and the technical objectives will be framed in the overall demonstration goals. The uniquely extreme environments of direct rocket impingement will be discussed and some representative ranges for the operating conditions will be given (albeit not completely due to sensitivity). This superset of environments formed the basis for selection criteria for candidate materials. A wide range of material types and configurations were considered and evaluated using existing performance data augmented by laboratory and field experiments. Representative results from various material classes will be given along with a discussion of their survivability in rocket exhaust and the role of various physical damage mechanisms (directly observed and/or inferred) will be highlighted.

Simulating Meteor Ablation at the Hypersonic Materials Environmental Test System

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Abstract

The ablation mechanisms of a stony meteorite material and a terrestrial analog were investigated at the Hypersonic Materials Environmental Test System (HyMETS) at NASA's Langley Research Center. The primary analyte (Tamdakht-H5) and arc-jet test conditions were chosen to simulate the entry of an ordinary chondrite through the Earth's mesosphere.[1] Basalt was selected to compare the meteorite response against material with enhanced polymerization and an elevated concentration of volatile species.

The initial ablation process for each material commences with the vaporization of volatile species and germination of a viscous melt layer on the stagnation surface. However, each material exhibited distinct mass loss mechanisms (fig. 1), with basalt recessing at twice the rate of Tamdakht. Inspection of high-speed video and chemical analysis of the post-test melt layer suggests the dominant mode of mass loss of Tamdakht is expressed through the vaporization of volatile compounds. Vaporization rates of Tamdakht are 18x higher than basalt under the most severe test conditions which provides enhanced thermal shielding. Furthermore, Tamdakht produces a relatively stable melt flow, as evidenced by perpetual growth at the sidewall and the exiguous detachment of molten material into the flow.

The ablation mechanism of basalt is markedly different from Tamdakht and is governed by volatile species in the virgin material. The dominant mode of mass loss for basalt is attributed to the detachment of large sections of the stagnation surface near the edge radius. A subordinate mode of mass loss is assigned to the removal of melt flow as it passes over the edge radius, where shear forces overcome the rheological properties of the molten matter.

Finally, mechanistic details will be discussed in terms of designing future test campaigns, developing meteorite-based materials response models, and impacting the broader scope of the Asteroid Threat Assessment Project (ATAP).

Keywords: Meteorite, Ablation Mechanisms, HyMETS

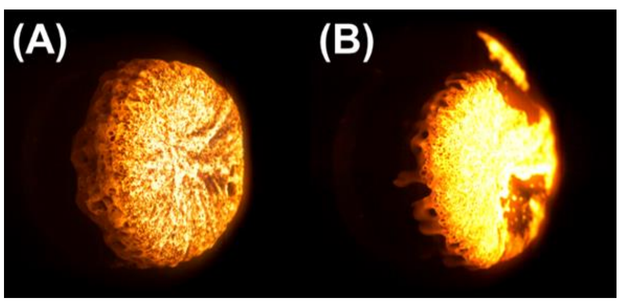

Figure 1: Still images of the stagnation surfaces of (A) Tamdakht and (B) basalt during arc-jet testing at the Hypersonic Materials Environmental Test System (HyMETS).

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Characterization of the Oxyacetylene Free Stream and UHTC and Graphite Oxidation Material Response

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Abstract

The material response during high temperature material testing in an oxyacetylene torch is a result of the thermochemical reactions between the sample surface and the torch flame. The oxyacetylene torch test facility is a reliable, high-throughput, and low-cost alternative screening tool for measuring the oxidation response of aerospace materials under high heat fluxes, high temperatures, and high flow velocities using a high enthalpy flame and oxygen rich environment. New methods have been developed to spatially characterize the local free-stream flame environment with advanced characterization of the velocity and pO2. The free stream environment was verified by measuring the ablation rates of graphite pucks to theoretical rates obtained from Fick's First Law. The testing of ultra-high temperature ceramics of zirconium diboride (ZrB2) and silicon carbide (SiC) were tested in high heat flux and oxygen rich flames. The oxidation of graphite and UHTC components were investigated using a computational thermodynamic model to estimate the reactivity when exposed to molecular oxygen as produced in an oxyacetylene torch in addition to monoatomic oxygen from a plasma/arc jet.

Calibration of nitridation reaction efficiencies from plasma wind tunnel data and beyond

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[d]*Department of Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, MN, 55414*

Abstract

Experiments and models are often used to understand the physics of ablation and improve our predictive capabilities. On the experimental side, the stochastic nature of the data must be accurately described and modeled to produce reliable experimental data on which to base our analyses. On the modeling side, many different sources of uncertainties in the form of model parameters can affect the predictions considerably. Objectively characterizing and quantifying such uncertainties is important to make comparisons to experimentally observed quantities useful, providing a more consistent/quantifiable way of defining new research directions rather than informed guesses.

Overall, the process of inferring ablation parameters from experimental data poses many questions concerning our experimental capabilities as well as the assumptions in our models. In particular, the carbon nitridation reaction $C_s + N \rightarrow CN + 0.34$eV on a solid (s) carbon surface is still hard to predict accurately at temperatures above 1000 K. The models found in the aerothermodynamics literature are derived empirically by fitting experimental data [1–5] which span several orders of magnitude and show great scatter. In many cases, not all aspects of the experimental facilities are completely understood. This issue adds important uncertainties to the inference process both in terms of experimental data and relevant physical processes considered to play a role under different experimental conditions. In this regard, severe lack of knowledge greatly affects our abilities to build predictive models.

Over the years, we have been continuously improving our tools and theoretical background on rigorous uncertainty quantification methods to tackle such challenging problem. In this work, we survey the evolution of our nitridation research through four main developments: First, we present plasma wind tunnel data collected to extract a carbon nitridation model following a deterministic inverse approach [6]. Second, we show how we introduce parametric and experimental uncertainties, recasting the whole problem as a stochastic inverse problem [7]. Third, we incorporate model-form uncertainties by entertaining several different models that pertain to the gas and the gas-surface interface and assess their comparison with the experimental data in a stochastic framework [8]. Lastly, we discuss our recent development in merging the experimental data from molecular beam [9] and plasma wind tunnel to obtain a more comprehensive and detailed picture of nitridation reactions [10] while fully characterizing uncertainties in both cases.

Keywords: Thermal Protection System, Nitridation, Uncertainty Quantification, Bayesian Inference, Molecular Beam

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Assessment of Surrogate Modeling Techniques for use in 2D Uncertainty Quantification of Ablation Heat Transfer

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Abstract

There is continual pressure to reduce timeframes and budgets for designing, building, and testing solid rocket motors (SRM's). One of the key elements associated with both cost and schedule is the number of static tests that are conducted prior to production and flight. Large test campaigns were used historically as a foundation for robust SRM development and design. Test results were used to anchor predictive codes that would then be used to define margins and demonstrate compliance to design requirements. Without post-test data to inform design and anchor analyses, more reliance is placed on predictive capability and uncertainty. Two-dimensional Uncertainty Quantification (2D-UQ) is a proven process to quantify uncertainty in predictive analyses. The final step in the 2D-UQ process is propagation of aleatory and epistemic uncertainties in two Monte-Carlo sampling loops. The number of individual simulations needed to obtain adequate aleatory and epistemic distribution sampling in these loops can exceed one million. For ablative heat transfer predictions used in the assessment of SRM nozzles this is computational intractable, even on modern super computers. To overcome this computational roadblock, surrogate models are needed. Surrogate models mimic complex ablation code outputs but are solved exponentially faster. In the work presented here, approaches to create surrogate models for nozzles are given and assessed based on computational efficiency and accuracy.

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Micro-Tomography Based Analysis of Thermal Protection System Materials

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Abstract

The microstructures of thermal protection systems (TPS) materials were characterized using the Lawrence Berkeley National Laboratory's Beamline 8.3.2 at the Advanced Light Source [1]. The Synchrotron-based Hard X-ray Micro-Tomography instrument allowed for non-destructive 3-Dimensional imaging of 33 different samples of TPS materials. The tomography voxels were used to reconstruct images using the rendering software Dragonfly [2]. These images are examined and compared to create new learnings about the microstructure differences between different thermal protection materials. Challenges associated with the preparation of samples, the use of this technique, computational requirements, and the limitations of the rendered images are also discussed. Future work includes the analysis of material properties, such as tortuosity, conductivity, and porosity using NASA's Porous Microstructure Analysis (PuMA) software [3, 4]. Additionally, machine learning methods are being applied in order to investigate and quantify the microstructural characteristics that lead to the optimal ablative performance.

Keywords: Micro-Tomography, Micro-CT, Microstructures, Machine Learning, TPS, Ablatives

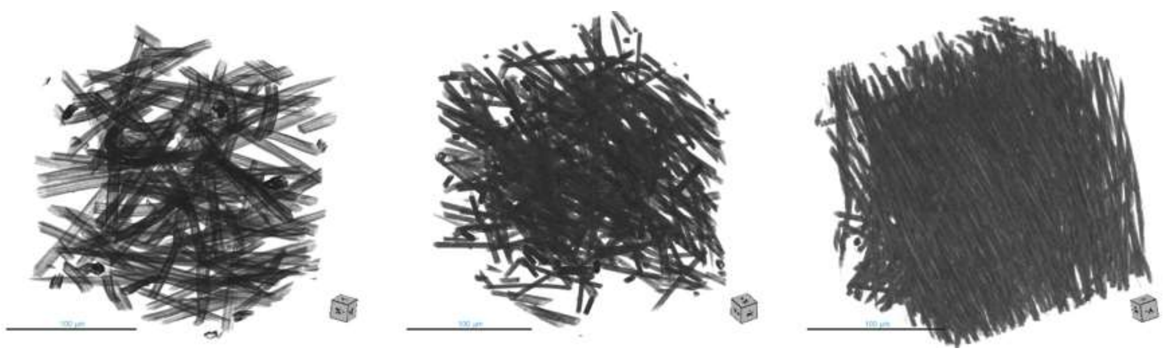

Figure 1: Regular Carbon Felt (left), Regular Graphite Felt (center), Regular Quartz Felt (right).

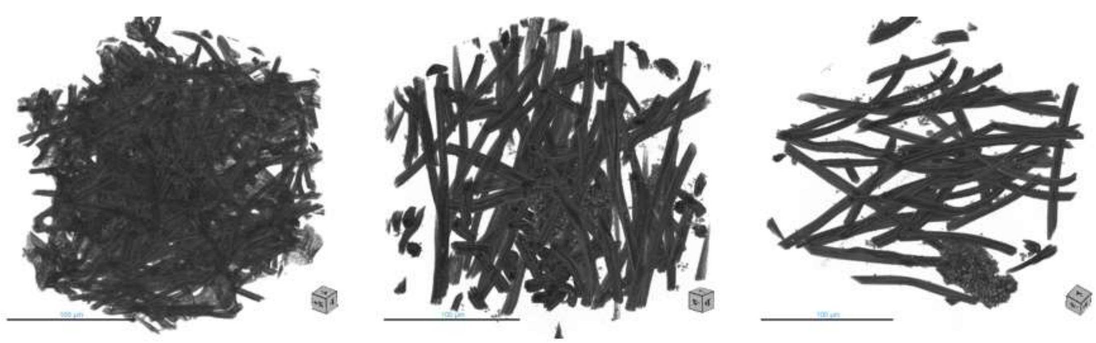

Figure 2: Virgin Carbon Felt with UHTR (left), Charred Normal Carbon Felt with UHTR (center), Charred Purified Carbon Felt with UHTR (right)

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HyCUBE: An Emission Spectrometer Payload on a Hypersonic Reentry CubeSat

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Abstract

The ultimate goal of the HyCUBE program is to collect aerothermodynamic data during hypersonic vehicle reentry at altitudes ranging from 90km to 50km while traveling at speeds between 8km/s and 5km/s. Spectroscopic data characterizing the chemical species and reactions in the air downstream of the bow shock is desired in order to validate and improve existing models in hypersonic flow computations. Spectra collected during descent will be passed to the flight computer, which will create data packets tailored for download in a radio datalink. Given these flight conditions, the use of an adequate thermal protection system is imperative. Both ablative and non-ablative options are being considered.

In the near term, HyCUBE proposes flying an emission spectrometer on several NASA Ames TechEdSat (TES) series CubeSats, with TES-12 being the first. The instrument selected for the payload is an OceanInsight FLAME-S, chosen primarily for its compact size and ability to probe the ultraviolet region of the electromagnetic spectrum where nitric oxide (NO) is the most prevalent emitter. Most recently, plans for the spectrometer's electrical and mechanical integration into NASA TES-12 were developed and tested. The flight computer delivers power to the instrument and communicates with the spectrometer's serial port, using a converter to step between appropriate voltage levels. When integrated into TES-12, the spectrometer viewing element points perpendicularly out of the vehicle's side panel. Operational scenarios of increasing scope have been designed to test the instrument in orbit. These procedures will ensure that enough data is collected in order to capture significant light sources, such as the sun, whose expected spectrum will be compared against the output. The flight computer processes the spectra collected by the spectrometer into smaller size packets for uplink using various datalinks including the low bandwidth Iridium short burst data modem.

The poster will describe the preparation of the spectrometer payload for TES-12, including its preparation for operation in the space environment (i.e., staking, outgassing, etc). We also include further details on the mechanical interface, the electrical interface and communication protocols, and the operational scenarios with the associated software. Future TES vehicles will fly our choice of TPS (TUFROC, AETB, and a carbon-carbon composite by C-CAT are being considered) with an aerodynamic 3U body, and an Arcjet ground experiment will be performed to test the vehicle and further develop the emission spectrometer payload.

We thank the AFOSR for supporting this work under grant number FA9550-19-1-0308, as well as the Minnesota Space Grant Consortium for supporting the development of this project during time spent at NASA Ames. We also thank the TES team at NASA Ames for all the assistance and expertise they shared with us to accomplish this design.

Keywords: CubeSat, emission spectrometer, hypersonic, atmospheric re-entry, ablative, TPS

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Microstructure and Oxidation Behavior of Fibers and Binders in Charring Ablator Preforms

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Abstract

FiberForm, the substrate of the Phenolic Impregnated Carbon Ablator (PICA), is manufactured from a slurry of carbon fibers, phenolic resin, and water. The fibers are typically processed at higher temperatures and different heating rates than the conditions for charring the binder material. This results in carbon phases of different microstructure and varying thermal-chemo-mechanical properties. Of particular interest is the material response to oxidation and the effect of pitting on material properties. The reactivity of the charred matrix in comparison to the fibers has been hypothesized in theoretical studies as ten times that of the fibers but has yet to be experimentally verified [1]. In this study, several characterization techniques such as SEM, Raman, XRD, XPS, and BET are used to separately characterize the carbonaceous constituents of FiberForm: fibers and binder. Virgin lyocell and rayon fibers used in the manufacturing of heritage and domestic FiberForm are analyzed. A process is developed to cure sole Varcum samples in graphite crucibles and char them in an inert environment to temperatures ranging from 700 – 1600 ℃. The virgin fibers are observed to have pitting, a behavior usually observed only under oxidation, on the scale of tens of nm. This is important to account for in microscale models in addition to accurate representations of the fiber geometry. With higher temperature treatment, the amorphous content of the Varcum decreases with an increase in the calculated sp^2/sp^3 ratio as determined from XPS and XRD characterizations. TGA is used to measure the oxidation rate of Varcum and higher oxidation temperatures are found to correlate to higher oxidation rates and reactivity. These experimental measurements are used to inform amorphous carbon carbon structures generated in simulations intended to represent the binder material at the atomic level, which is presented in a companion study [2]. This work aims to provide a better understanding of FiberForm microstructure under ablation and provide data to enable micro-mechanical failure models for the material.

Keywords: *Carbon Fiber, Amorphous Carbon, Varcum, Oxidation*

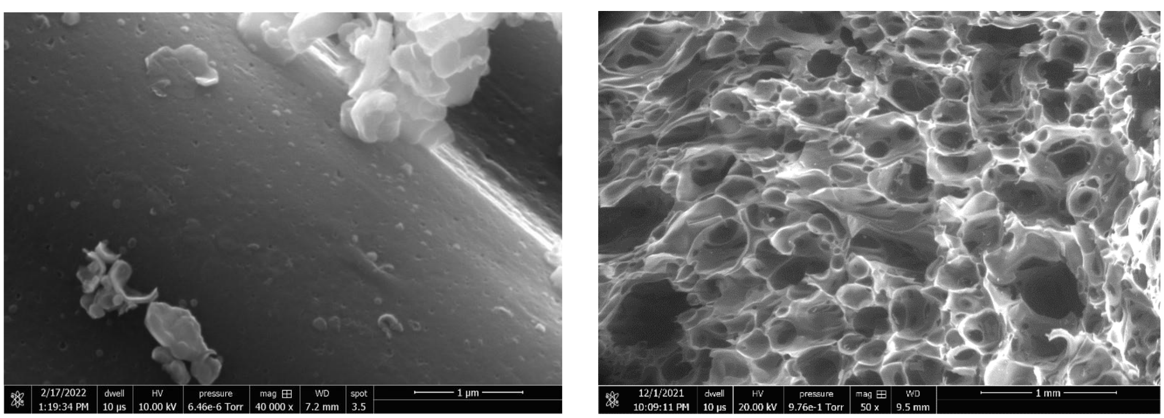

Figure 1. SEM imaging of the pitting observed in virgin fibers (left) and a cross sectional view of Varcum charred at 800 ℃

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Development of a Computational Framework to Investigate Thermochemistry of Molten Flows in Aerothermal Entry Physics

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Abstract

A hypersonic flow effect which has traditionally been disregarded is the flow of molten heated silica-type material, such as that present within the composite material mixture of Avcoat or applied as a surface coating to PICA thermal protection system (TPS) material. Diffuse interface multiphase methods [1] provide a simple, computationally efficient, and numerically robust approach to model this multiphase gas/liquid phenomena. Here, fluid interfaces are modeled as a mixture between the flow components with no sharp distinction. The authors of this work recently presented validation of a solver which implements an extended version of this method for high speed droplet and impingement flows [2]. The stage of this work described in the current presentation pertains to modeling phase transition between flow components. In general, phase transition can be quantified by computing the thermodynamic state at which the Gibb's free energy function is minimized. In this work, Gibb's free energy minimization is accomplished through use of a fast thermodynamic relaxation solver [3] which computes modified mass fractions for each flow cell in the system by performing a single mass/energy change limiter calculation every simulation time step. The method has been implemented into an in-house fluid solver, and preliminary results (Figure 1) show notable temperature differences between solutions in which phase transition is implemented or neglected.

Keywords: Computational fluid dynamics, phase transition, diffuse interface, molten flows, thermochemistry

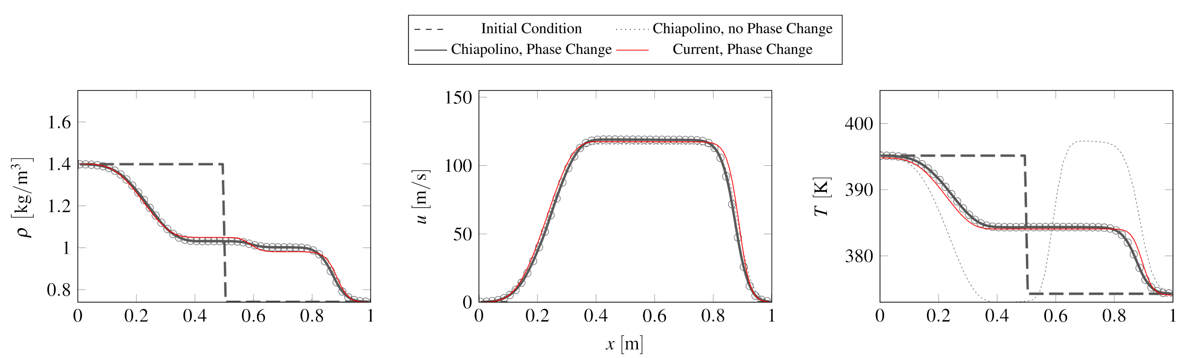

Figure 1: Primitive variables of vapor/liquid water shock tube problem with phase change at $t = 8.0 \times 10^{-4}$ s validation based on Chiapolino [3].

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Decomposition and permeability of room temperature vulcanizing (RTV) silicone rubber used in thermal protection systems for re-entry capsules

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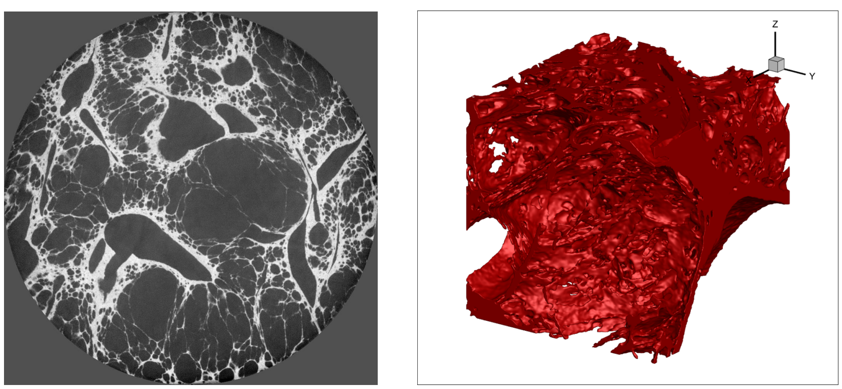
Abstract

Room temperature vulcanizing (RTV) silicone rubber is placed between thermal protection system (TPS) tiles on space capsules to attach the TPS to the surface of the capsule. This arrangement allows expansion and contraction from the high-temperature experienced during re-entry while avoiding cracks in the brittle TPS tiles. RTV 560 and RTV 511, also referred to as red and white RTV, respectively, are heated to various temperatures and heating rates in an oven to recreate the burning of RTV during re-entry. X-ray computed tomography (XRCT) is used to create three-dimensional virtual volumes of the actual material at various stages of burning. These volumes are used as inputs in simulations using the direct simulation Monte Carlo (DSMC) technique. DSMC simulates the flow of gases through the volume structures, and the flowfield can be used to calculate Klinkenberg constants and extract the effective permeability of the porous media. From the rendered three-dimensional volumes, it is observed that the RTV material burns from the inside, creating cavities inside the material while pushing the exterior material outwards, causing inelastic deformation to the RTV during heating. Currently, flow through the RTV materials is being simulated through the DSMC technique to extract a set of Klinkenberg constants for a range of temperatures and pressures and relevant gaseous species.

Keywords: Porous media, permeability, RTV, DSMC



(a) Slice of XY plane.

(b) $1500 \times 1500 \times 1500$ volume render at 2.2485 μm voxel size.

Figure 1: Burned RTV 560 sample at 600 ^oC for 7 mins.

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Mechanical Erosion Modeling of TPS Materials

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Abstract

The goal of this work is to predict the mechanical response of TPS materials, and specifically, to determine if there is additional surface recession in the heat shield's surface as a result of mechanical erosion due to the mechanical and thermal loads experienced during atmospheric entry. To accomplish this, a solid mechanics module was integrated within the PATO material response code [1], enabling it to model the potential mechanical erosion in three steps: first, having the effective mechanical properties as function of temperature, the implemented stress analysis solver computes the stress and the displacement fields for the TPS material using the wall shear stress tensor, computed with the DPLR hypersonic CFD code [2], as boundary conditions; then, regions on the surface where the stress meets the failure criteria are identified; finally, the failed material is removed and the mesh is redistributed accordingly. The outcome is a model capable of predicting the total recession in the TPS material due to surface chemistry and mechanical erosion.

Keywords: *Stress Analysis, Material Response, Mechanical Erosion, Spallation, TPS*

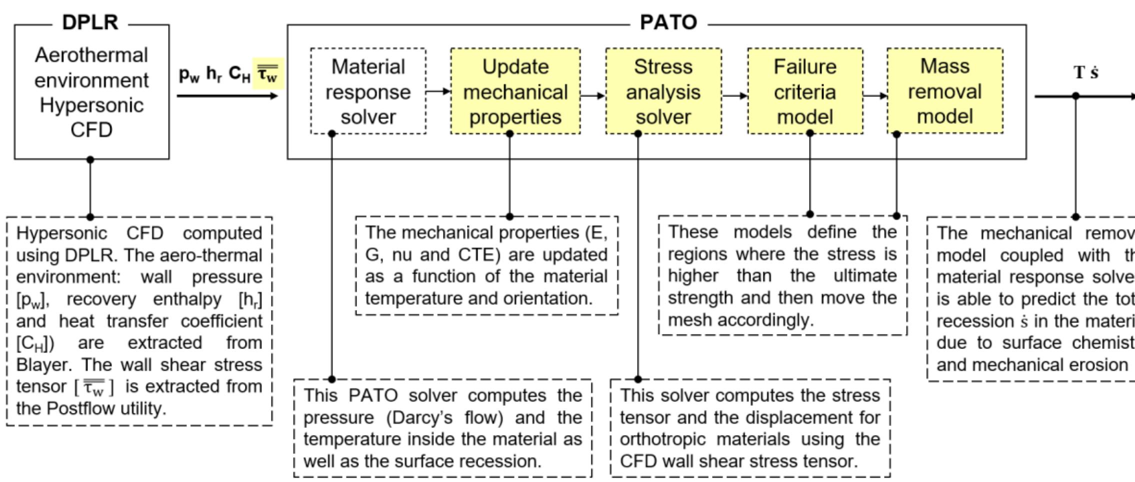

Figure 1: Diagram of the mechanical erosion model implementation.

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Preliminary analysis of multi-dimensional material response of DragonFly heat shield

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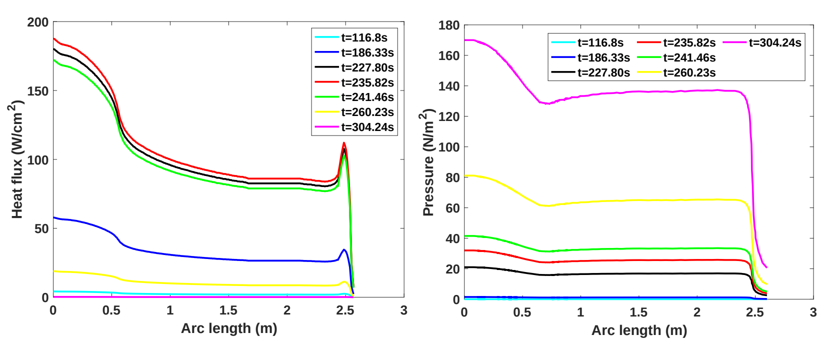
Abstract

The research consists of the multi-dimensional material response of the DragonFly heat shield along its trajectory using KATS-mr. The material response includes mass, momentum, and energy equations. The heat flux and pressure profiles extracted from flow field simulations along the trajectory are used as boundary conditions for simulation. The results from the simulation are presented and thoroughly studied to evaluate the complete behavior of the heat shield during the entry. An ablative TPS material is used as the forebody heat shield for the Dragonfly mission. The charring ablators are made of organic resin-infused porous fibers that undergo thermal decomposition under severe aerodynamic heating, which results in pyrolysis gas flow through the material and subsequent injection into the boundary layer. This results in the formation of a char layer, mass removal from the material, and the pyrolysis gas that removes the energy from the surface. The study considered different heat flux components such as aerothermodynamic, re-radiative, pyrolysis gas, and conduction heat fluxes. Based on the multi-dimensional material response simulation the study showed an expected behavior with the stagnation point reaching a maximum value of 2040 K and bondline temperature reaching around 600 K. It was observed that the aerothermodynamic and re-radiative heat fluxes are major contributors to heat flux during the simulation.

Keywords: Heat shield, Aerothermodynamic modelling, DragonFly, Trajectory simulation



(a) Heat flux profiles along the surface at different time of flights

(b) Pressure profiles along the surface at different time of flights

Figure 1: Heat flux and pressure profiles along the surface at different time of flights

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Trajectory Modelling of Re-entry Vehicles

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Abstract

The Kentucky Analysis of Re-Entry Trajectories (KARET) is a three degree of freedom program that predicts trajectory profiles for re-entry flight experiments. This was developed for the profiling of the Kentucky Re-entry Universal Payload System (KRUPS), and is solved using a Newton's method for systems. The previous flight code used for KRUPS was providing inaccurate data outside of short-range hypersonic cases. KRUPS experiments undergo a wide variety of Mach numbers, creating a need for this program. KARET encompasses conditions from subsonic to hypersonic re-entry by the implementation of several drag models. In order to account for long range missions, Coriolis force terms are included in the flight equations. The code was validated by comparing KARET predictions to previous flights such as a high altitude drop test and the Stardust Return Capsule (SRC). This validated code is needed to model an atmospheric breakup of the Kentucky Re-entry Probe Experiment (KREPE). KREPE capsules were onboard Cygnus NG-16 during it's re-entry from the International Space Station (ISS). Cygnus was designed to breakup in the atmosphere to dispose waste from the ISS, allowing the capsules to continue their decent independently. KARET aims to estimate the intermediate conditions between an intact Cygnus and capsule splashdown.

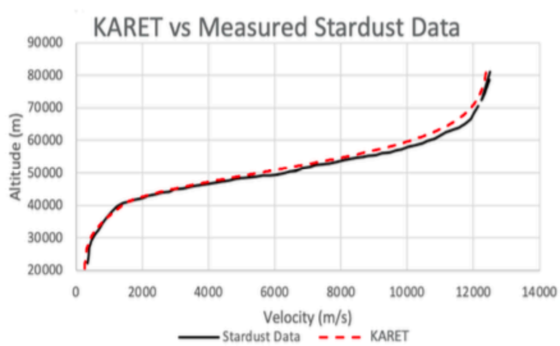

Figure 1: KARET: Stardust Return Capsule

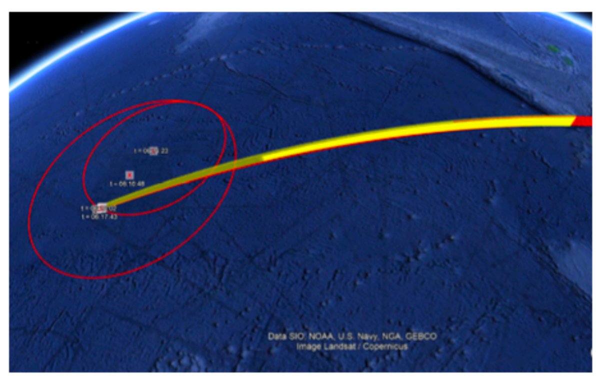

Figure 2: KARET: Cygnus profile (yellow) and recorded data (red)

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A combined CFD/material response analysis of 3MDCP arcjet experiments

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Abstract

The Mars Sample Return Earth Entry System (MSR-EES) project has selected 3-D Woven Mid-Density Carbon Phenolic (3MDCP) [1] as the baseline TPS material for the EES capsule that will return Martian soil samples to Earth sometime in the 2030's. In order to gain experimental data to characterize the performance of 3MDCP and to develop and refine material response models for it, a series of arcjet experiments were performed in the NASA Ames AHF and IHF arcjets in November 2021. The test objectives for these experiments included obtaining in-depth and surface temperature data, and high-definition IR video of the test article front face. Mass loss and surface recession of the 3MDCP material was measured as well as char-depth measurements.

Pre-and post-test analysis on the 3MDCP arcjet experiments was performed using the DPLR CFD [2] and Icarus material reponse [3] codes. The codes were not tightly coupled, but boundary condition data required by Icarus (e.g., heat transfer coefficients and surface pressures), were extracted from the CFD solutions. This presentation will show comparisons between DPLR/Icarus and the experimental data taken during arcjet experiment AHF-348 where 4-inch diameter iso-q models made from 3MDCP were tested in the 12-inch nozzle of the AHF arcjet.

This presentation will also include a top-level overview of the CFD/material response arcjet simulation process. A discussion will be made on the best-practices for running CFD solutions of arcjet experiments including how to determine the inflow conditions for the CFD solution from the arc heater settings. The required inputs to the material response solver will be presented, as well as a discussion of how they can be extracted from the CFD solution. Grid requirements for both the CFD and material response solver will be explored.

Keywords: Thermal Protection Systems, material response, CFD, arcjet experiments

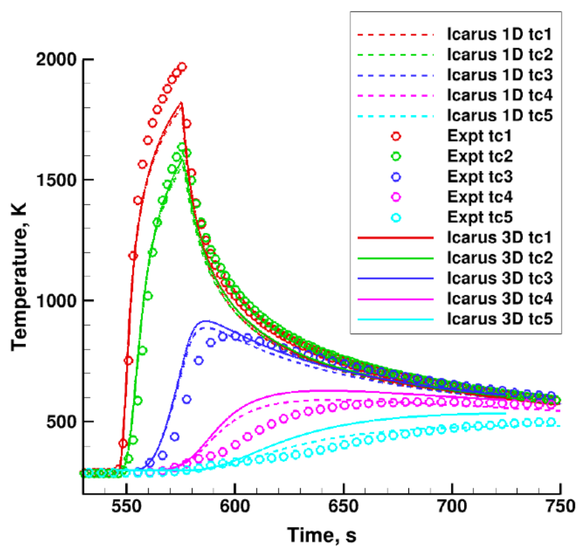

Figure 1: Comparison of Icarus and experimental in-depth temperature profiles.

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Ablation and Oxidation Behavior of Aerospace Materials Using an Oxyacetylene Torch Facility

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Abstract

Development of materials for aerospace applications, such as thermal protection, requires rigorous testing at facilities capable of simulating a hypersonic reentry environment. Oxyacetylene torch facilities are often utilized for low-cost and high throughput screening of a material's response at high temperatures prior to arc jet or flight testing. Globally, these facilities vary with their torch setup and method of mounting samples into the flame leading to discrepancies in ablation and oxidation data for a given material. The University of Arizona's oxyacetylene torch facility has been characterized for heat flux, pO_2, and velocity as a function of linear and radial distance from the torch tip. Graphite samples, having an outer diameter and height of 20 mm, were used to validate this characterization of the torch by comparing experimental results to theoretical ablation calculations. Trends yield that free stream flame velocity and heat flux decrease as a function of increasing distance from the torch tip, whereas pO_2 increases with increasing distance. The impact of sample holder design on the mass loss and ablation rate of graphite was investigated using three different sample holders. Under similar flow conditions, the average mass loss varied from 1.54% to 13.94% between the three holders. Fluid dynamics models were used to investigate how the flow field in front of the sample is affected by the sample holder.

Keywords: Oxyacetylene Torch, CFD Modeling, Heat Flux, Ablation, Oxidation

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Investigation of the effect of etch pits on the material properties of carbon fiber structures

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Abstract

It is well known that etch pits are formed on carbon surfaces during their consumption in reactive gas environments such as during ablation of carbon-based thermal protection system (TPS) materials. These pits start out from atomic defects on the carbon surface, grow in size and then ultimately lead to the complete removal of the solid carbon material [1, 2]. However, the effect of such etch pits on the material properties of carbon ablators such as FiberForm is poorly understood, as the maximum size of pits are on the order of microns in size, which makes them hard to observe experimentally. Hence, we have developed a module within the Porous Microstructure Analysis code PuMA [3] that can generate etch pits on an arbitrary material surface, with a prescribed distribution of pit size and density. Figure 1 shows a FiberForm sample with artificially generated pits of varying radii and pit density. We use this newly developed module to calculate material properties of FiberForm, which is the base material for one of the most commonly used TPS materials - Phenolic Impregnated Carbon Ablator (PICA). The detailed micro-structure of FiberForm in PuMA will either be generated synthetically or obtained from X-ray microtomography [4]. Our simulations show that material properties such as the thermal conductivity and tortuosity decrease with increasing degree of pitting. This will be helpful to more accurately predict the degradation of carbon-based TPS during ablation, and furthermore may allow us to identify previously unknown TPS failure modes due to pitting.

Keywords: PuMA, microstructure, carbon, pitting

Acknowledgements

This work was supported by the Entry System Modeling project (M.D. Barnhardt project manager, A. Brandis principal investigator) as part of the NASA Game Changing Development program. The authors were funded by NASA contract NNA15BB15C to Analytical Mechanics Associates (AMA), Inc.

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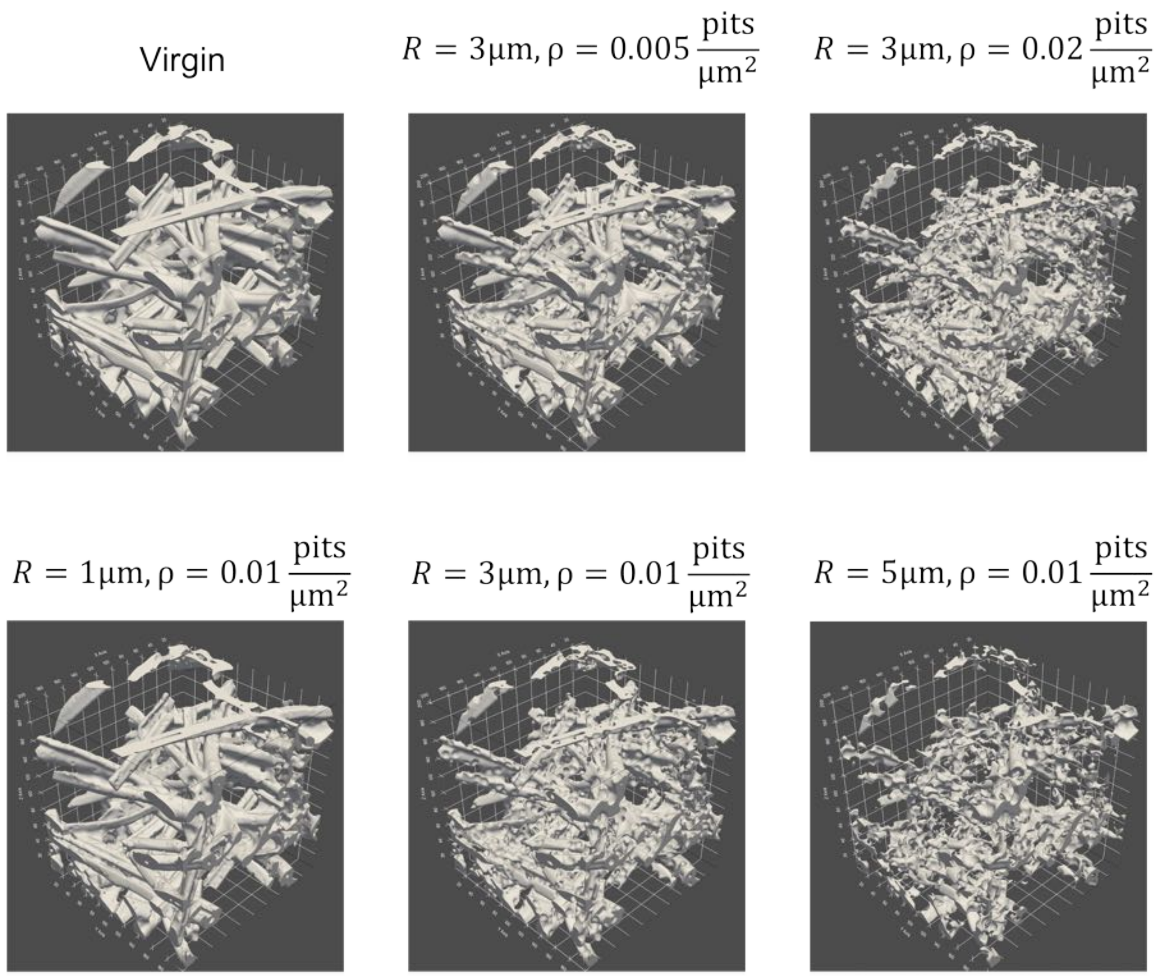

Figure 1: FiberForm sample with various artificially generated pit distributions.

Finite Rate Ablation Model Applicability: Diffusion versus reaction limited regimes

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Abstract

While previous research has focused on developing finite-rate gas-surface reaction models for use in DSMC and CFD simulations [1], the current study focuses on determining when such a model is necessary for a given mission of interest. In order to do this, a non-dimensional Damkohler number is calculated at the vehicle wall (Da_W). The value of Da_W represents the ratio between the time scale for diffusive flux across the boundary layer to the wall and the time scale for chemical reactions on the surface. In the case where the Damkohler number is large, chemical reactions are extremely fast compared to the supply of reactants via diffusion. In this case surface chemistry is diffusion-limited, indicating that a detailed finite rate model may not be needed. Conversely, when the Damkohler number is small, chemical reactions at the surface occur relatively slowly and the supply of reactants is large, indicating that the overall amount of surface chemistry (ablation for example) will be sensitive to individual rates and a finite rate model should be used. The current research uses freestream conditions and basic vehicle geometry, combined with stagnation-line aerothermodynamic theory to estimate Da_W for specific missions of interest. Preliminary results are shown in Fig. 1, where both the value of Da_W and the flux of reaction product species leaving the wall are indicated. Titan entry may require a finite-rate ablation model due to the low Damkohler number. However, the overall flux of reaction products is very low compared to other mission types. The nitridation reaction (forming CN) is very low, however, the recombination reaction (forming N) is more than an order of magnitude higher and may be an important finite-rate reaction. It is important to note that Fig.1 makes only relative comparisons between mission types. Currently, we don't have a "cut-off" line on Fig. 1 to indicate when a finite-rate ablation is needed. Future work will focus on performing CFD simulations of different missions with our finite-rate ablation model, which can be used to verify our estimates from Fig. 1 and help us determine a meaningful "cut-off" point for when such a surface chemistry model is required.

Keywords: Finite-rate, Heat Transfer, Gas-surface Interactions, Damkohler Number, Recombination

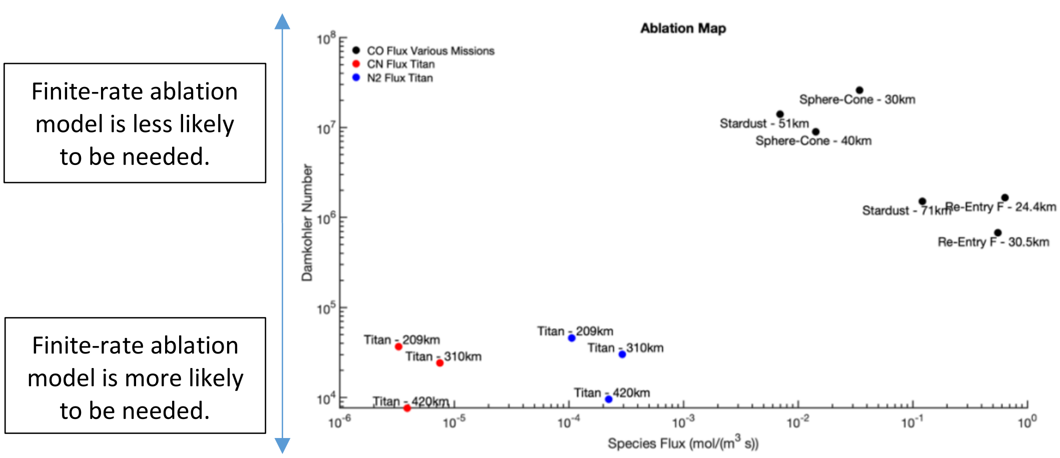

Figure 1: Ablation map of different missions at select altitudes

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Crack modeling in ablative materials

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Abstract

Modern Thermal Protection Systems (TPS) used for planetary exploration missions often utilize light-weight porous materials as its isolating layer. The combination of large heat flux and shear force during the atmospheric entry can compromise the TPS overall integrity. Therefore, it is of paramount importance to accurately understand how and when these porous materials fail. In this study, a crack model is developed and implemented into a material response solver for charring ablation problem. The numerical model is validated through comparison with experimental data on FiberForm. Results show that a higher level of scattering in material properties leads to more localized failure, yet it is not a sufficient factor for crack penetration and development. In addition, the developed model shows a great capability to capture the thermal-mechanical erosion, which accelerates the energy penetration and result in unexpected failure mode such as tunneling. Three-dimensional modeling also shows different results, including the tunneling-like failure on the exposed surfaces.

Keywords: TPS, crack propagation, failure

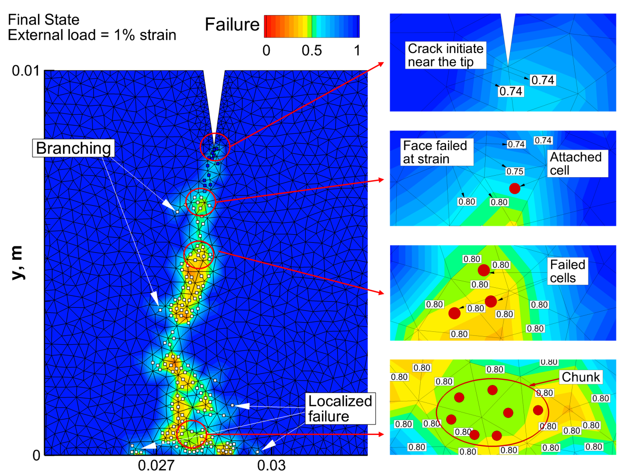

Figure 1: Detailed crack analysis. The developed model can capture crack initiation, branching and failure.

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Boundary layer flow over resolved material microstructure using air-carbon ablation model

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Abstract

Accurate numerical modeling of porous ablative thermal protection systems (TPS) require capturing many distinct phenomenon including gas surface reactions between the boundary layer gases and carbon surface, surface/volume ablation of the material surface, blowing of pyrolysis gas into the boundary layer, and mechanical erosion of the material surface by shear stress. The focus of the current work is to examine the interaction of gas surface reactions with a hypersonic boundary layer on a carbon surface at the microscale. There is a strong inter-dependence of ablation material response and boundary layer transport phenomena and the need for a coupled solution [1] in evaluating the performance of an ablative material. For example, surface coverage dependent finite rate models require an accurate representation of mass flux to the surface as diffusion of the gas from the boundary layer dictates the supply of reactive species to the surface.

This work examines the transport of mass,momentum, and energy and chemical species throughout the chemically reacting boundary layer, heterogeneous chemical reactions at and near the ablating surface, and removal of surface material due to oxidation and nitridation using the recent air-carbon ablation model (ACA) of Prata *et al.*[2]. Mass loss by spallation and sublimation is not considered. The current work builds upon the previous work of Ramjatan *et al.* [3, 4] where DSMC simulations of flight-relevant boundary layer flow over resolved material mesostructure was performed. However, these simulations did not implement a gas-surface reaction model which is thereby addressed in this work. In addition, a preliminary study of gas-phase chemistry will be performed, where ablation products such as CO and CO_2 may react to form CN (a strong radiator).

Preliminary results of boundary layer flow using the Stardust entry over a representative mesostructure where the ACA model is input as a surface boundary condition can be seen in Fig. 1. The conditions correspond to Stardust re-entry conditions at approximately 69 km altitude. Regarding nitridation, in Fig. 1d, there is a steeper mass fraction gradient of N-atoms as compared to O-atoms as the mesostructure is approached. Near the surface, the composition is mainly N2 (due to the high rate of N-atom recombination), followed by CO and CN produced by oxidation and nitridation reactions according to the ACA ablation model.

Keywords: Ablation, Material Response, Boundary-Layer Flow, DSMC

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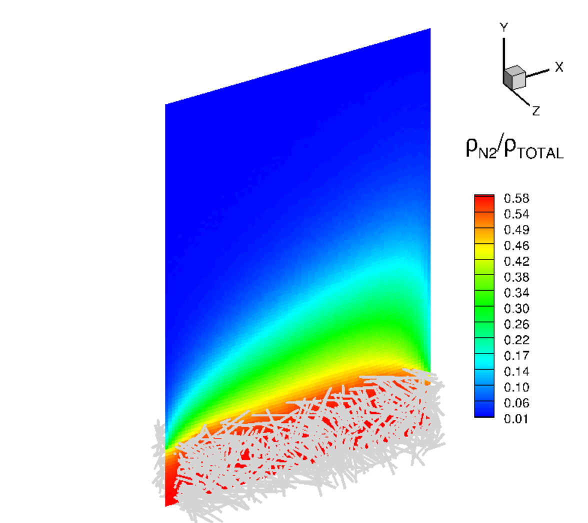
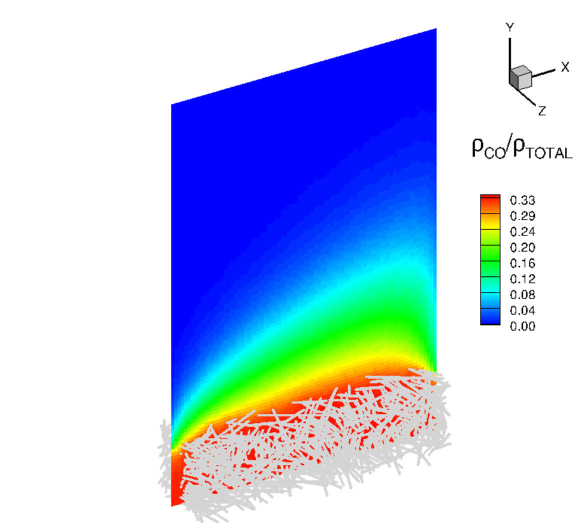
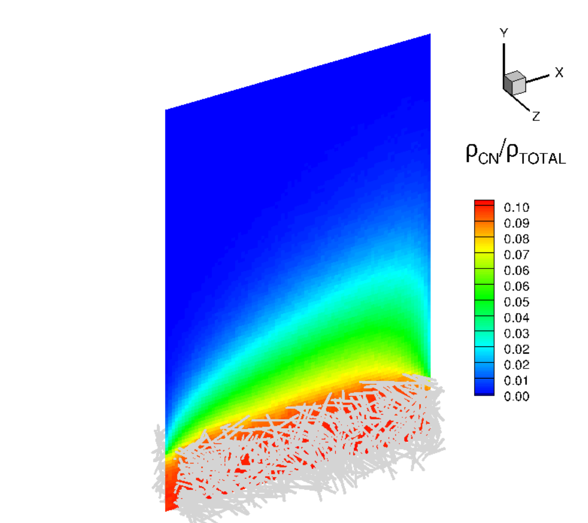


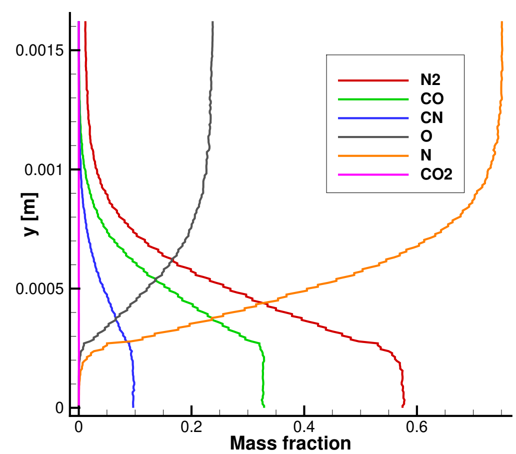
(a) N_2 mass fraction



(b) CO mass fraction



(c) CN mass fraction



(d) Line plot of mass fractions in boundary layer

Figure 1: Mass fraction contours at 68.9km.

A Combined Convolutional Neural Network (CNN) and Multi-Layer Perceptron (MLP) to Predict Effective Permeability

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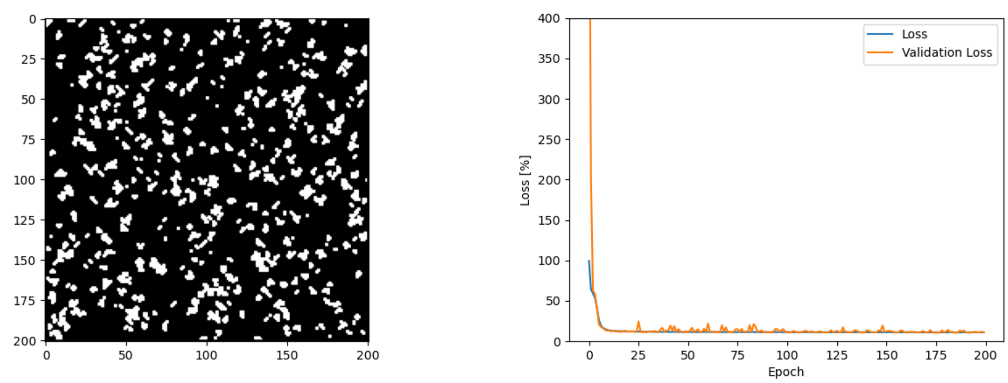
Abstract

A common way to close the conservation equations for transport through porous ablators, is through the use of Darcy's Law; however, this becomes a difficult task, as effective permeability needs to be recomputed anytime there is a minor change in the microstructure of the material. To address this issue, a neural network is being built to train a model that will accurately and readily predict effective permeability while being informed both by the microstructure of the material and flow parameters such as temperature and pressure. The overall goal is to develop a model that will predict the effective permeability of fibrous porous ablators. In the current work, the model is developed of two-dimensional (2D) quartet structure generation set (QSGS). Two-dimensional images of QSGS are reduced using CNN and then combined with temperature and pressure in a MLP network. Such a model can be used to predict permeability even when there are changes to the microstructure without explicitly computing or measuring permeability.

Keywords: Permeability, neural network, convolution, multi-layer perceptron, quartet structure generation set, Latin Hypercube sampling



(a) (b)

Figure 1: Example QSGS structure used for training (a) and convergence of loss values over the course of training (b)

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Incorporating Ablation Physics in Fluid Ablation Interaction Model

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Abstract

Hinge method is a novel immersed boundary method to model fluid ablation interactions. Hinge method controls the fluxes passing through the computational grid-points with the help of a gateway matrix [1]. The advantage of the Hinge method being it can be easily deployed in a Finite Volume framework and has comparable accuracy with other Immersed Boundary methods. Hinge method has been deployed in KATS-SM while Ablation physics and boundary conditions have been factored in to model the recession in the 1D Ablation test case. Ablation physics and its associated boundary conditions including aerodynamic heating, pyrolysis energy loss, ablation blowing flux have been incorporated in KATS-SM. These fluxes are computed using the Hinge matrix after locating the interfaces along the charring surface. A 1D geometry model with convective boundary condition and fixed surface recession was considered to determine the rate of ablation [2, 3]. A comparative study is being performed to validate the model through the results from KATS-MR. The goal is to calculate the surface recession rate and mass loss due to ablation in the KATS-SM code and validate the same with the results from KATS-MR. It has been found that there is an increasing jump in the temperature of outlet faces that are undergoing ablation and charring. After incorporating the aerodynamic heating boundary conditions and porosity models, comparable surface recession rates and heating of the surface has been observed. The rate of recession and mass loss in the first time step is exactly the same in both KATS-MR and KATS-SM. The rates continue to be extremely close with a deviation of less than 1% in the 1st 1000 timesteps.

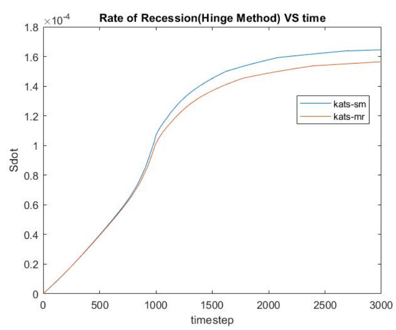

Figure 1: Rate of recession (Hinge Method) vs time.

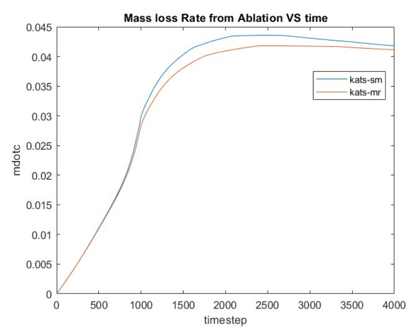

Figure 2: Mass loss rate (ablation vs time).

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Arc jet CFD/ablation simulations using a plasma flow model in the arc heater

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Abstract

High enthalpy arc jets are the established ground-test technology used to evaluate the performance of Thermal Protection Systems (TPS) materials for space exploration missions. By providing a highly energetic flow over prolonged test times, arc jet facilities enable testing materials under extreme aerothermal heating experienced by spacecraft during planetary entry. The constricted arc heater part of an arc jet increases the test gas temperature. The large difference in electric potential between the electrodes generates the extreme current necessary to heat the test gas via Joule heating. To complement the mission design cycle process and reduce the need for extensive testing, NASA is developing modeling and simulation tools that characterize the arc jet flow and the material response of the test sample. The Data Parallel Line Relaxation (DPLR) code [1] was used in this work to characterize the flow inside the NASA's Aerodynamic Heating Facility (AHF) arc jet [2] through Computational Fluid Dynamics (CFD) simulations. The aerothermal environments computed in DPLR were provided to the Porous material Analysis Toolbox based on OpenFOAM (PATO) software [3], where the thermal response and the surface recession were computed. Although the supersonic aerothermal modeling technology from the nozzle throat to the test chamber is well established and routinely used, the inlet conditions from the arc heater section have always been approximated in the literature [4]. Heritage CFD simulations were first performed using inflow conditions constant in the radial direction and computed with an equilibrium solver based on the arc heater settings. These traditional arc jet simulations did not model the plasma flow inside the arc heater.
An accurate model of the plasma physics that occurs in high pressure and high enthalpy arc heater was implemented in the ARC Heater Simulator (ARCHeS) software [5]. Three-dimensional unsteady simulations of the plasma flow inside the AHF were performed. The averaged plasma flow solutions from ARCHeS were used as CFD inlet conditions for the DPLR and PATO simulations (Fig. 1 and 2). These arc jet flow and ablation simulations using inlet conditions based on arc heater plasma flow modeling were then compared to heritage ones based on arc heater settings.

Keywords: Arc Jet, Arc Heater, Plasma Flow, Heat Transfer, Mass Transfer, Ablation.

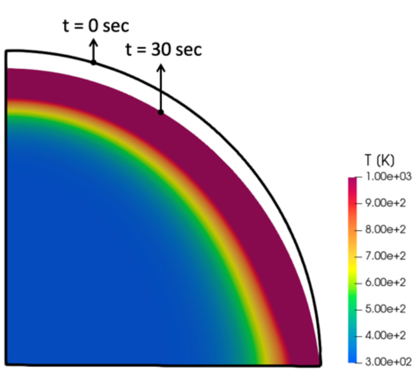

Figure 1: PATO thermal response simulations of a 4-in hemisphere sample in the AHF arc jet.

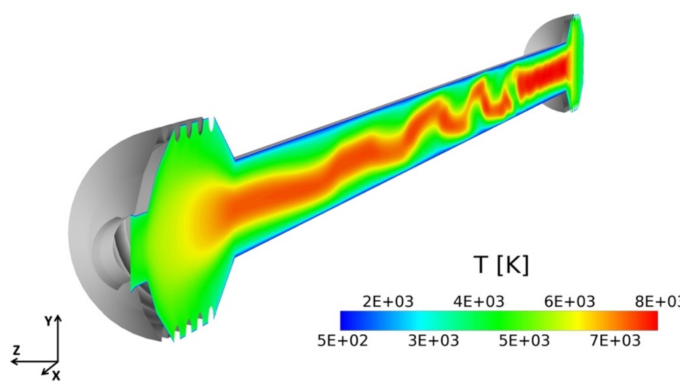

Figure 2: ARCHeS plasma flow simulations in the AHF arc heater.

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Modeling the effective elasticity of anisotropic porous materials

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Abstract

The development and optimization of composite materials designed for thermal protection of NASA's spacecraft require understanding their physical response to high-enthalpy environments. To predict their macro-scale properties and behavior, high-fidelity 3D simulations are performed at the microscale on realistic representations of these composites. The digital microstructures are generated either synthetically or through X-ray micro-computed tomography reconstructions.

One of the main challenges in the prediction of the structural response of heatshield materials is the computation of the effective elasticity of the fibrous composite, as well as the understanding of the deformation and stresses generated at the microscale. These are driven by the fiber layout within the microstructure and the distribution of the infused matrix. In this effort, the micro-mechanical linear elastic behavior of fibrous ablators is modeled using a numerical method based on the Multi-Point Stress Approximation (MPSA) finite volume scheme [1], a generalization of the more commonly used Multi-Point Flux Approximation (MPFA) [2,3] that was presented at the 10^{th} Ablation Workshop. To predict the behavior of fibrous and woven architectures, algorithms that compute the local fiber orientation are used [4].

The implementation of the MPSA was verified using analytical solutions, engineering test cases, and compared against legacy Finite Element Analysis (FEA) software. The stress analysis models were then applied to real geometries used by NASA in thermal protection systems such as fibrous preforms and woven materials and the results were compared to experimental data.

Keywords: elasticity, anisotropic materials, finite volume, MPSA, material modeling, computed tomography

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The effect of pitting on the tensile behavior of amorphous carbon and carbon fiber

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Abstract

FiberForm, the substrate of the Phenolic Impregnated Carbon Ablator (PICA), contains different fundamental forms of carbon: vitreous/HOPG-like microconstituents in the fiber/core and amorphous/turbostratic carbon structures in the binder material, which acts as the "glue" between fibers providing rigidity to the material. The thermo-chemo-mechanical response of each are fundamentally different [1], for example, in their oxidation-induced pitting behavior. In this study, we use the molecular dynamics code, LAMMPS, to investigate the effect of pitting on the mechanical behavior of carbon fiber (CF) and amorphous carbon (AC) atomistic/microstructures. The generation, characterization, and mechanical loading of the pristine AC and CF structures are compared to their pitted states; in addition, the AC structures are generated and tested at a range of densities from 1.27 g/cm^3 to 2.93 g/cm^3. Our simulated structures are validated against characterization techniques such as SEM, XRD, Raman and tensile experiments. Findings indicate degradation of tensile properties for the pitted counterparts, across all densities. We also observe AC to have weaker tensile behavior for both oxidized and pristine states, providing evidence to the growing theory that FiberForm is likely to fail at the binder material [2], with profound implications for the spallation behavior when the material is exposed to a high shear environment. The present work advances fundamental understanding of the coupling between oxidation and mechanical behavior of carbon-based TPS materials and serves as a basis for larger-scale simulations.

Keywords: *Carbon Fiber, Amorphous Carbon, Molecular Dynamics, Tensile Behavior, Oxidation*

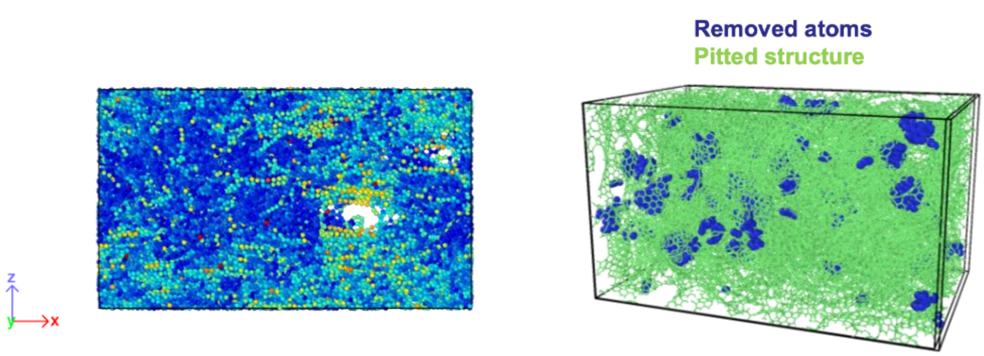

Figure 1. left: stretched AC at its tensile strength; right: example of the carbon fiber atomic structure, where removed atoms (in blue) represent pitting due to oxidation, and the bonds (in green) are the resulting pitted structure

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Hypersonic and Ablation Capabilities at JHU/APL

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Abstract

Johns Hopkins University Applied Physics Laboratory (JHU/APL) has been actively involved in hypersonic research for decades. JHU/APL conducts design, analysis, and fabrication of hypersonic vehicles and thermal protection systems in collaboration with government, national laboratories, universities, and industry partners. Applications span from system-level design/analyses down to detailed material characterization and phenomenology. Hypersonics is considered a core competency, and ablation phenomenology is important to hypersonic applications of interest at JHU/APL.

This poster presents an overview of the ablation capabilities and activities at JHU/APL. A wide range of community-developed software is leveraged, as well as substantial in-house code development, such as the ATLAS thermal solver. Results from ATLAS are compared to previous validation cases from the Ablation Workshop Test Case Series. In addition to modeling and simulation capabilities, JHU/APL is actively engaged in advanced materials research and development to improve hypersonic vehicle performance.

Keywords: Hypersonic, ablation

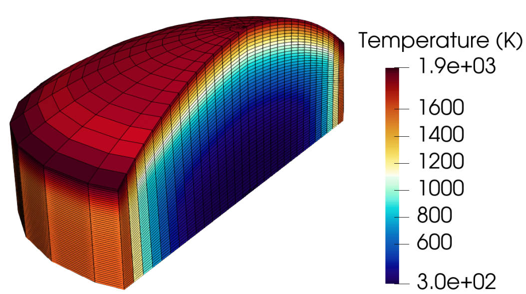

Figure 1: Ablation Workshop Testcase 3.0 performed with ATLAS thermal solver

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Multi-physics simulation workflow for ablating Thermal Protection Systems (TPS)

Bruce Crawford, Valerio Viti, PhD

Ansys

Abstract

Ablating Thermal Protection Systems (TPS) have been the most prevalent solution to protect those areas on the airframe with the highest heat fluxes, such as vehicle noses, leading edges, engine inlet cowls and, for re-entry systems, the blunt end of the vehicle. However, the design of TPS systems is a challenging endeavor given the difficulty in generating accurate and reliable experimental data. Because of the almost impossibility of reproducing realistic flow conditions in a ground-based testing facility, and because of the extreme costs and difficult data reduction associated with flight experiments, computer simulations have become a key enabling technology in the design of modern re-entry vehicles. Once validated, high-fidelity computer simulations can reproduce accurately the physical phenomena and their complex interactions, thus reducing drastically the need for wind tunnel and flight testing.

In the present work we are proposing an innovative Multiphysics workflow to address the high-fidelity modeling of realistic TPS geometries and materials embedded in a high-enthalpy environment, including heat conduction effects into the airframe, TPS recession rates and boundary layer blowing effects. Depending on the level of fidelity, the ablating surface is modeled using an empirical and/or first principles models and methods, which include surface reactions, discrete particles, and conjugate heat transfer to name a few. This framework includes the new panels to specify ablation dynamics, such as Vielle's Law and/or with gas and surface reaction models, and an automatic workflow for the mesh deformation and motion (MDM). Relevant open-literature case studies will be presented and a roadmap for future development will be discussed.

Keywords: Thermal Protection System, TPS, ablation, atmospheric re-entry, surface chemistry, conjugate heat transfer, airframe heat transfer

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KREPE-2: The Second Orbital Entry Mission for the KRUPS Capsule

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Abstract

The Kentucky Re-Entry Universal Payload System (KRUPS) is a project that began at the University of Kentucky in 2013 [1]. Thus far, KRUPS has flown four sounding rocket missions, one high atmospheric balloon flight, and one orbital re-entry from the International Space Station (ISS). Kentucky Re-entry Probe Experiment (KREPE-1), KRUPS' first orbital mission, featured two different TPS materials produced by NASA Ames and Johnson Space Center, respectively [2]. KREPE-2, currently planned for launch in 2023, will fly five KRUPS payloads with five heat shields, allowing for the testing of new or experimental TPS materials. KREPE-2 will be the biggest mission for the KRUPS project to date, and will pave the way for the next generation of KRUPS launches. KREPE-2 will be flown onboard Northrop Grumman's Cygnus vehicle, and upon vehicle breakup after leaving the ISS, five capsules will be released and begin their re-entry. This mission features several updates from its predecessor, KREPE-1, including new subsystems and an additional two capsules. A successful mission for KREPE-2 will mark the beginning of a new era for the KRUPS project, and will pave the way for future orbital missions that can be used to demonstrate new TPS technology and materials.

Keywords: Re-entry, material response, thermal protection system.

Figure 1: Artist Rendering of KRUPS Orbital Re-entry, courtesy of Lincoln Young, Josh Adams and Paul Rodgers, UK

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Simulation of heat transfer of carbon fibers felts and microstructure effects on thermal conductivity of carbon/phenolic ablators

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Abstract

Accurate modeling of the thermal response of Thermal Protection Systems (TPS) requires adequate characterization of thermophysical properties. According to the literature [1], the effective thermal conductivity of carbon/phenolic ablators is one of the significant factors of heat transfer towards the interior of the material. It is primarily driven by the intrinsic thermal conductivity of carbon fibre felts and it is influenced by the geometry and arrangement of the constituents. With increased computational capabilities, numerical simulations of materials at microscale resolution have become more affordable. These simulations allow obtaining effective properties, which can be used in volume-averaged design codes, minimizing the need for expensive experimental campaigns. For example, one can simulate the heat transfer inside a carbon fiber felt and obtain the effective thermal conductivity. This can be achieved with the Porous Microstructure Analysis software (PuMA) and its Python version pumapy, developed by NASA Ames Research Center. [2, 3]. In this work, we have analysed the effect of the microstructure and the different intrinsic properties on the effective thermal conductivity.

The first step consisted in developing a numerical model for CALCARB 18-2000, the carbon preform of the material in the study, ZURAM, by artificially generating a transverse isotropic material with a normal distribution in the Through-Thickness (TT) and a uniform distribution in the In-Plane (IP). This material model was verified and validated from available experimental measurements furnished by the manufacturer [4, 5]. For the thermal simulation, it is necessary to know the intrinsic conductivity of each material constituent. The intrinsic conductivity of the fibers was obtained from Pradere [6], while the conductivity of the gas was determined using Mutation++. Therefore, it was possible to conduct a general parametric study to evaluate the impact of microscopical parameters on thermal conductivity, such as porosity, fiber length and diameter and angular variation of the fiber orientation on the developed numerical model of CALCARB. Afterwards, a sensitivity analysis based on a surrogate model was performed to quantify how the previous most important parameters, such as porosity, fiber length and angular variation, influence the overall performance of porous materials. We observe that for the IP direction, porosity has a more considerable influence on the thermal conductivity, whereas in the TT plane is the fiber orientation and that porosity and angle associated have a considerable effect. The results of this analysis are showcased in Figs. 2 to 4.

In addition, two cases have been analyzed: charred and virgin carbon/phenolic materials. The char resulting from pyrolysis, as depicted in Figure 1, leads to a variation in the overall material's porosity and effective thermal conductivity. Hence, it is necessary to accurately characterize the material's thermal response after pyrolysis. A geometry generator for the material in the charred state that creates a uniform coating on top of the fiber by generating a coaxial cylinder was developed in pumapy. This code was later applied to compare the simulation results to the available experimental data [7] to understand if the developed numerical tool can accurately simulate the material's thermal response after pyrolysis. To study the virgin carbon/phenolic, it must be taken into account that the material comprises fibers, gas and phenolic resin. A new material generator has been implemented which combines the previous code developed for CALCARB with a generation of uniformly distributed voxels in the domain that mimics the gas trapped inside the material. In the latter, the medium represents the phenolic resin. Finally, the effect of the change in the conductivity due to the graphitization of the fibers was also evaluated.

The results obtained in both thermal simulations differ from the experimental results. Even though it is fair to say that there is an agreement between the behaviour of the simulated and measured conductivities, the disparity can reside in the fact that some of the properties are not known. For the coating simulation, the charred resin's intrinsic conductivity is unknown. In the case of the virgin material simulation, the resin's and the fibres' intrinsic conductivity at the experiments' temperature are also unknown. These factors, along with the simplicity in the assumption for both geometry generations, can lead to an error in the output of the effective thermal conductivity simulations.

This work provides important information about the effect of the different components and geometrical features of the microscopic properties of porous ablative materials on their macroscopic model evaluation.

As further developments, the artificially generated material models should be improved since they require adjusting the assumptions to consider a more realistic physical geometry. The charred and virgin resin conductivities should be assessed with experimental measurements. Extrapolation of the intrinsic conductivity of the fibers at temperatures not referred to in the literature should be carefully evaluated and validated. The inability to account for the impacts of radiative heat transport on thermal models at high temperatures should be solved.

Keywords: Thermal protection systems, carbon/phenolic ablators, thermal conductivity, microscale numerical simulations

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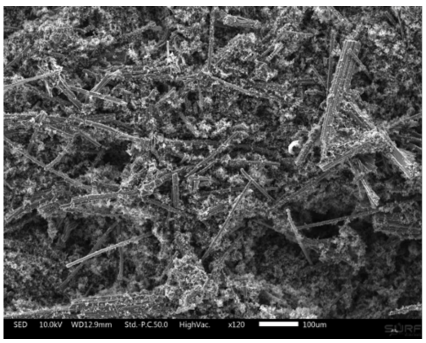

Figure 1: SEM picture of ZURAM at a charred state [7].

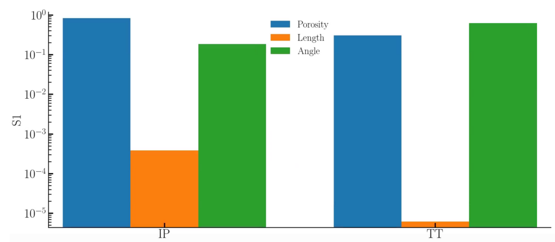

Figure 2: First-order indices. The blue bar represents the influence of porosity, the orange bar the effect of length and the green bar the impact of the fiber's orientation on the effective thermal conductivity.

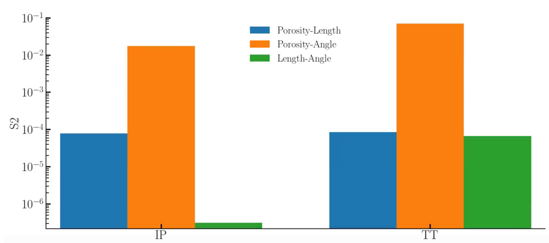

Figure 3: Second-order indices. The blue bar represents the influence of porosity-length, the orange bar the effect of porosity-angle and the green bar the impact of the fiber's length-angle on the effective thermal conductivity.

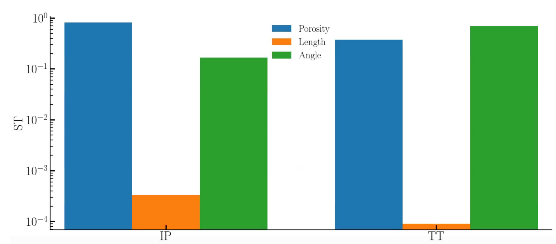

Figure 4: Total-order indices. The blue bar represents the influence of porosity, the orange bar the effect of length and the green bar the impact of the fiber's orientation on the effective thermal conductivity.

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In-depth analysis of ablated carbon fiber preform in high-enthalpy plasma air

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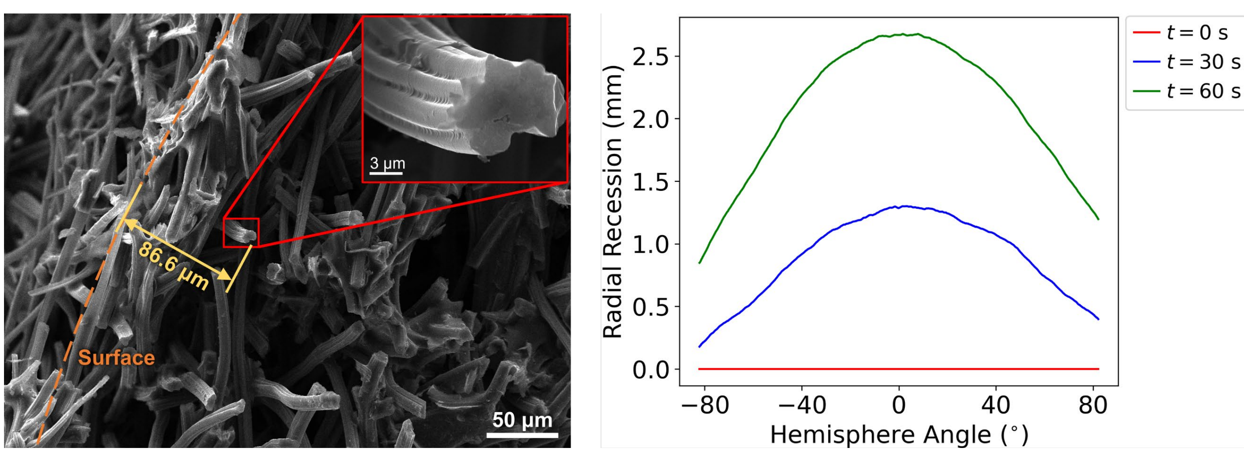
Abstract

Hypersonic entry of a planetary body requires a thoroughly tested and well understood thermal protection system (TPS), able to shield the hypersonic vehicle from the extreme aerothermal environment experienced throughout the duration of entry. For sufficiently high velocity entries, an ablative TPS material must be selected, such as Phenolic Impregnated Carbon Ablator (PICA), as other reusable TPS materials cannot survive the severe peak heating. In addition to strong convective and radiative heat fluxes, these ablative TPS materials can experience highly dissociated flow, leading to an increase in total heat flux imparted to the material surface.

Due to the complex thermochemical nature of the hypersonic environment for ablative TPS materials, it is critical that these materials and their components are characterized at varying entry-like conditions. To this end, FiberForm® (Fiber Materials, Inc., Biddeford, ME, USA), the structural carbon fiber preform of PICA, was subjected to high-enthalpy plasma air in the von Karman Institute for Fluid Dynamics' 1.2 MW Plasmatron facility. These hemispherical carbon fiber preform samples were exposed to plasma air flow at four separate conditions, with heat flux ranging from 12.5 W/cm^2 to 51.2 W/cm^2 and pressure ranging from 0.6 kPa to 10.0 kPa. Analysis was performed using collected temperature, high-speed, and post-test scanning electron microscope (SEM) image data. [1]

In this work, analyses of collected data and post-test samples are presented. Details of the oxidation environment experienced during testing are discussed using qualitative and quantitative SEM image analysis, including oxidation depth estimates (Fig. 1a) and Thiele oxidation regime assessment, where both reaction-limited and diffusion-limited oxidation is observed at different conditions. In addition, recession of samples as a function of hemisphere angle will be presented (Fig. 1b), demonstrating a novel method able to evaluate surface removal beyond the sample stagnation point. These analyses will provide a deeper understanding of FiberForm response to the hypersonic environment, allowing for higher fidelity modeling, and ultimately, greater efficiency in the engineering of space vehicles.

Keywords: carbon fiber preform, recession, thermal protection materials, oxidation regime



(a) (b)

Figure 1: (a) SEM image showing a lightly oxidized fiber found at approximately 86.6 µm below the surface of a cross-sectioned FiberForm sample and (b) radial recession along hemispherical sample surface measured using high-speed camera data and a custom Python image analysis module.

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Coupling CFD and Material Response for Analysis of Mars Entry

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Abstract

In computing the response of an ablating thermal protection system during atmospheric entry, the aerothermal environment and material response are generally computed separately with a blowing correction term in the material response model to account for the blowing of char and pyrolysis gases [1]. In this work, we apply a coupled approach in which pyrolysis blowing gases, computed in the PATO material response code [2], are used with a blowing boundary condition in the DPLR hypersonic CFD code [3]. This leads to an iterative method in which blowing products from PATO are input into DPLR to update surface heating estimates. The full iterative method, with the addition of radiative heating estimates using the NEQAIR radiation solver [4], is shown in Fig. 1. The method is demonstrated on a sphere case with the environment and material properties based on the Mars Science Laboratory entry. Future work includes utilizing this method in computing full 3D material response during the Mars 2020 entry.

Keywords: Heat Transfer, Mass Transfer, Material Response, Ablation, CFD

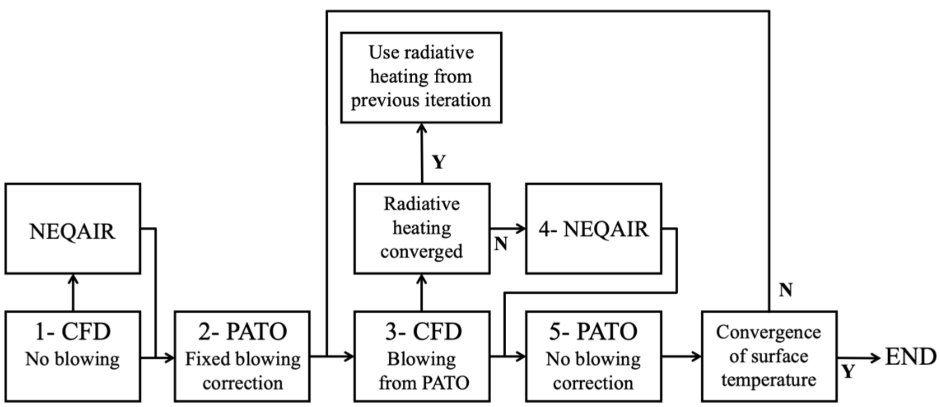

Figure 1: Methodology for coupling material response and aerothermal environment.

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Infrared ablation metrology in the VKI Plasmatron Facility

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Abstract

In this poster we present an overview of the experimental set-up and processing tools recently developed for detailed in-situ ablation metrology in the VKI Plasmatron facility by means of non-intrusive infrared techniques. This involves innovative infrared thermography techniques, traditional radiometers and surface spectrometry. In particular we show:
1) Infrared temperature mapping over 3D objects with surface recession: an optical calibration technique is used to extract 3D metric information from the 2D thermal images, thanks to a specific calibration target with control points. The evolution of the sample shape during the experiment is tracked from a side view, using a visual-range high-speed camera with dedicated image processing, and reconstructed in 3D under the assumption of axi-symmetry. Band angular emittance is used to correct the thermograms. Surface temperature is hence reconstructed on the time-varying geometry;
2) Multi-band in situ emittance measurements: we formulate a general model of the IR instrument response, including detector sensitivity, optics and atmospheric path spectral transmission. The model is applied for detailed radiometric calibrations at different bandwidths and validated with transmission measurements. The methodology is applied for multi-band in situ emittance measurements of a graphite sample exposed to nitrogen plasma.
3) Validation of two-color temperature measurements: two-color pyrometry, traditionally used to provide emittance-independent measurements of stagnation point temperature during ablation testing, is very sensitive to changes in the spectral emittance of the surface in the measurement range. We use a surface spectrometer to provide in situ validation of the technique.
These techniques aim at expanding the in situ metrology capabilities of PWT material response testing by providing quantitative temperature data over the surface of the test sample as its recedes due to thermochemical ablation, together with accurate band emittance and reliable temperature measurements.

Keywords: Plasma Wind Tunnels, IR thermography, IR radiometry, Ablation

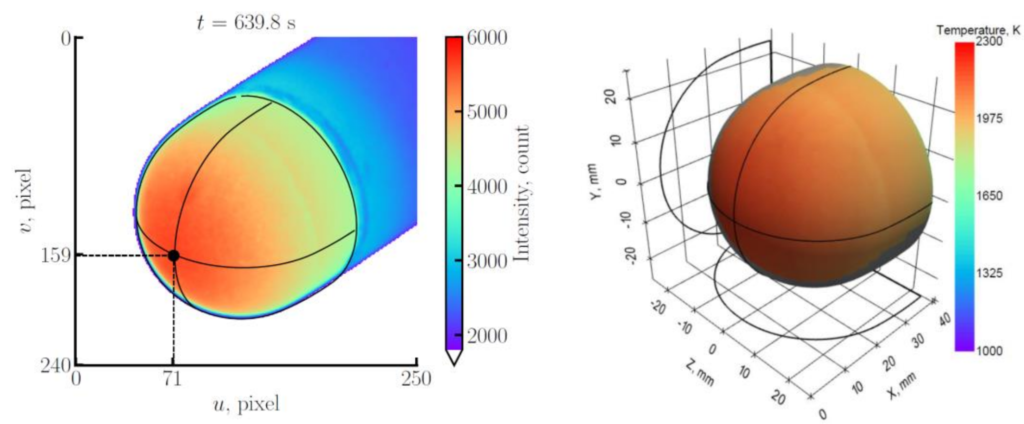

Figure 1: Example of raw IR thermogram (left) and 3D reconstructed temperature map over the ablated sample geometry (right).

Plasmatron X: a New Ground Testing Platform for Hypersonic Ablation Research

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Abstract

The complex combination of aerothermal, chemical, and mechanical processes that characterize hypersonic flights drives the selection and sizing of materials for Thermal Protection Systems (TPS) [1]. Carbon-carbons, carbon-phenolics, ceramic matrix composites, ultra-high temperature ceramics, and high-temperature super-alloys are preferred material technologies for TPS applications [2, 3]. Since the outset of hypersonic flight, ground testing in plasma wind tunnels has been critical in developing, characterizing and engineering TPS material technologies [4]. Although arc-jet facilities are generally favored for large-scale component qualification, as well as for tests under high stagnation pressure and shear conditions [5], the electrodeless plasma discharge technology used in Inductively Coupled Plasma (ICP) wind tunnels provides a pristine environment that is attractive for studying gas-surface interactions for ablative TPS materials [5]. In this study, the aerothermal capabilities of the Plasmatron X are presented with emphasis to ground testing of ablative materials. The Plasmatron X facility is a new 350-kW-ICP wind tunnel, developed by the Center for Hypersonics & Entry System Studies (CHESS) at the University of Illinois Urbana-Champaign, which enables fundamental and applied research on gas-phase and near-surface non-equilibrium processes, as well as advanced high-temperature materials for hypersonics. The operational envelope of the Plasmatron X is characterized as a function of control parameters (input power, static pressure, gas flow rate) and presented in terms of spatially resolved cold-wall heat flux and stagnation pressure maps of the flow, high-speed imaging of plasma jet unsteadiness, and chemical composition of the jet through optical emission spectroscopy. We present design and preliminary experiments on ablator samples, along with modeling support to the design of experiments. Emphasis is made on the unique capabilities of the Plasmatron X to support gas-surface interaction and ablation research, including hour-long test times, multi-sample testing, and rapid material screening of a wide range of gas mixtures including air, nitrogen, argon, oxygen, carbon dioxide, and flammable gases, and the ability to tailor oxygen partial pressures and flow shear stresses under subsonic and supersonic flow conditions.

Keywords: Ablation; Material response; Hypersonics; ICP wind tunnels; Aerothermochemistry.

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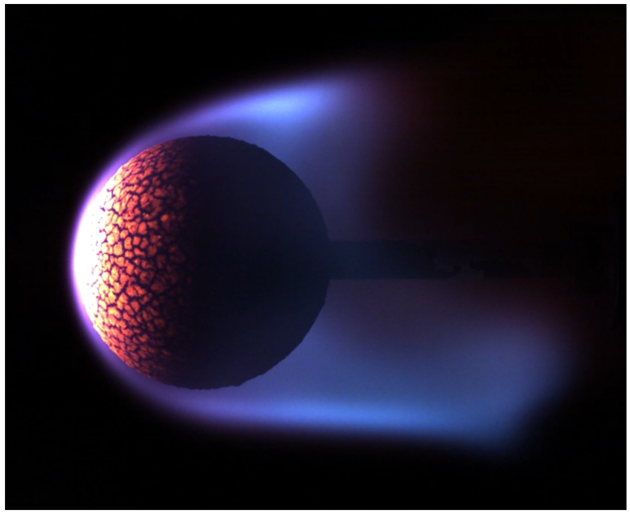

Figure 1: Ablation experiment of cork material in air plasma jet at Plasmatron X

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Table-Top Shock Tunnel for Studies of Shock Layer Chemistry and Rapid and Low-Cost Testing of Materials for Hypersonics

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Abstract

A "table-top shock tunnel" (TTST) has been constructed for rapid and low-cost testing of shock layer chemistry and materials response. The system uses a laser detonation molecular beam source to generate well-characterized pulsed hypersonic molecular beams. The TTST can provide fundamental data for the development of models as well as validation of new models by the production of controlled shock layers above ablating and non-ablating surfaces and the measurement of their phenomenology. Material response can also be tested in well-characterized environments to aid in the development of materials for hypersonics applications. Initial characterization of the TTST has been carried out by studying the ablation of Kapton H polyimide surfaces exposed to a hypersonic O/O_2 beam as a function of nozzle-to-sample distance and comparing the experimental observations to the results of direct simulation Monte Carlo (DSMC) calculations. The Kapton samples ablated at all distances, with the mass loss being consistent with the expected $1/r^2$ dependence of incident flux. However, measurement of the surface roughness of the exposed samples as a function of distance revealed a rapid transition from rough to smooth as the sample was moved from 40 to 30 cm from the nozzle, suggesting the formation of a weak shock layer as the sample moved closer to the nozzle and the incident flux increased. The DSMC results predict the largest change in flux of unimpeded O atoms across the surface at about the same nozzle-sample distance where the largest change in surface roughness was observed. The agreement between experiment and DSMC results add validity to the simulations, which can provide a quantitative description of the gas environment above the sample with essentially any hypersonic beam that is used in the TTST.

Keywords: Molecular beam, atomic oxygen, vitreous carbon, hypersonic flow, DSMC

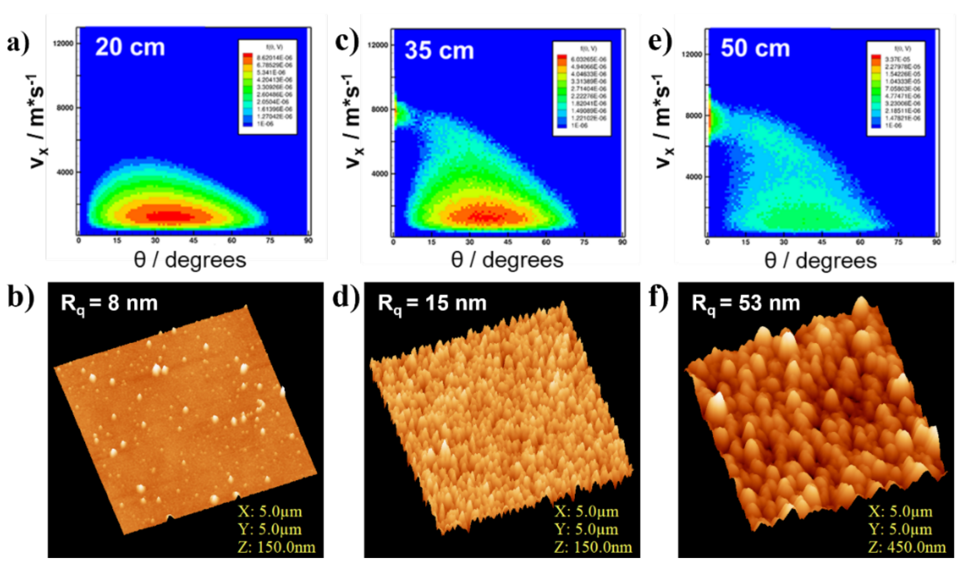

Figure 1. Comparison of simulated incident velocities from DSMC to final surface morphology of Kapton H, with nozzle-to-sample distances of of 20, 35, and 50 cm. (a, c, e) Incident velocity of O atoms versus impact angle with respect to nominal surface normal. (b, d, f) Atomic force microscope (AFM) images of ablated samples, with root mean square surface roughnesses (R_q) shown.

Particle based simulations of the high temperature oxidation of carbon fibers

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Abstract

Oxidation at high temperatures is an important factor in ablation of highly porous carbon fiber materials. In depth diffusion of oxygen coupled with surface reactivity greatly affects effective oxidation rate and mass loss of these materials. Image based particle simulations are useful tools to accurately represent porous materials in computational domain, capture in depth diffusion and oxidation profiles of porous materials [1, 2]. We developed a particle-based simulation code using PuMA [3] library. We use a Volume of Fluids method to construct complex microstructures characterized by X-ray microtomography [4]. Mean free path of the gases can approach to same order of magnitude of fiber radius or pore size in carbon fibers which would introduce non-continuum diffusion through medium. We assume a simple gas based on a Maxwell-Boltzmann distribution without any continuum assumptions and move particles according to their mean free paths [4]. Resulting oxidation rates and surface recession in simulations are compared to the experimental data.

Keywords: Oxidation, Carbon Fiber, Ablation, Porous Material, Gas-Surface Interactions

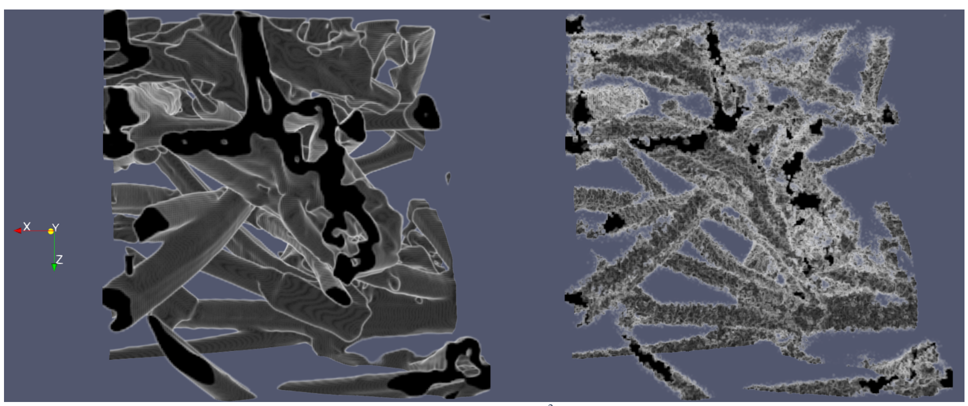

Figure 1: Simulated volume ablation of (0.23 mm)^3 section of a carbon fiber material.

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Development of an immersed boundary heterogeneous isotropic heat equation solver in the Porous Microstructure Analysis (PuMA) software

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Abstract

Microscale modeling, based on x-ray microtomography, has become an important component of materials modeling of Thermal Protection Systems (TPS) [1]. Effective material properties and response models, needed by volume-averaged material response tools [2, 3, 4], are highly influenced by the microstructure of the material.

Past microscale modeling of TPS systems have included determining simple geometric parameters, thermal response [5], continuum and rarefied mass transport [6, 7], simulation of material decomposition via oxidation [8, 9, 10], and simulation tools specifically designed for woven architectures [11, 12]. At NASA Ames Research Center, the Porous Microstructure Analysis (PuMA) software [13, 14] was developed to serve as an open-source framework for microscale simulations. PuMA simulations tools were developed and optimized for x-ray microtomography datasets, which take the form of very large 3D Cartesian domains with scalar values corresponding to the local x-ray attenuation.

Some of the PuMA solvers, such as the permeability and effective thermal conductivity, operate directly on the voxel grid while others, such as the random walk diffusion and microscale oxidation solvers, utilize immersed boundary methods to create a higher fidelity surface representation.

In this work, we present an immersed boundary heat equation solver, suitable for the calculation of continuum tortuosity and isotropic effective thermal conductivity. A cut-cell method has been developed to divide boundary voxels (cells which contain more than one material phase) into sub-volumes. The geometric parameters of each sub-volume - mass, center of mass, connection areas, and connection lengths - are determined from triangulations generated by the Lewiner Marching Cubes algorithm [15] and a modified Marching Squares algorithm. The steady-state heat equation is solved using the biconjugate gradient stabilized method (BiCGSTAB).

Verification cases are presented to ensure correct implementation and expected order of accuracy. A domain convergence study is presented to demonstrate the advantage of the immersed boundary method as compared to the legacy voxel based solver. The solver is implemented into the PuMA software and will be included in a future release.

Keywords: PuMA, heat transfer, tortuosity, microscale, immersed boundary

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Utilizing x-ray computed tomography to validate microstructures generated through fiber-generation algorithm

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Abstract

Effective permeability is a key parameter to model pyrolysis and oxidation during ablation. To calculate the effective permeability, a reliable model for material microstructure is necessary. An in-house fiber generation algorithm, Fibergen, is used to create volumes replicating the porosity of the FiberForm microstructure. To validate the ability of this algorithm to produce volumes which accurately replicate the FiberForm microstructure, x-ray computed microtomography (XRCT) is utilized to image the true microstructure of the material. The Heliscan Mk2 by Thermo Fisher Scientific is used to image the microstructure of FiberForm. Heliscan Mk2 uses helical scans, an innovative alternative to circular tomography, where the sample is rotated and elevated during imaging. By allowing the sample to pass through the source beam, the distance between the source and sample can be minimized thereby increasing resolution, decreasing distortion, and increasing signal to noise ratio. The output of this process is grayscale tomographs of the sample. Following the acquisition of raw data, the slices are filtered, segmented, and stacked to produce a digital volume representing the true microstructure. The verification of the Fibergen algorithm to produce volumes with effective permeability consistent with that of the true FiberForm microstructure is achieved by generating a microstructure using Fibergen with the same porosity as the XRCT scan, and computing the permeability for both structures. XRCT is also being used within our group to determine the permeability and porosity of room temperature vulcanization (RTV) materials used to bind heat shield panels, and to investigate the presence and development of a material called tylose within the inner vessels of charred white oak for bourbon barrels.

Keywords: X-ray computed microtomography (XRCT), effective permeability, FiberForm

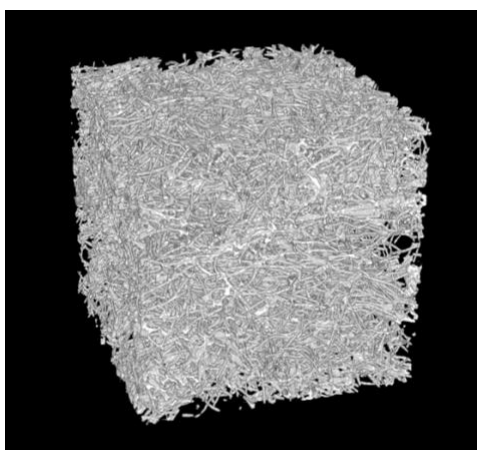

Figure 1: Volume rendered using Avizo and XRCT performed using Heliscan Mk2.

Ablation of Rocket Nozzles in PATO

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Abstract

Solid and hybrid rocket motors rely on the use of passive thermal protection systems to preserve the shape of the nozzle during firing and to insulate the underling structure of the engine. Low erosion materials typically feature higher thermal diffusivity and density, whereas the best insulators tend to have higher erosion rates when exposed to the combustion chamber environment. For these reasons, the nozzle of this solid and hybrid motors is often an assembly of components made of different materials with specific functionality, optimize to maintain the mass of the system as low as possible. Reliable and accurate numerical models are critical to define material selection and component sizing. In the present work, 2D-axysimmetric material response simulations of different rocket nozzle configurations have been performed using the Porous material Analysis Toolbox based on Open-FOAM (PATO) [1]. The code has been used to predict the ablation rate of the materials exposed to reference thermochemical environment for rocket engines. Comparisons of in-depth temperature and density profiles of all the components of the nozzle assembly are presented. The material selection ranges from non-pyrolyzing materials like refractory metals and graphite, to charring phenolic-based composites, such as carbon- and silica-phenolics. The results of the simulations are compared to demonstrate the importance of such numerical tools in the preliminary design phase of a rocket nozzle.

Keywords: Rocket nozzles, Ablation, PATO, Material Response Modeling

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Experimental and numerical study of graphite ablation in air plasma

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Abstract

In this poster we present a study of the ablation and transient thermal response of a graphite sample in air plasma. The experiment is carried out in the Plasmatron facility of the von Karman Institute for Fluid Dynamics. The aero-thermodynamic environment reproducing the atmospheric entry in the boundary layer of a test object is selected with cold-wall heat flux around 1.5 MW/m2 and test chamber pressure of 100 mbar. Stagnation point surface temperature is monitored by means of two-color pyrometry, while IR thermography, featuring 3D optical calibration, allows to reconstruct 3D temperature maps over the ablating surface. Band emittance is measured in situ using different IR radiometers. Time-resolved recession profiles are measured by means of side-view camera imaging.
The test conditions lead to a stagnation point surface temperature of 2300 K at steady-state and an overall recession of 4.5 mm after 640 s. We propose a numerical comparison based on in-house 1D and 2D ablation codes featuring a traditional transfer coefficient model with thermochemical ablation tables, starting from a CFD simulation calibrated on the measured free-stream flow temperatures. While a 1D ablation code overestimates both the front and back surface temperature of the sample, the 2D code captures the temperature histories, while the ablation rate is underestimated.

Keywords: Plasma Wind Tunnels, Ablation, Graphite

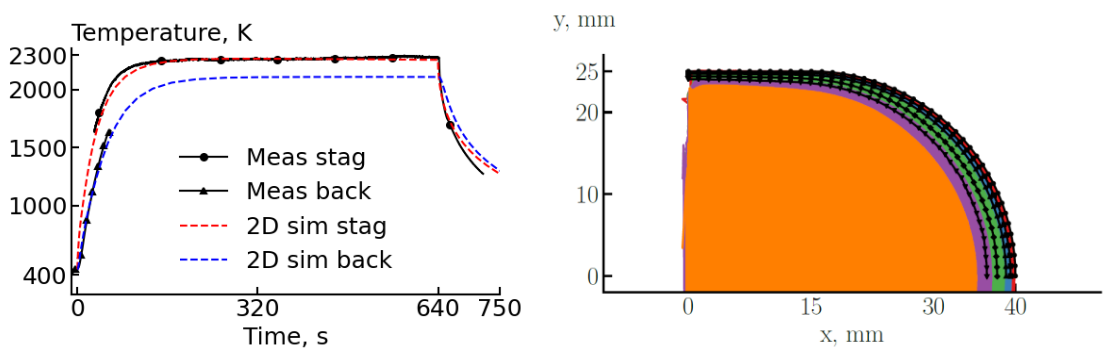

Figure 1: (left) Simulated stagnation and back surface temperature with the 2D ablation code follow the measured trend. (right) Simulated recession profiles (black curves) underestimate the measured values (colored shapes).

Modeling material response for the orbital Flight of the Kentucky Re-Entry Universal Payload System (KRUPS)

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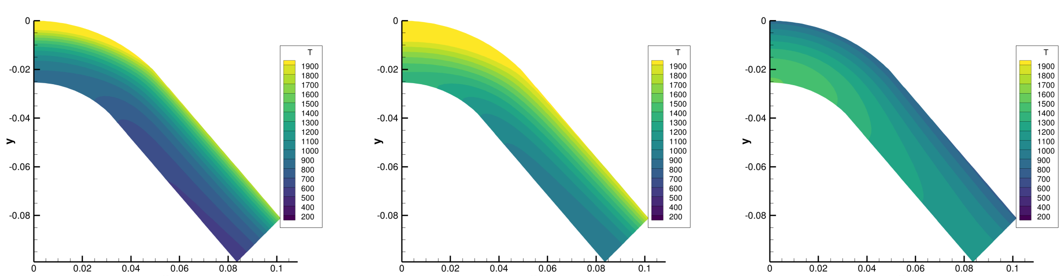
Abstract

Kentucky Re-Entry Universal Payload System (KRUPS) is a small spacecraft developed to provide flight data during atmospheric re-entry [1]. The purpose of this work is to model the material response behavior of the thermal protection system (TPS) of the KRUPS capsule during flight, using the Kentucky Aerodynamic and Thermal-response System Material Response module (KATS-MR) [2]. The trajectory of the flight is based on the Kentucky Re-Entry Probe Experiment (KREPE), a flight launched from the ISS, and the data is provided by a simulation using the Kentucky Trajectory Modeling Program (KTMP) [3]. This trajectory data is used to modify pressure and heat flux profiles from CFD simulations using the fluid dynamics module of KATS (KATS-FD) [4], which are then used as the boundary condition for the outer surface. Theoretical Ablative Composite for Open Testing (TACOT) is used as the reference TPS material for the simulations. The end result is a simulation from an altitude of 86 kilometers down to 21 kilometers, capturing 350 seconds of the trajectory.

Keywords: Re-entry, material response, thermal protection system.



(a) time = 100s (b) time = 200s (c) time = 350s

Figure 1: Results from material response simulation.

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Multi-Fidelity characterization of an under-expanded/supersonic high-enthalpy jet under uncertainty

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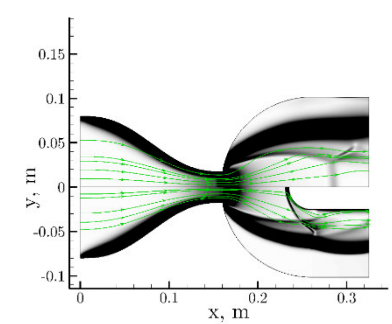
Keywords: High-enthalpy facility, Uncertainty Quantification

Abstract

Thermal Protection Materials for aerospace atmospheric entry applications are generally characterized by means of high-enthalpy facilities, such as Inductively Coupled Plasma torches or arc-jets. Whether the facility is, the intrinsic complexity of the flow physics makes hard the determination of the free-stream conditions to which a given sample is exposed.

A robust characterization should be thus conducted by accounting for the several sources of uncertainty in a UQ framework. For such practical applications, UQ studies are generally efficiently performed through surrogate models. These are trained on CFD computations, and they mimic the CFD response in terms of input-output relationship for a negligible computational cost. Polynomial chaos or Kriging surrogate models are widely used for this scope. For example, in the work of Brune et al. [1] a polynomial chaos representation of the sample heat flux/pressure response was built considering 47 sources of uncertainty. Even if associated only with the surrogate model training, the computational cost can be high. Multi-fidelity representation [2] allows for lowering the computational effort by leveraging on cheaper lower fidelity representations.

This work presents a robust and efficient methodology for high-enthalpy facility characterization, applied on an under-expanded supersonic high-temperature flow, obtained in the von Karman Institute Plasmatron wind tunnel. A Bayesian framework allows us to access the probabilistic densities for the reservoir's total temperature and pressure, which are not accessible by means of the experimental set-up. A Kriging surrogate model was trained to mimic the high-fidelity CFD response and accelerate the analysis. It is built in a multi-fidelity/adaptive way to enhance efficiency. The analysis also allowed us to determine the nitridation catalytic efficiency of the probe used to measure the heat flux and the Pitot pressure.



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Manufacturing HARLEM Lightweight Carbon Phenolic Ablator with Domestic Constituents

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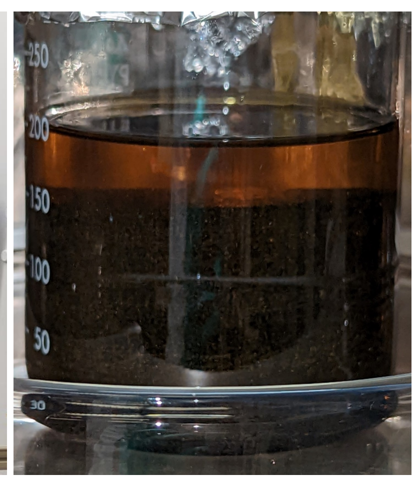
Abstract

A process to produce an accessible lightweight carbon phenolic composite for research relevant to thermal protection systems has been of significant interest for the ablation community. The process for manufacturing HARLEM (HEFDiG Ablation Research Laboratory Material) makes significant progress towards wider accessibility to these materials [1, 2]. In the interest of validating this process as a feasible solution to this problem, the Center for Hypersonics and Entry Systems Studies (CHESS) and the Center for Exascale-enabled Scramjet Design (CEESD) at the University of Illinois at Urbana-Champaign have undertaken an effort to manufacture an analogous material using domestically sourced constituent materials.

The constituent materials are off-the-shelf components. The process uses polyvinylpyrrolidone molecular weight 10000 (Sigma-Aldrich, Inc., St. Louis, MO, 68178), ethylene glycol 99% purity (Lab Alley, Spicewood, TX, 78669), and Durite SC-1008 (Bakelite Select, Bellevue, WA, 98004) for the phenolic resin solution. A rigidized pan felt carbon fiber board, with a nominal density of 0.18 $g\,cm^{-3}$, is used as the preform (Ceramaterials, Dingmans Ferry, PA, 18328). The manufacturing process was performed in a fume hood capable of fitting a mechanical convection drying oven (CP52411-11, Cole-Parmer, Vernon Hills, IL, 60061), a vacuum oven (DZF-6020-ETL-110, MTI Corporation, Richmond, CA, 94804), and an Edwards vacuum pump (nXDS series, Edwards Ltd, Burgess Hill, UK, RH15). We will present results from preliminary manufacturing cycles along with microscopy characterization of the material.

Keywords: Phenolic composite, porous media, thermal protection system

(a) Curing oven setup



(b) Preform in phenolic [post-impregnation pre-cure]

Figure 1: Experimental pictures of equipment and specimen

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Characterizing and modeling the spallation phenomenon utilizing arc-jet experiments

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Abstract

The process of spallation occurs when pieces of thermal protection system (TPS) material break off and are ejected into the flow. Understanding the process of spallation is important to refining existing models and designing accurate TPS. In current TPS models, spallation is typically modeled using an empirical rate, although there is little experimental data available to use for validation. Analysis from recent arc-jet experiments, however, resulted in a better knowledge of the causes of this process, as well as the types of particles produced. In particular, this provided insight about the size of particles, the number of particles, and how the production of these particles are affected by various factors. This information can be integrated with the existing spallation module of the Kentucky Aerothermodynamics and Thermal-response System (KATS) to model the process of spallation more autonomously. The goal is to replace the existing parametric approach with a probabilistic model for the creation of particles that better represents the physical process. For example, the range of particle sizes seen in previous experiments can be used to produce various particle diameters within the model that better mimic the actual statistical distribution of particle sizes occurring.

Additionally, preparations are underway for an additional arc-jet test campaign to be conducted in the Aerodynamic Heating Facility (AHF) arc-jet at NASA Ames Research Center. The goal of these experiments is to better understand this process and characterize these spalled particles by physically capturing them so that their size and shape can be directly measured. In preparation for these experiments, various methods of particle capture are being tested, as well as processes to measure particle size and hydraulic diameter once these particles are captured. Additionally, numerical models of these samples are being used to investigate any biases in the type of particles being captured. The distribution of particle size found from these experiments, along with additional data found from previous arc-jet tests, can then be implemented into existing spallation models to better improve their accuracy.

Keywords: thermal protection systems, spallation, material response, computational fluid dynamics

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Tensile properties, density, diameter, and coefficient of thermal expansion of commercial carbon fibers as a function of heat treatment temperature

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Abstract

A key component to building an accurate ablative model is gathering reliable material property data as a function of temperature. For carbon fiber, graphitization heat treatments, above their original highest heat treatment temperature, irreversibly affect several properties, such as density, tensile modulus and strength, filament diameter, and coefficient of thermal expansion which we will report for T300, AS4, and IM7. However, obtaining the longitudinal coefficient of thermal expansion (CTE) for carbon fibers is especially challenging. Known measurement methods require long, small count tows mounted in a pulley system to measure the micron-scale contraction carbon fiber will exhibit upon heating. However, to keep filaments taut, a force must be applied that ultimately affects the CTE measurement [1]. In this presentation, we propose an alternative method where both a minimal force, 0.01 N, is applied and entire tows are measured for CTE. We prepared collimated carbon fiber bundles, up to 1 million filaments, heat treated to up to 2700 °C and measured the CTE via compression clamps in a thermo-mechanical analyzer (TMA) across the range of 25 °C to 900 °C.

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The Old Two-step: oxyacetylene combustion using a a two-step reaction mechanism and the effects on ablation.

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Abstract

Oxyacetylene combustion experiments can be a simple method to test ablative materials for thermal protection systems; however, they are not without drawbacks. Using ANSYS Fluent to model the combustion flow domain using a two-step reaction mechanism, and the Kentucky Aerothermodynamics and Thermal-response System (KATS) to model material response, a cost effective and safer analysis can be done on a variety of materials, both theoretical and real-world. Flow and species parameters are resolved in Fluent then incorporated into KATS as initial conditions. This allows us to model how materials ablate and respond. The future work is a conjugate heat transfer model with material properties.

Keywords: Combustion, material response, transient analysis

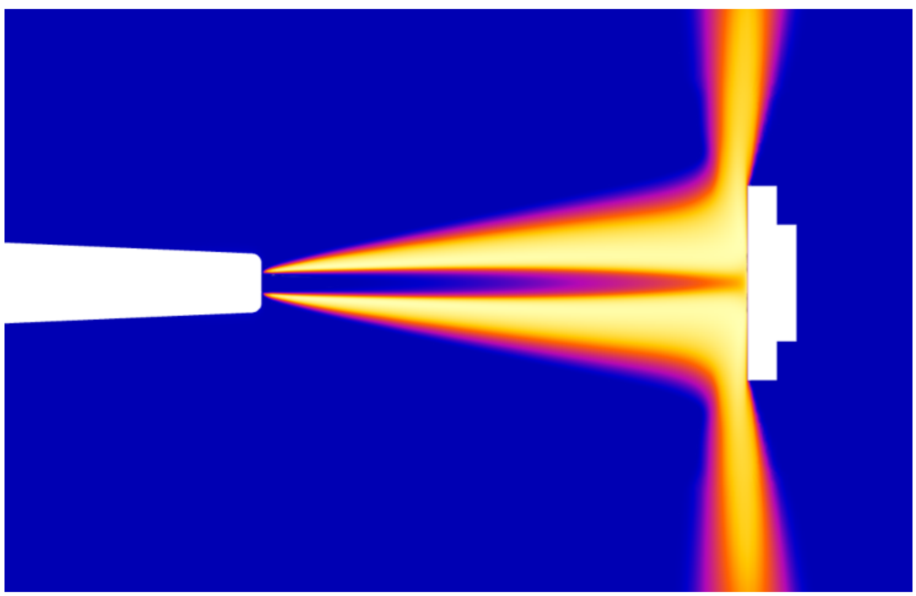

Figure 1: Torch Flow

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Estimating radiative coefficients and their influence on in-depth heating in porous ablators

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Abstract

In modeling the heat load in the hypersonic entry of a vehicle, penetration of radiative signatures was ignored or combined with convective heat flux because it was assumed that it would be absorbed within 1 mm of the TPS material. New experimental work shows that spectral radiation can penetrate into the material and affect the material response over a significant depth, with higher intensity emissions penetrating deeper into the material. Since the physical processes governing the transport of radiative energy are different from conductive heating, an analysis of radiative penetration into the TPS could be important for sizing, and design. Our primary objective is to compute the radiative coefficients of TPS materials and solve the radiative transport equation (RTE) inside the TPS materials, coupling it with the mass, momentum, and energy equations to understand the material response of porous ablators [1]. To compute the radiative coefficients, a microstructure surrogate is generated using FiberGen (Fig. 1), and a geometric optics approach (based on the photon path length method) is implemented in the in-house radiative Monte Carlo solver SPARTA-RMC. The probabilities of reflection, transmission and absorption (collectively extinction) are computed using Snell's and Fresnel's relations as a base function. The coefficients serve as an input to solve the RTE, and in-depth heating in the TPS is computed. Fig. 2 demonstrates a baseline case for LI 900 TPS material to show the importance of solving radiation and convection heat flux through their respective modes rather than combining them into total heat flux and only solving the conduction equation inside TPS materials.

Keywords: In-depth heating, porous ablator, microstructure, Monte Carlo radiation, surrogate modeling

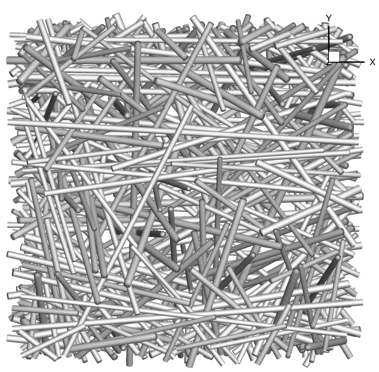

Figure 1: Microstructure of LI 900 TPS material.

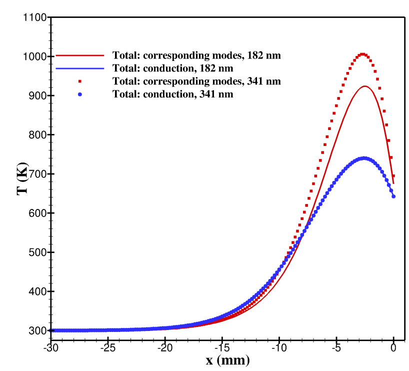

Figure 2: In-depth heating profile of LI 900 using Dragonfly heat flux trajectory.

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Development of a custom supervised learning network to model ablation of TPS materials

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Abstract

Detailed macro-scale simulation of thermo-fluidic phenomenon experienced by thermal protection systems (TPS) material is performed by utilizing dedicated material response codes. However, the state-of-the-art material response codes require micro scale properties such as permeability and thermal conductivity to ensure closure of the conservation equations. The empirical relations formulated from physical experiments to determine the micro scale properties fail to capture the effects of ablation on the micro scale properties. This is evidenced from the DSMC simulations of isolated microstructures, which mimics the exposed char layer during re-entry. The type of degradation (thinning/needling) (Fig. 1) of carbon fibers directly influences the changes in micro scale properties which are not considered by the current state-of-the-art modeling approaches. However, determining the influence of ablation on micro scale properties using isolated DSMC simulations is computationally ineffective, not to mention the complexities involved in coupling these micro scale effects with material response codes. Supervised machine learning networks offer a unique alternative to the DSMC simulations by predicting the oxidation of fibers subject to varying input parameters (pressure, temperature and reaction probabilities). Once trained high-fidelity data, the network can be easily integrated into material response codes to capture micro scale ablation and determine micro scale properties. A supervised learning network inspired by conventional neural network is developed to replace the computationally intensive DSMC simulations and provide a pathway to connect microscale simulations with macroscale modeling.

Keywords: TPS material, material response, ablation, micro scale properties, supervised learning

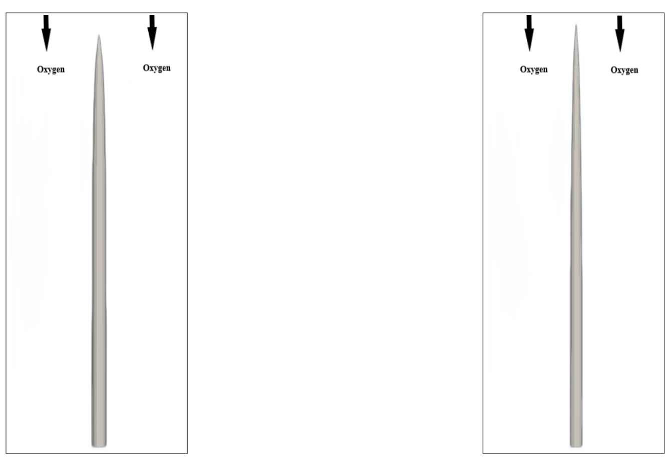

Figure 1: Oxidation of an isolated cylindrical fiber with two different reaction probabilities. At higher values, the fiber tends to form a needle like shape upon oxidation (Fig. 1(a)) in contrast to the thinning (Fig. 1(b)) that occurs at lower reaction probabilities.

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Pyrolysis of Ablative Heat Shields: Phenolic Resin

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Abstract

Quantification of pyrolysis products of thermal protection system (TPS) materials are required in order to mitigate the need for overbuilt TPSs and improve materials response models and heat shield designs. Most pyrolyzing ablative heat shields contain phenolic resin; therefore, a good understanding of the thermal decomposition mechanism of this material provides a foundation to develop improved materials response models that can, in turn, lead to better heat shield design and prediction of performance. To obtain high fidelity data on the thermal decomposition mechanisms of phenolic relative molar yields of gaseous pyrolysis products have been determined as a function of sample temperature (room temp – 1200 ºC) at five heating rates (1, 3, 6, 12, and 25 °C/s), using a method that is based on work by Bessire [1] on PICA, a composite of phenolic resin and carbon fiber preform (FiberForm. Pure phenolic resin discs were embedded in FiberForm, which was heated (in vacuum) resistively, and the evolved gases were collimated by two apertures as they passed through two regions of differential pumping and into a mass spectrometer detector. Mass spectra were collected rapidly as the sample was heated, and these spectra were fit appropriately to determine relative molar yields of the gas-phase species. Like PICA, the relative molar yields appear to be dependent on heating rate, suggesting that the thermal decomposition pathways do not reflect equilibrium chemistry. The relative molar yields are different from those found for PICA, and some reasons for the observed differences will be presented. Finally, the phenolic resin char was found to have different morphology when the sample was heated at different rates. In particular, higher heating rates tend to produce more crack sin the charred samples (see Figure 1). S

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Keywords: Pyrolyzing ablator, phenolic resin, thermal decomposition, moral yields.

Figure 1: Pure phenolic resin before and after pyrolysis.

References

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MDSuite: comprehensive post-processing tool for molecular dynamics simulations

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Abstract

With the recent increase in computational capabilities and the development of accurate interatomic potentials based on *ab-initio* calculations and machine-learning models, particle based simulations such as Molecular Dynamics (MD) have become an attractive option to study relevant systems. MD simulations provide access to system observables that are not easily available experimentally. For example, one can extract properties and upscale them to be used in other codes in conditions where experimental conditions are difficult to achieve [1].

A typical MD simulation relies on classical mechanics (Newton's laws of motion) to describe the position, velocity and energy of each particle in the system. Most other system properties are then obtained from those by means of post-processing. One of the main challenges in post-processing MD simulations is managing the large amounts of data typically generated without incurring memory or computational capacity limitations.

In this work, we introduce an integrated MD post-processing tool: MDSuite [2]. This software is developed in Python and it combines state-of-the-art computing technologies such as TensorFlow or JAX, with modern data management tool-kits (HDF5 and SQL). This allows for a fast, scalable, and accurate MD data processing while keeping a developer-friendly environment. Furthermore, the SQL database is used to store parameters and results, such that one can easily re-call computations done with a specific set of parameters without having to recompute or creating an intricate folder structure with cumbersome names. Part of the architecture of the code is shown in Fig. 1

The structure of the code relies on an object-oriented framework and code abstraction. This means that pieces of the code such as simulation data readers or calculators can be easily implemented and used without the need of updating the core of the code. Currently, the code supports data from several MD software such as `xyz` format, LAMMPS trajectories and fluxes, tabular files, chemfiles trajectories, etc. We have implemented several calculators to compute system properties such as diffusion coefficients, thermal conductivity, viscosity, radial distribution functions, coordination numbers, etc.

The code has been used to analyse MD simulations of carbon, and the effect of thermal treatment on them. Fig. 2a shows the initial amorphous structure and Fig. 2b the graphitized structure after thermal treatment. In purple, one can see the atoms identified as being in a graphene structure, and this increased from a 4.3 to a 70.1 % after thermal treatment. Fig. 2c shows a comparison of the radial distribution function computed using MDSuite for these two structures and the bond distance of graphite. It can be seen that the graphitized structures (blue [3] and green [4]) have a narrow peak at this distance, while the amorphous structure has a much wider peak.

In addition, we have also carried out calculations of thermal conductivity of these structures and the results are $18\,\mathrm{W\,m^{-1}\,K^{-1}}$ for the amorphous material and $184\,\mathrm{W\,m^{-1}\,K^{-1}}$ for the graphitized. It can be seen that the values are much higher to the typical values of rayon fibers used in aerospace [5]. This is mainly due to the periodic boundary conditions applied which artificially increase the conductivity, while in a real material grain boundaries would prevent such increase.

MDSuite is a project under development and we have shown some of the capabilities already available in the code. The python front-end provides a familiar interface for many users in the scientific community and a mild learning curve for inexperienced users. Regarding the analysed test-case, further developments in the MD simulations are required to obtain more realistic values for the properties analysed, in particular, the thermal conductivity.

Future developments include the introduction of more analyses associated with ab-initio methods such as the phonon spectrum, Raman lines, structure analyses, and hydrogen bond statistics, as well as a larger suite of ion-correlation metrics, ring statistics, and molecule building methods for classical MD.

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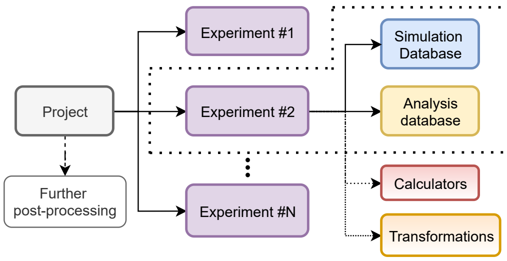
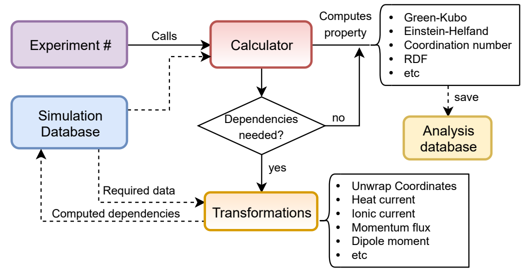
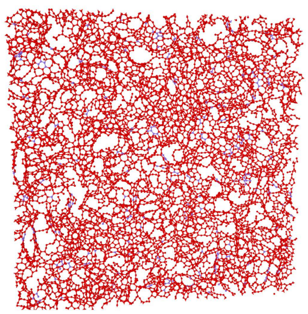


(a) Project

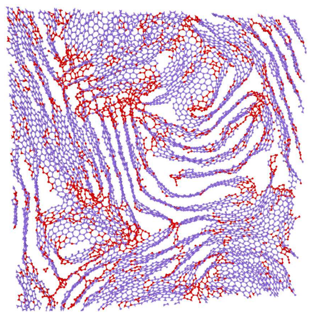


(b) Calculator

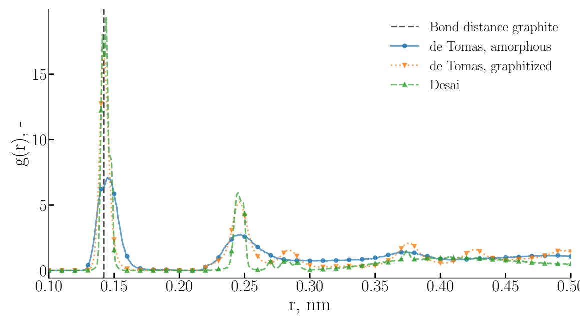
Figure 1: Workflow for different components of MDSuite.



(a) Amorphous, 4.3 % of graphene structures



(b) Graphitized, 70.1 % of graphene structures



(c) Radial distribution function of the analysed structures.

Figure 2: Analyses of carbon simulations.

Keywords: Material properties, molecular dynamics, carbon fibers

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URL `http://www.sciencedirect.com/science/article/pii/S0008622308006015`

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HyCUBE: An Emission Spectrometer Payload on a Hypersonic Reentry CubeSat

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Abstract

The ultimate goal of the HyCUBE program is to collect aerothermodynamic data during hypersonic vehicle reentry at altitudes ranging from 90km to 50km while traveling at speeds between 8km/s and 5km/s. Spectroscopic data characterizing the chemical species and reactions in the air downstream of the bow shock is desired in order to validate and improve existing models in hypersonic flow computations. Spectra collected during descent will be passed to the flight computer, which will create data packets tailored for download in a radio datalink. Given these flight conditions, the use of an adequate thermal protection system is imperative. Both ablative and non-ablative options are being considered.

Leveraging a formal space act agreement between NASA and University of Minnesota, HyCUBE proposes flying an emission spectrometer on several NASA Ames TechEdSat (TES) series CubeSats, with TES-12 being the first. The instrument selected for the payload is an OceanInsight FLAME-S, chosen primarily for its compact size and ability to probe the ultraviolet region of the electromagnetic spectrum where nitric oxide (NO) is the most prevalent emitter. Most recently, plans for the spectrometer's electrical and mechanical integration into NASA TES-12 were developed and tested. The flight computer delivers power to the instrument and communicates with the spectrometer's serial port, using a converter to step between appropriate voltage levels. When integrated into TES-12, the spectrometer viewing element points perpendicularly out of the vehicle's side panel. Operational scenarios of increasing scope have been designed to test the instrument in orbit. These procedures will ensure that enough data is collected in order to capture significant light sources, such as the sun, whose expected spectrum will be compared against the output. The flight computer processes the spectra collected by the spectrometer into smaller size packets for uplink using various datalinks including the low bandwidth Iridium short burst data modem.

The poster will describe the preparation of the spectrometer payload for TES-12, including its preparation for operation in the space environment (i.e., staking, outgassing, etc). We also include further details on the mechanical interface, the electrical interface and communication protocols, and the operational scenarios with the associated software. Future TES vehicles will fly our choice of TPS (TUFROC, AETB, and a carbon-carbon composite by C-CAT are being considered) with an aerodynamic 3U body, and an Arcjet ground experiment will be performed to test the vehicle and further develop the emission spectrometer payload.

We thank the AFOSR for supporting this work under grant number FA9550-19-1-0308, as well as the Minnesota Space Grant Consortium for supporting the development of this project during time spent at NASA Ames. We also thank the TES team at NASA Ames for all the assistance and expertise they shared with us to accomplish this design.

Keywords: CubeSat, emission spectrometer, hypersonic, atmospheric re-entry, ablative, TPS

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Mesoscale structural analysis of inhomogeneities in ablative materials using statistical distribution of properties derived at the microscale

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Abstract

Low-density ablative materials commonly used for Thermal Protection Systems (TPS) are composed of a porous, fibrous structure. These materials appear homogeneous at the macroscale, they are made up of layers of disordered fiber networks and thus are intrinsically inhomogeneous. Their material properties are non-uniform and non-isotropic at the mesoscale as a result of this disordered fiber network. This work focuses on calculation of mesoscale property distributions using model representative volume elements (mRVEs). These mRVEs are created by using information gained from micro-CT renderings to create a model of the material microstructure using geometric primitives (overlapping cylinders). Initial efforts have focused on FiberForm. These mRVEs are generated using a modified version of a code for generating mRVEs of material microstructures (OTTER). This code allows for the creation of unique sets of mRVEs by altering structural parameters such asthe fiber length, the fiber diameter, and the maximum contact area between fibers. These parameters are used to define mathematical rules for the computational generation of the mRVEs. Once a mRVE set is created, FEM calculations are run on the mRVEs to generate a statistical distribution of mechanical properties accounting for the large variabilities in these materials. These property distribution can be used in material response codes, such as KATS to create a more accurate simulation.

Keywords: Thermal Protection Systems, Ablative materials, FiberForm, Micro-CT Images, Representative Volume Elements, Microscale, Mesoscale

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Porous Flow Analysis in the Presents of Thin Layers for Material Response

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Abstract

The thermal protection material is assumed to be homogeneous in the analysis of the thermal protection systems. In truth, during the assembly process of the material, bonding agents, and ceramic coatings are used to bond it or the thermal protection system can be hit by a micro-meteor while reentry, which causes inhomogeneities inside the material. These usually have lower permeability and porosity. Therefore, they can affect the behavior of the thermal protection system, like temperature distribution or the pressure distribution of the pyrolysis gasses. It is possible to solve the behavior of the material by resolving the thin layer. However, this leads to an expansive computational cost. Previously, a volume-averaging method was introduced to get rid of this cost. In this approach, the thin layer occupies a single cell and material properties for this cell are interpolated from what percentage that the thin layer occupies in the cell. The method was proven to predict temperature distribution inside the material. The pressure distribution of the pyrolysis gases is also proven to follow Darcy's Law. All the analyses were made in 1D, but the material response analyses are usually made in 2D. Therefore, the volume-averaging method will be updated so that it can handle 2D effects. Finally, the properties of the pyrolysis gases can be modified to model real ablation cases.

Keywords: Porous media, permeability, volume-averaging, thin layer, material response

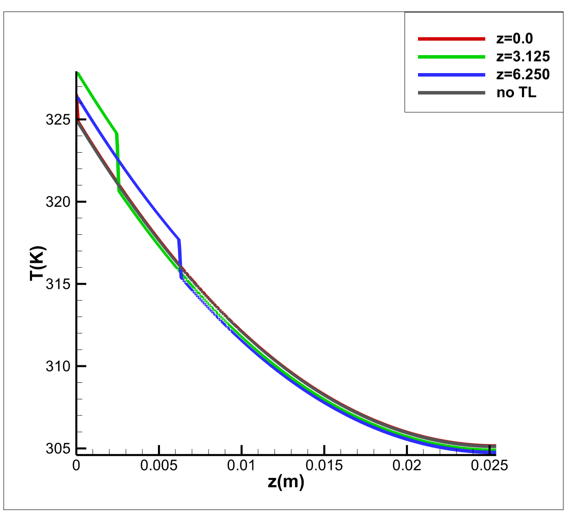

Figure 1: Temperature distribution with different thin layer location

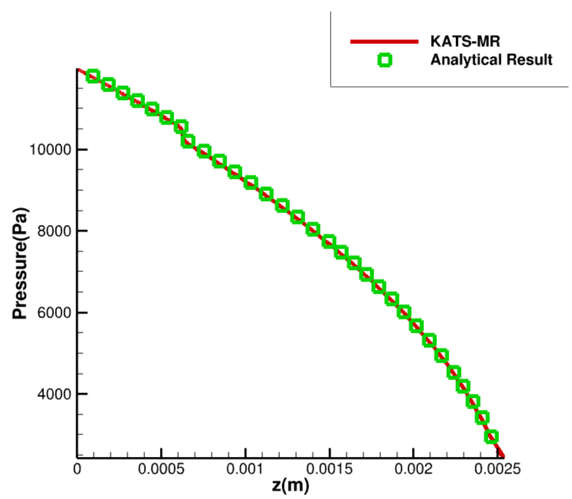

Figure 2: Pressure distribution inside porous material for KATS-MR (red) and analytical result (green) with a thin layer

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Strain-Dependent Measurement of Conductivity in Fibrous Insulation Materials

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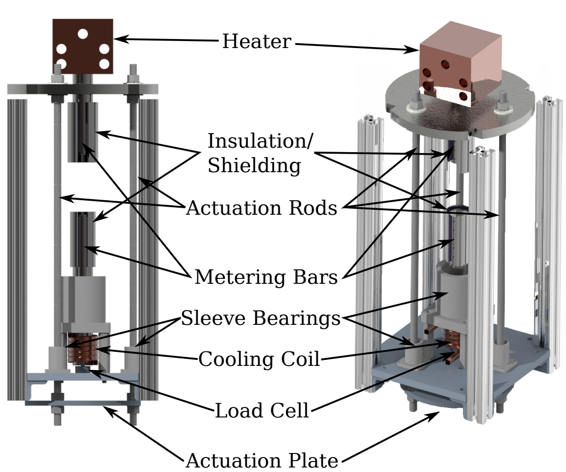
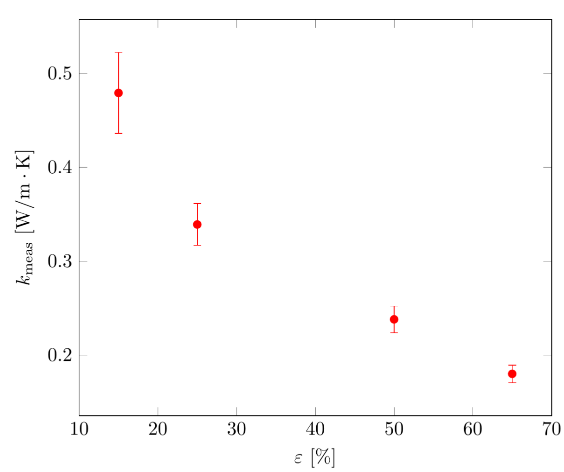
Abstract

Fibrous insulation materials are commonly used in thermal protection system applications to insulate the vehicle from the thermal environment of re-entry and hypersonic flow. Protection from the external environment can take multiple forms, such as endothermic reactions and out-gassing of chemical reactants; however, the primary mode comes from the low thermal conductivity of these materials. The conductivity is a function of temperature, gaseous pressure and composition, and the fiber material properties, but these dependencies are all affected by the internal geometry of the fiber matrix. Internal geometry affects radiation exchange between fibers, conduction paths between the fibers, and pore size for internal gas conduction. Altering the geometry will therefore change the conductivity characteristics, which can happen under material strain. This strain can be induced by mechanical stresses experienced during re-entry or through folding and stretching of the material such as in HIAD systems. To explore the impact of strain on conductivity, a comparative cut-bar measurement system was constructed that would allow variable strain of the material during conductivity measurement. This utilizes an external actuator with a built-in rotary encoder and in-line load cell for use in zeroing the strain measurement. Conductivity measurements have been taken of alumina paper (APA) at different strain levels and found a strong dependence with negative correlation. This work will be expanded by studying materials under current evaluation by HIAD and combined with previous work on separating conduction modes.

Keywords: Heat Transfer, Conductivity, Fibrous Insulation, Strain, Conductivity Decoupling



Rendering of strain-inducing metering bar apparatus



Measured conductivity versus strain for Alumina Paper at atmospheric pressure and T_{avg} = 400 K

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Flow-tube furnace evaluation of the high temperature oxidation response of zirconium carbide

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Abstract

A promising material for use in ultra-high temperature (UHT) applications and as a shape-stable leading-edge material in thermal protection systems (TPS), zirconium carbide possesses excellent thermal, mechanical, and chemical properties [1] [2]. Given the lack of substantial data on material performance and response at high temperatures, however, more well-studied carbides are often used in its place [3]. In this study, the oxidation behavior of hot-pressed zirconium carbide was investigated using a flow-tube furnace at temperatures ranging from 1000 to 1600 C. Mass gain, oxide formation characteristics, and oxide transitions were evaluated at various experimental conditions. Variations in oxidation behavior across the range of temperatures investigated show both kinetic and microstructural dependence with implications pointing to this materials efficacy in ultra-high temperature applications. Supporting post-mortem materials characterization techniques including scanning electron microscopy, electron dispersive x-ray spectroscopy, 3D optical profilometry, and x-ray diffraction were employed to further define material response.

Keywords: Oxidation, UHTC, Microstructure, Porosity, Ceramic, Leading-edge

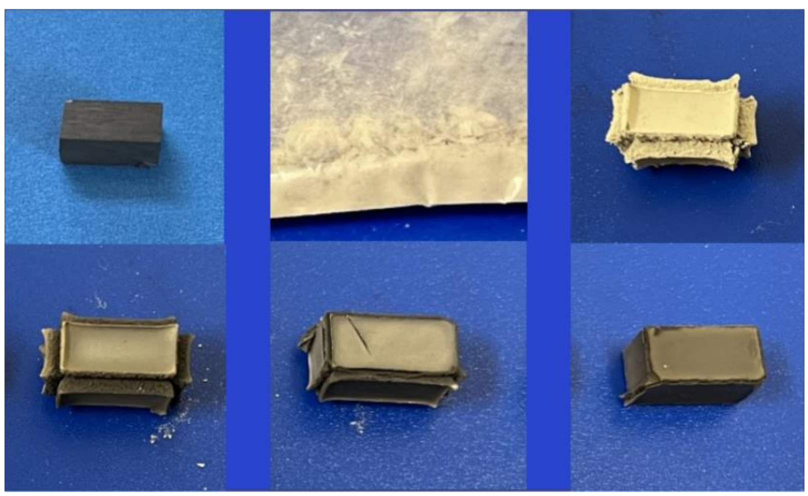

Figure 1: Oxidized zirconium carbide specimens exposed to an air environment for 40 minutes.
Top row, left to right: unoxidized specimen, 1000C, 1200C. Bottom row, left to right: 1400C, 1500C, 1600C treatment temperature.

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Solving radiative transfer equation inside porous ablators using reverse Monte Carlo ray-tracing method

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Abstract

The hypersonic atmospheric entry is associated with extreme heat fluxes, where radiative heat flux produced from the shock is significantly dominant. The radiative intensity at specific shock layer emissions can penetrate the vehicle surface resulting in a peak temperature inside the thermal protection systems. An in-house reverse Monte Carlo ray-tracing (RMCRT) solver is developed to solve the radiative transfer equation (RTE) inside porous materials to understand the penetrative depth of radiative heat flux. The RMCRT solver is validated against a series of analytical solutions in one, two, and three dimensions. The RMCRT solver is then coupled to a material response solver to obtain the in-depth temperature and decomposition profiles of different ablative materials. A comparison study is conducted between the high-fidelity RMCRT solver and the P1 approximation method to show the capability, accuracy, and efficiency of each method.

Keywords: Radiative heat transfer, Reverse Monte Carlo, ray-tracing, RMCRT, porous media, ablators

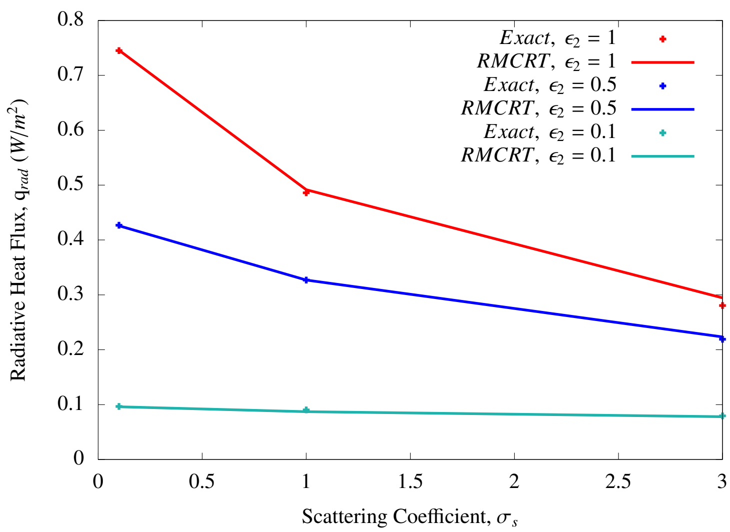

Figure 1: Heat flux of gray plates with isotropic scattering medium against exact solution of Heaslet and Warming [1]

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Modeling carbon fiber oxidation utilizing the hinge method

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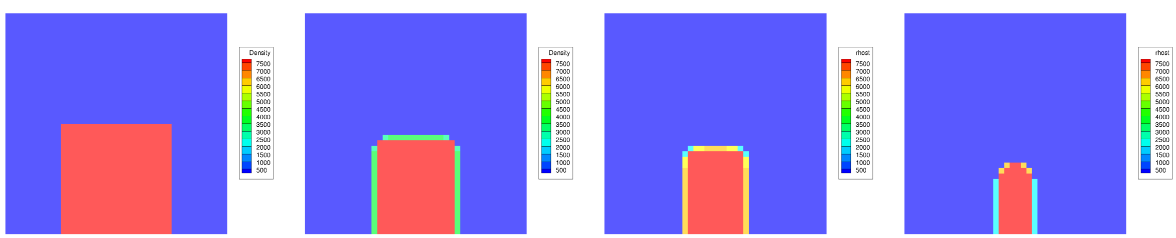
Abstract

The carbon fibers and the surrounding matrix ablate at different rates during oxidation at high temperatures creating surface roughness, which enhances the surface roughness exacerbating the oxidation process. While analytical solutions have been developed in the past that model the shape change from oxidation, these studies have been limited to the oxidation of a single fiber [1]. The differential oxidation of carbon fibers and resin is captured utilizing the hinge method within KATS [2]. The hinge method is an alternative approach to solving immersed boundary problems, where a hinge matrix is applied to the flux terms within conservation equations that modifies the amount of flux between two cells. The key advantage of utilizing the hinge method is that the differential oxidation over a representative composite structure can be captured. This work is part of a larger project with the aim to better capture the effects of surface oxidation. This will be accomplished by capturing the surface shape change at the micro-scale and learning how this affects the predictedoxidation using new carbon oxidation models [3].

Keywords: Carbon, oxidation, hinge method, fiber needling



(a) time=0 s (b) time=0.3 s (c) time=0.5 s (d) time=0.8 s

Figure 1: Oxidation of single carbon fiber with constant oxidation rate

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Commissioning and characterization of semi-elliptical and conical supersonic nozzles for material characterization in the VKI Plasmatron

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Keywords: Ground-testing, nozzle flow, demise

Abstract

In the frame of an ESA research program on the characterization of demise phenomena on space debris materials, the VKI designed two conical and one semi-elliptical nozzle for supersonic experiments in stagnation point and flat plate configuration. The goal was to expand the Plasmatron operational envelope and to increase the aeromechanical shear stress on a test sample compared to the conventional subsonic testing regime with very low dynamic pressure.

The poster will present the first characterization campaign of the three nozzles using experimental and numerical tools. Firstly, based on the data collected during the test campaigns, the CFD simulations performed using CFD++ have been validated. To obtain a comprehensive view of the nozzles' capabilities and to perform a thorough comparison between experiments and CFD, many mass flow, i.e. reservoir, conditions have been explored and various measurement techniques have been implemented. The divergent part of each nozzle hosts two or three pressure ports as well as two or three thermocouples for determination of the pressure and temperature distributions. Stagnation point measurements have been performed over a hemispherical probe (50 mm diameter) to evaluate the stagnation pressure and the available heat-flux regimes for future material testing. Measurements of the reservoir and chamber pressures allowed considering the same conditions in the simulations. Moreover, flow still images enabled the analyzation of distinctive features in the supersonic jet (shock cells, jet boundary, shock stand-off distance), which was directly compared to CFD simulations.

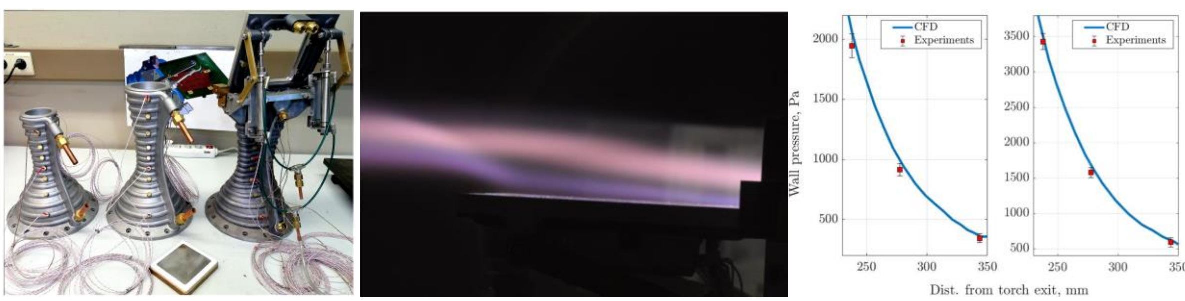

Figure 1: Three new supersonic nozzles commissioned at VKI (left);
flat plate copper calorimeter test with semi-elliptical nozzle (middle);
comparison of pressure distribution along divergent nozzle part for two conditions to simulations (right).

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Micro-structural feature analysis of American white oak in different conditions

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Abstract

Diffusion of liquids or gas through wood structure is an important feature for the plant itself and any possible exploitation of wood material such as the maturation of Bourbon requires an understanding of the structure at the microscales because the diffusive behavior occurs in the micro-scale realm. Therefore, analyzing the wood material's microstructure is one of the best ways to examine diffusion properties of that wood material. In order to study the wood material's microstructure, a precise 3D acquisition of tiny section of the wood material and reconstructing, visualizing, and analyzing 3D data sets are required. Instruments utilized for this study includes x-ray micro-computed tomography (MicroCT), Fiji-ImageJ, and Avizo. MicroCT enables the capturing of smaller portion of the wood material in extremely high-resolution 3D data format. The set of 3D data then can be transferred to Fiji-ImageJ where it will be cropped down to a more manageable computational size. Finally, the data set will be filtered, segmented, and reconstructed in Avizo. After the data preparation, Avizo or other supported softwares can be used to perform analysis on micro-scale structural characteristics of the wood material. This work attempts to capture and bring microstructure of American white oak wood material sample to a computable state to analyze its unique micro-structural features per various conditions and seek how such properties may affect diffusion behavior of fluids in the wood.

Keywords: Diffusion, X-ray microcomputed tomography, micro-structure, reconstruction

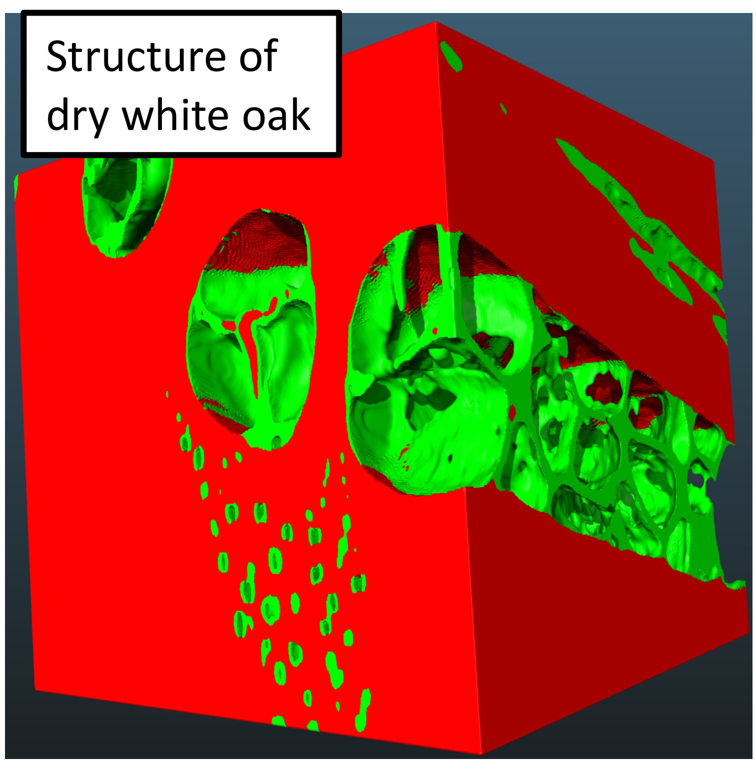

Figure 1: American white oak wood material reconstructed utilizing MicroCT, Fiji-ImageJ, and Avizo

Measurements of permeability of different virgin and charred materials (Fiberform, NORCOAT®LIEGE, ASTERM) used for thermal protection systems (TPS) inside a vacuum system.

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Abstract

Materials used in the Thermal Protection Systems (TPS) of hypersonic vehicles undergo several physical phenomena during ablation. Pyrolized gases formed during decomposition of resins in the TPS must permeate through the material and reach the outer surface, where the flow can help transport energy away from the vehicle. Permeability, a measure of the ease by which a gas may pass through a porous medium such as a TPS layer, is an important property which must be known if the response of a material in a hypersonic flow is to be understood. In this study we use pressure driven flows to measure the permeability of a range of ablative materials at varying levels of thermal decomposition. Permeability of any ablative material depends on temperature, pressure, microstructure geometry, porosity, and several other parameters.

Fiberform, a substrate from which composite TPS materials can be created, is a highly porous carbon foam comprised of approximately ninety percent void space. As a result, the permeability of this material heavily depends on the pore geometry which is in turn determined by the alignment of the carbon fibers. NORCOAT®LIEGE and ASTERM, on the other hand, are complete TPS materials based on phenolic resin bonded to cork particles and carbon fiber, conversely. To quantify permeability, we expose the materials in question to a flow of Nitrogen gas in a vacuum system. A given mass flow rate through a sample is associated with a specific drop in pressure as a result of flow resistance produced by the porous medium. The relationship between pressure drop and flow rate forms a slope which is proportional to permeability. By exposing a given material to many different mass flow rates, a collection of pressure drops may be gathered to determine the permeability for that material. Performing this experiment at different levels of thermal decomposition allows for a more complete understanding of the material's response in all conditions encountered during the ablation process. To create samples with varying decomposition, virgin samples are heated in a furnace to a set maximum temperature for a fixed time and then cooled. Mass loss of the sample measured before and after heating is used to characterize level of thermal decomposition. Due to resulting geometry changes that occur, a method for casting the charred materials in an epoxy with fixed geometry has been developed so that it can seal in the experimental system. Permeability versus char for these samples have then been conducted.

The Determination of Geometric Tortuosity via Spectral Analysis of Gaseous Diffusion in Porous Thermal Protection System Materials.

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Department of Mechanical and Aerospace Engineering, University of Kentucky

Abstract

In ablative Thermal Protection Systems (TPS), properties relating to porous flow are highly important in the context of understanding and modeling material behavior in hypersonic conditions. Tortuosity, a measure of the average convolution of a porous microstructure, is a dimensionless parameter which describes the ratio between the path traveled by a gas molecule through a given layer of porous material and the thickness of that layer. The process of determining the tortuosity of a TPS material has historically involved using x-ray computed tomography to digitally reconstruct a sample at the microscopic level so that Monte Carlo methods could be applied, averaging over many simulated paths through the material. In this experiment, we instead employ an experimental approach which uses the time response of diffusing gases to measure the relative diffusivity of a porous TPS test article.

The experimental procedure, which is currently in development, involves placing a cylindrical sample of material between two gas reservoirs each at atmospheric pressure. Initially, one reservoir will be filled with a" diffusing gas", such as Argon or Helium. The other reservoir will be filled with atmospheric air. The addition of a leak valve in the air volume allows a very small amount of gas to escape into a chamber at high vacuum containing a residual gas analyzer (RGA). Spectrographic observation of the increase in the concentration of diffusing gas with respect to time will indicate the rate of diffusion through the sample. By comparing this rate of concentration change with the rate from a similar experiment where no sample is present, or in a case where a sample of known diffusivity is present, it will be possible to estimate a value of relative diffusivity for each material. From this relative diffusivity it becomes possible to calculate a value for tortuosity.

Supervised learning model to predict the permeability of porous carbon composites used as TPS materials

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Abstract

Detailed macroscale simulation of thermo-fluidic phenomenon experienced by thermal protection systems (TPS) material is performed by utilizing material response codes. The state-of-the-art material response codes used to perform these macroscale simulations require microscale properties such as permeability to ensure closure of the conservation equations. Klinkenberg formulation is normally used to estimate the permeability of the porous TPS materials in material response codes to account for non-continuum effects. However, the Klinkenberg formulation involves the need to determine the Klinkenberg constants which are dependent on temperature, pressure, and type of gas species associated with the macroscale simulations. Hence, the Klinkenberg formulation suffers from interpolation errors, not to mention the tedious work involved in determining the Klinkenberg constants every time the material response codes require permeability for closure. To solve this multi-dimensional problem, we developed a supervised learning model capable of capturing the inherent relationship between permeability and the input parameters (temperature, pressure, and gas species). Once trained against high-fidelity data, the supervised learning model can accurately predict the changes in permeability with respect to temperature, pressure, and type of gas species as evidenced from Fig. 1 and Fig. 2. A modified version of the supervised learning model was also developed to capture the length scale dependency of permeability for FiberForm and a PICA-like composite.

Keywords: Supervised machine learning, DSMC simulations, Non-continuum permeability

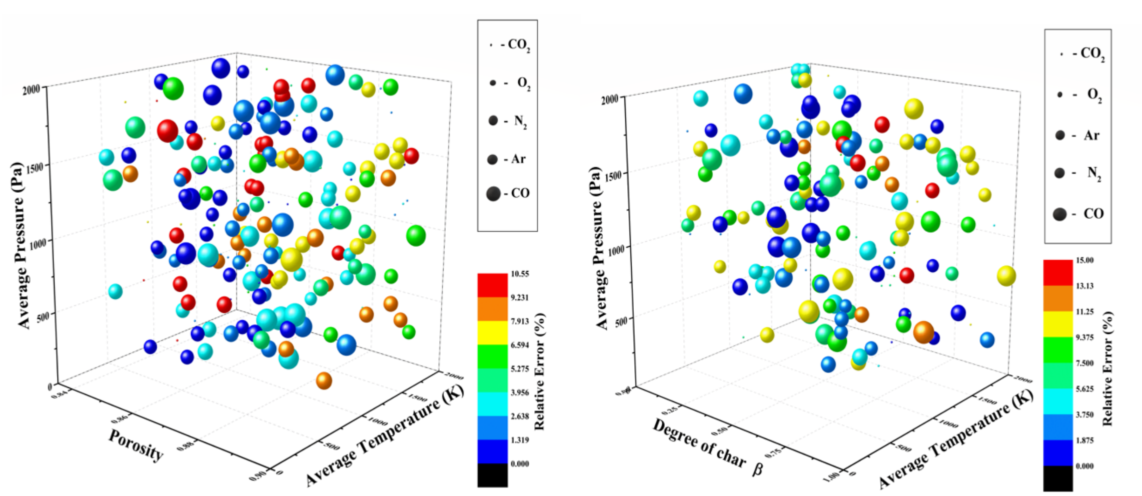

Figure 1: Relative error between permeability data and predictions using a supervised learning model

Solar-Thermal Testing of Ablative Materials in Atomic Oxygen Plasma

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Abstract

Hypersonic flight creates an environment of extreme aerothermal heating and chemically reactive flows, a combined environment that must be recreated in a lab setting for ground testing. Accurate measurements of the complex gas-surface interactions, surface recession, mass loss, and heat diffusion are a challenge but will ultimately lead to improved ablative material designs and more informed computational models.

Sandia National Laboratories has addressed these challenges with a newly designed and constructed experimental capability, an atomic-oxygen plasma chamber operated within the Solar Furnace at the National Solar Thermal Test Facility. This new technical approach provides high heat flux (up to 550 W/cm^2) to a sample with precise control (±4.7%) and operable for extended test times (15 minutes). A pre-mixed gas stream of 20.3% oxygen and balance argon flows into a vacuum chamber (1-10 Torr). A 500 W, radio-frequency signal excites the mixture, generating atomic oxygen in the test chamber to recreate the low-Earth-orbit environment.

In addition to demonstrating these new experimental capabilities, this work addresses volume ablation in highly porous carbon materials and challenges a prevailing school of thought in the ablation community. Rather than focusing on empirically measured reaction rates we instead investigate physical mechanisms by which surface interactions occur to describe oxidation. FiberForm (FF) and Reticulated Vitreous Carbon (RVC) foam were selected as the first two materials to be investigated as they promote diffusion into the bulk media and produce a distinct oxidation profile that depends on the material microstructure. The objective of this study is twofold: a.) describe gas-material interactions within anisotropic (FF) and isotropic (RVC) architectures and b.) compare oxidation rates for two different carbon types. The materials selected differed in surface chemistry, surface area, porosity, and density.

The solar thermal oxygen plasma facility was designed in partnership with a similar setup at the University of Illinois at Urbana-Champaign (UIUC). The plasma production method is similar while the heating methods differ: solar-thermal heating at SNL's facility and Joule-heating at UIUC's facility. The two facilities will continue to operate in tandem and complement each other in that SNL's setup allows higher temperatures and dynamic mass loss, while the UIUC setup enables high throughput, rapid screening of materials. Plans are discussed for comparison between the two sites and for accurate quantification of products and atomic oxygen reactants.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Keywords: Solar Thermal, Oxidation, Plasma, FiberForm, Ground Testing, Thermocouples, Mass Loss

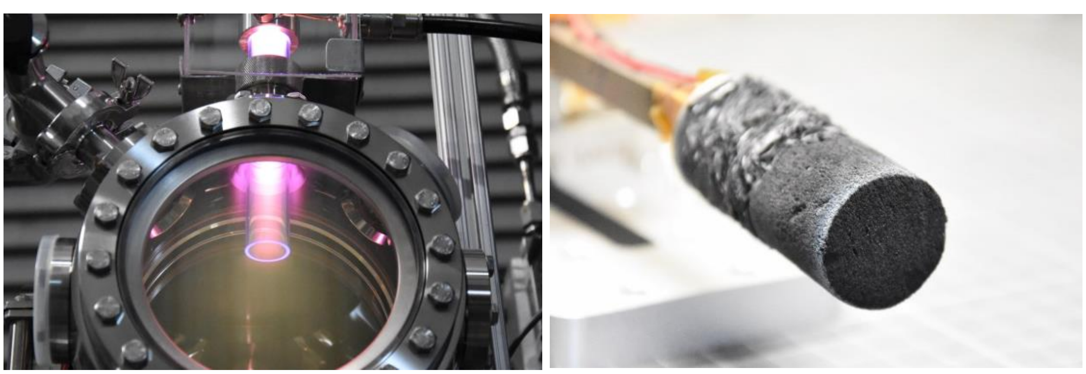

Figure 1: (left) Atomic oxygen plasma chamber (right) FiberForm sample post oxidation

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Directionally dependent mesoscale mechanics and strain localization in FiberForm under compression

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Abstract

Porous materials comprised of carbon fibers are used in thermal protection systems (TPS) for aerospace applications due to their attractive functional properties. Optimal use in these applications requires these materials to be mechanically robust to withstand the various stresses experienced during their lifecycle. Microspecimen compression testing was conducted on FiberForm, the carbon substrate of the widely used TPS material PICA, to observe its mechanical behavior both on the mesoscale and macroscale. The elastic modulus of the material was found to be directionally dependent, with loading in-plane to the general fiber orientation resulting in an approximately one order of magnitude greater stiffness compared to the through-the-thickness direction. Compressive strength did not have this same dependency as the ultimate strength was between approximately 0.6 – 0.7 MPa for both loading orientations. These macroscale mechanical properties were tied to the mesoscale deformation behavior through digital image correlation strain mapping. For the out-of-plane loading orientation, damage accumulation mainly occurred via large-scale fiber compaction and reorientation as a function of local relative fiber density. Damage accumulation during in-plane loading resulted from fiber bending and buckling. Final global failure for both loading orientations occurred via shear localization and cracking. Complementary computational investigation utilized a stochastic modeling approach to calculating mechanical properties of mesoscale structures with finite element analysis. The distribution of elastic properties, in addition to the expectation value (first moment), was computed for a large set of FiberForm model representative volume elements (mRVEs). In agreement with experiment, these results showed FiberForm to be transverse isotropic, with the elastic modulus of the in-plane direction one order of magnitude higher than the through-the-thickness direction. Together, these results improve the current understanding of the relationship between the macroscale mechanical properties, mesoscale deformation behavior, and microstructural features in carbon-based porous materials, allowing for improved tailoring and optimization for use in thermal protection systems.

Keywords: FiberForm, compression, mechanics, deformation, strain localization, directional dependence

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Microstructure and Pyrolysis of Superlight Ablators for Entry Systems Backshell

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Abstract

We present a study on the 3D and 4D resolution of Superlight Ablators (SLA) microstructure during high temperature pyrolysis. The SLA class comprises highly filled elastomeric silicone ablators, used for the backshell thermal protection system of planetary entry probes. They combine low density, low thermal conductivity and heat capacity comparable to that of lightweight carbon-phenolic ablators for forebody heatshields [1]. Here, we focus on SLA-220 and SLA-561V, which have been selected for the backshell TPS of the Dragonfly mission to Titan. An accurate knowledge of the material microstructure and its evolution during pyrolysis is critical to enable high fidelity ablation response models [2], where decomposition-resolved effective properties and radiative heat transfer are determined using image-based simulations. The material microstructure of the SLAs is resolved using synchrotron X-ray microtomography. We show that tomographic measurements provide a high fdelity resolution of phenolic microballoons, silica microballoons, and refractory fibers used as fillers in SLA, as well as silicone resin and void phase fractions [3]. Finally, we present in-situ 4D imaging of the materials microstructure during pyrolysis, performed using a custom inert-gas, IR-heated reactor that enables decomposition analysis at selected heating rates and temperatures up to 1000°C. Quantitative analysis of density, shrinking and swelling, and porosity as a function of temperature are discussed.

Keywords: Ablation, Silica, Pyrolysis, Morphology, Porosity, Synchrotron tomography

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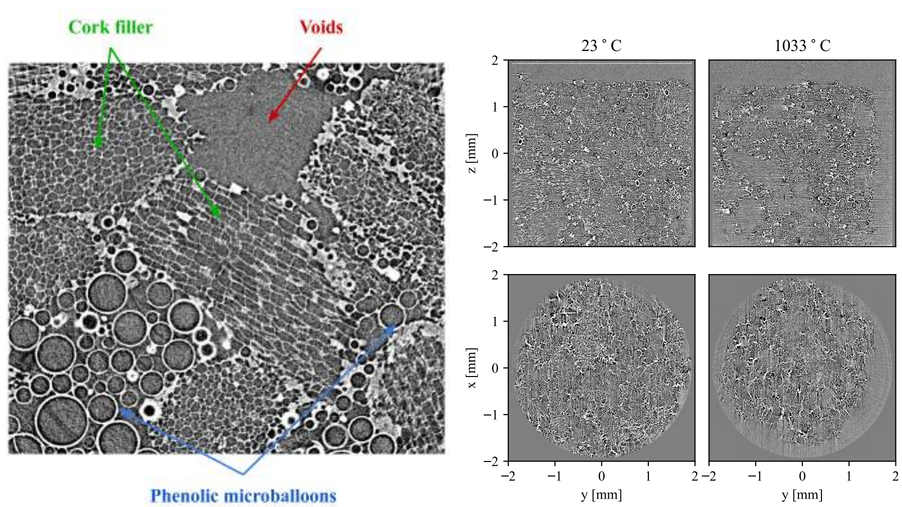

(a) Microstructure of SLA-561V

(b) *In-situ* SLA pyrolysis

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Stochastic mechanical modeling of fibrous ablators: the influence of defects on directional behavior

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Abstract

FiberForm is a critical component of state-of-the-art thermal protection systems. However, its randomly-oriented mat-like constituent carbon fibers create a significant, inherent variability in properties. Unlike ordered, homogeneous materials, this variability in FiberForm requires its properties be defined as a distribution, rather than a single value. It also makes evaluating the effect of structural defects difficult, as separating the consequences of defects from intrinsic variability is not trivial. In this work, KRaSTk (Kentucky Random Structures Toolkit) is utilized to quantify the standard variability in both pristine (defect-free) and defected FiberForm. Three sets of 50+ mRVEs (model representative volume elements), generated to accurately capture the fibrous structure of FiberForm, allowed for a distribution of elastic properties to be computed with finite element analysis. In the pristine set, no defects were intentionally introduced. In the other two sets, cylindrical cavities were included that represent the remnant damage of an MMOD (micrometeoroid and orbital debris) impact. In one of these sets, cavities are oriented in precisely the through-the-thickness direction (cavity-90d); in the other, they are tilted 45 degrees towards the in-plane direction (cavity-45d). In both cases, each cavity has a volume 10% of the total mRVE. We find that the pristine set exhibits the transverse isotropic elastic mechanical behavior experimentally observed in FiberForm–the in-plane elastic modulus is about an order of magnitude higher than the through-the-thickness modulus. We also find that variation in elastic modulus in the two in-plane directions is negligible for the pristine and cavity-90d sets, though non-trivial in the cavity-45d set. This suggests that the orientation of the cavity, rather than simply its volume, affects elastic mechanical response. Most importantly, we observe that, in FiberForm, the effect of intrinsic structural variability always dominates that of defects. In all comparisons of mechanical properties, the distribution of results (i.e. the variability) was much wider than any discrepancies between the peaks (i.e. the effective property). Essentially, even though defects shifted the original pristine distribution, overlapping area remained. These overlaps represent regions where the predicted properties of two mRVE sets are indistinguishable. To summarize, the work presented here represents a crucial initial step in statistically quantifying and predicting the effect of damage caused by MMOD impacts on the mechanical behavior of thermal protection systems over their lifetime.

Keywords: FiberForm, defects, mechanics, deformation, directional dependence

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