14th Ablation Workshop

November 5-7, 2024
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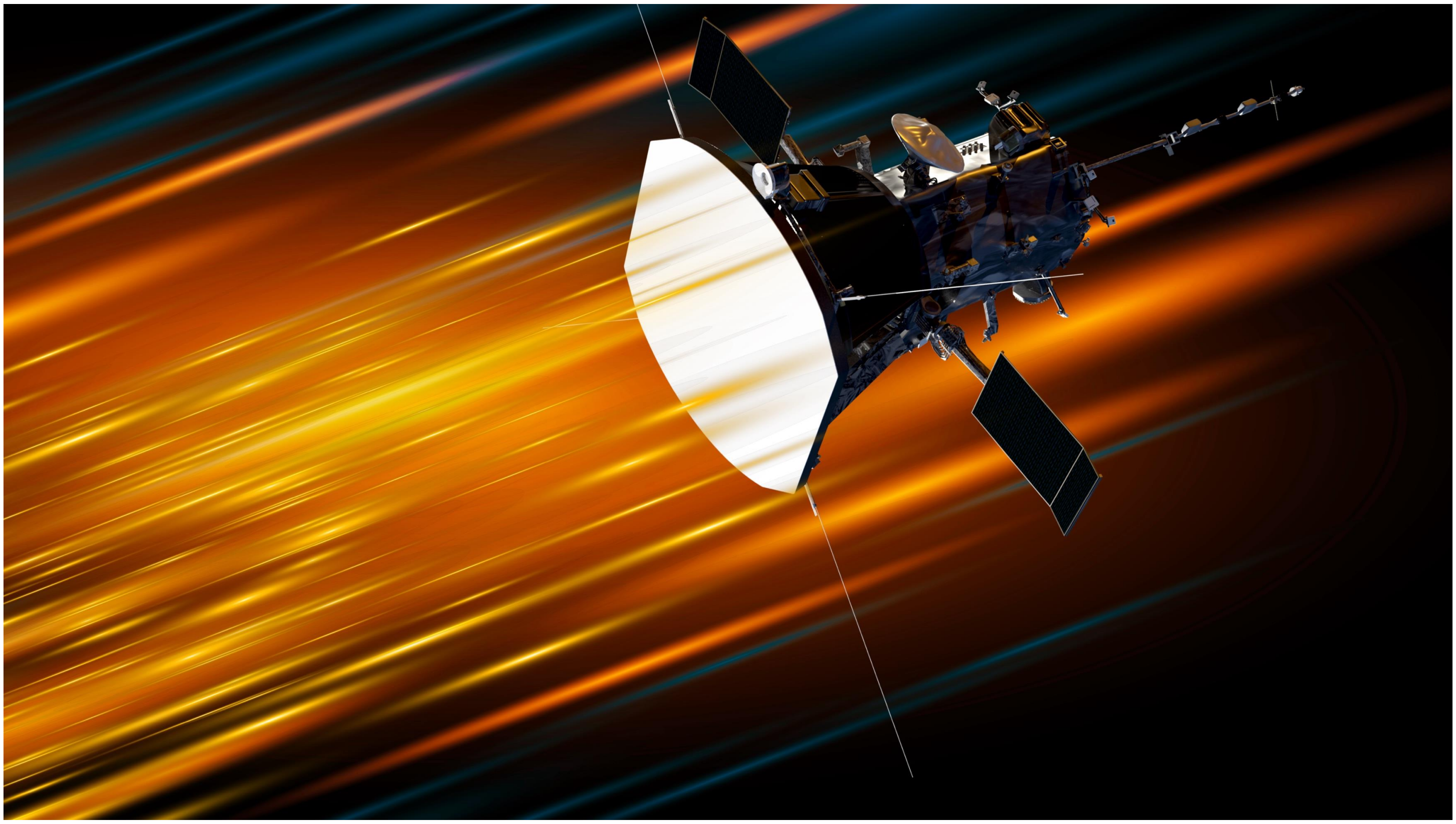

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Opening Remarks

APL/UK[1]

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Aerothermodynamics at APL

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Overview of Navy Ablation Activities (Part 1)

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Recent Advancements in Ablation Tools and Understanding at Sandia National Laboratories

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Ablation Activities in the NASA Entry Systems Modeling Project – 2024 Update

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Abstract

In support of NASA science and exploration missions, the Entry Systems Modeling (ESM) project aims to develop advanced computational analysis and experimental validation capabilities that enable improved understanding of ablative Thermal Protection System (TPS) performance. The computational capabilities under development include microscale representations of materials to characterize property variability, thermostructural models to characterize damage modes, and flow-coupled material response tools for mission design. Each of the computation efforts is supported by robust experimental investigations that leverage high-enthalpy facilities, such as arc jets and plasmatrons, and novel instrumentation for validation. Additionally, the project development efforts heavily leverage academic collaboration, address all mission-relevant ablative materials, and span technological readiness levels. This talk will provide an overview of ESM's TPS area, highlighting recent technical challenges, collaborations, capability developments, and mission applications of note.

Keywords: Thermal Protection System Materials, Modeling and Simulation, Experiments

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VKI activities related to ablative material characterization and FTPS research

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[b] *Aero-Thermo-Mechanics Department, Universite´ Libre de Bruxelles, Belgium*
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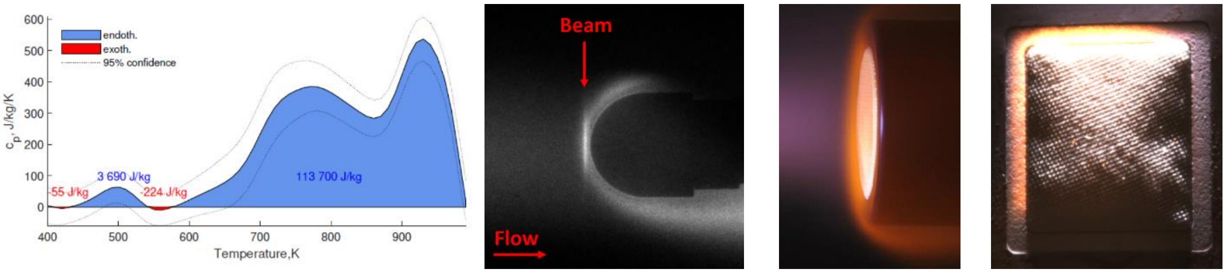
Abstract

This talk will provide a snapshot overview of ablation relevant activities carried out at the von Karman Institute for Fluid Dynamics (VKI), where we continuously try to extend our experimental and numerical capabilities in the field of high-temperature material research.

Especially regarding the high-temperature characterization of decomposing carbon-phenolic ablators, we closed this year our ESA project *ReChar-TPS* on the development of new measurement standards for the determination of relevant material properties. In particular, the quantities of interest were *thermal conductivity* (through Laser Flash Analysis, Guarded Hot Plate, and Transient Plane source), specific heat (Differential Scanning Calorimetry), and heat of pyrolysis (Simultaneous Thermal Analysis). The developed measurement methods have been compared at different European laboratories in a round robin exercise and will be discussed at the workshop.

Within our new research grant ‘DraGroundFlight’ awarded by AFOSR, we plan to define and implement an innovative testing strategy for the calibration and validation of ablation models developed by the University of Minnesota team led by Prof. Schwartzentruber. This involves a comprehensive ablation test campaign on graphite in air and nitrogen plasmas along with the development of new measurement methods. A collaboration with the University of Texas allowed us to perform the first laser-induced fluorescent measurements of CN in the boundary layer of ablating graphite samples and more testing will follow in the future.

Other research projects of interest to the TPS community involve stagnation point and flat plate experiments of a flexible TPS material to be used on reusable satellites or inflatable structures. Difficulties when testing those material types arise from their low apparent emissivity and highly varying emissivity over the spectral range of different radiometric devices, making surface temperature measurements difficult. This leads to further difficulties when trying for the estimation of the catalytic efficiency of the surface. A selection of results on this matter will be presented.



(a) (b) (c) (d)

Figure 1: ZURAM heat of pyrolysis from DSC measurements (a), CN LIF on graphite in air plasma (b), Flexible TPS (Refrex) tested in stagnation point (c) and flat plate (d) configurations.

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Pyrolysis models and simulation tools across communities

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Abstract

To start, I will present a brief historical overview of the interconnected progress of pyrolysis science and technologies, which involves well-known scientists who made critical contributions to the field, such as Aristotle (-340), Boyle (1661), Lavoisier (1783), Lebon - the inventor of city gas lighting (1799), and Edison - the inventor of the carbon filament for electric lighting (1884). Following a description of the peak era of gas plants between the late 19th and early 20th centuries, this overview will highlight the contemporary context that motivates this review, particularly in three key applications: the production of biofuels and green molecules from biomass, fire safety, and the thermal protection of space vehicles. For these applications, pyrolysis may not be considered a simple separation process within uniformly heated materials and researchers have been particularly focused on addressing this problem since the space race. The development of the first modern pyrolysis model is attributed to Bamford, Crank, and Malan in 1946. This iconic work begins with the textbook heat conduction equation and incorporates a sink term to account for the heat of pyrolysis. Since this pioneering contribution, addressing the state-of-the-art in pyrolysis modeling has become increasingly complex and multifaceted, as these three communities have progressed with little interaction, despite facing similar challenges. Materials that undergo pyrolysis share three common characteristics: they consist of at least one organic phase, they are porous or become porous during pyrolysis, and they typically react with the environment. Consequently, they must be modeled as multi-scale reactive materials with evolving porous microstructures. To systematically combine and compare the contributions and developments since the foundational work of 1946, a generic model is introduced. Particular attention is given to formulating the conservation equations at the pore scale and presenting their upscaling to clarify the assumptions applied in the macroscopic (engineering) models. The closure models proposed in the different communities for the chemical and physical parameters, such as pyrolysis rates, chemical reactions, phase changes, mechanical properties, and heat and mass transport properties, are described and compared. The boundary conditions used to model the interactions between materials and their environments are presented, ranging from fully coupled methods to simplified boundary layer approaches. Fifty models and simulation tools used in the aerospace, fire, and biomass sectors are compared in a detailed checklist, with term-by-term comparisons against the generic model. Information is provided regarding their numerical frameworks, original developers, owners, and recent updates. In conclusion, five common key challenges critical to advancing the field are outlined: conducting systematic studies to quantify uncertainties from model assumptions, generalizing pyrolysis mechanisms to align with homogeneous and heterogeneous chemistry frameworks - while better characterizing the 'chemistry' of pyrolysis, continuing the development of pyromechanics (the mechanics of pyrolyzing materials), measuring evolving material properties, and developing generic simulation tools to facilitate comparisons, collaborations, and shared contributions.

Keywords: Pyrolysis, modeling, simulation.

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Predicting Carbon Monoxide Production from Graphite Ablation in a Hypersonic Shock Tunnel

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Abstract

An experimental campaign was conducted in Sandia's Hypersonic Shock Tunnel (HST) and measured carbon monoxide (CO) temperatures and concentrations above an ablating graphite sample. Samples were exposed to flow conditions in air of $U_\infty = 2.73\,\mathrm{km/s}$, $P_\infty = 182\,\mathrm{Pa}$, $T_{\mathrm{rot},\infty} = 172\,\mathrm{K}$ and $H_0 = 3.79\,\mathrm{MJ/kg}$. Also, prior to experiments the samples were resistively preheated to representative wall temperatures ranging between approximately 1775 K and 2200 K with two different types of graphite investigated. Measurements of CO concentrations and temperatures were conducted in a wake region in which a tunable diode laser absorption spectroscopy (TDLAS) diagnostic capable of measuring non-equilibrium temperatures was employed. Experimental results of measured CO production and temperatures are given with notable differences between the different graphite materials. Results are compared to CFD predictions of CO temperature and concentration as modeled using multiple air-carbon gas-surface kinetics mechanisms.

Keywords: Graphite, carbon monoxide, experiment, shock tunnel, hypersonic, CFD, finite-rate modeling

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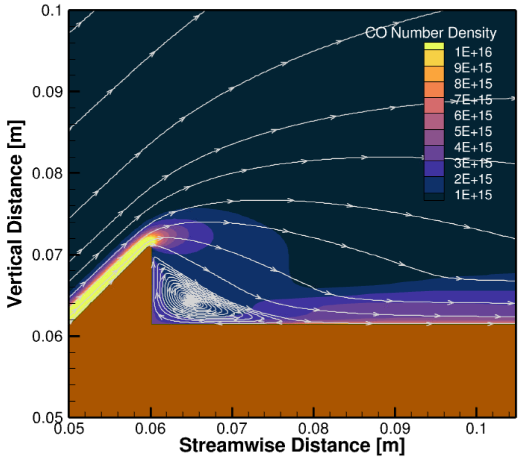

Figure 1: CO number density field above the preheated ablating graphite test sample from a US3D simulation with the air-carbon ablation (ACA) model applied on the sample wall.

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Icarus Application to Dragonfly Heatshield

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Abstract

Icarus [1], an in-house material response solver developed at NASA Ames, is applied to perform 2-D bondline-temperature analysis on the heatshield of the Dragonfly entry system design, which is scheduled to land at Titan in 2034 [2]. For the current work, two axisymmetric domains are used: the near-shoulder region and the entire heatshield. The heatshield consists of a PICA [3] TPS bonded to a layered system of Aluminum honeycomb wrapped by a carbon-composite facesheet. The backshell, included for more accurate analysis, consists of a similar material stack. Icarus simulations using both domains indicate that the in-plane thermal conductivity of the carbon-composite facesheet plays a dominant role in bondline temperature. Similarly, the maximum bondline temperature is found around the PICA-tile-interface region instead of the near-shoulder region or the stagnation point based on the current trajectory using the orthotropic properties of the carbon-composite facesheet. These findings indicate the significance of 2-D or higher-dimensional material modeling analysis in fully understanding how bondline temperature behaves across the heatshield and obtaining a basis for TPS sizing locations, as well as demonstrate Icarus capability to deliver similar findings for future missions. Verification at different radial locations ahead of the shoulder, where thermal conduction is close to 1-D, between Icarus (1-D and 2-D) and FIAT [4] is performed, and good agreement is observed. With the entire heatshield domain, the total mass loss of the aeroshell materials is approximately 3% of their initial mass due to thermal decomposition of phenolic resins inside PICA under the current high-heating environment.

Keywords: TPS material modeling, bondline analysis, thermal conductivity, code verification, Icarus, Dragonfly

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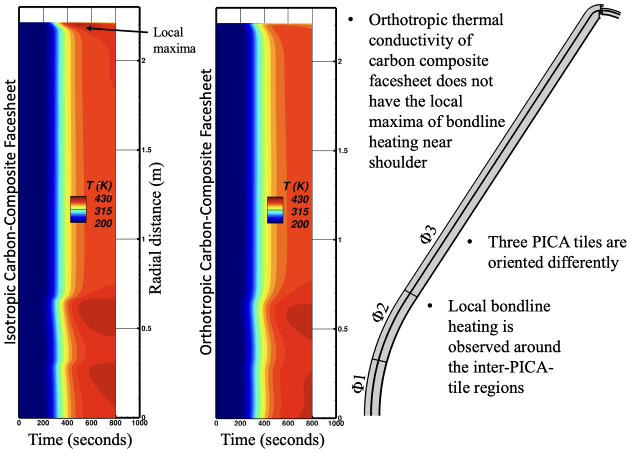

- Orthotropic thermal conductivity of carbon composite facesheet does not have the local maxima of bondline heating near shoulder
- Three PICA tiles are oriented differently
- Local bondline heating is observed around the inter-PICA-tile regions

Figure 1: Effects of thermal conductivity of the carbon-composite facesheet are shown on bondline across the heatshield with time. Here, Φ indicates different PICA material orientations (through-the-thickness direction) with respect to flow direction

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Aero-optical effects caused by ablation products

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Abstract

In hypersonic flight conditions, heating of surrounding air results in dissociation and excitation of internal degrees of freedom of molecules and atoms, ionization and plasma formation. Additionally, at very high temperature, air composition changes due to ablation from the vehicle surface. One of the experimental techniques to capture these changes is Michelson interferometry, which has been been explored for a large variety of hypersonic velocities, freestream conditions, and gas mixtures [1]. In this work we provided a numerical analysis of the refractive index changes caused by ablated species, concentrating on thermal protection systems, which utilize carbon-carbon (C-C) composite materials. To simulate the refractive index field we considered hypersonic flow over a cone at free stream conditions corresponding to an altitude of 60 km and M=24. First, a zero-dimensional chemical kinetics model, which includes the non-surface reactions from [2], was used to reveal the effect of initial carbon concentrations on plasma density. Second, two-dimensional two-temperature model of the hypersonic flow with one vibronic-electronic temperature for nitrogen and one translational temperature for a bulk gas has been used. To include the carbonaceous surface species a temporally constant mass flux distribution along the wall surface as a boundary condition was implemented along the cone wall. Combined with a semi-classical model of the refractive index on the basis of species polarizabilities, the refractive index field was calculated for ablating and non-ablating cases. Both 0D and 2D models showed that the maximum electron number density is higher in the ablation case than in the non-ablating flow, by at least one order of magnitude. The largest increase of the refractive index is seen near the leading edge, where the ablation flux is the highest. An increase of the initial carbon concentration results in a larger refractivity (Fig.1) and larger values of refractive index jump across the shock wave, also causing an increase in the electron density. These changes are large enough to be observable in future experiments in the Hypervelocity eXpansion Tunnel.

Keywords: Hypersonic flow, ablative carbon, refractive index, numerical modeling.

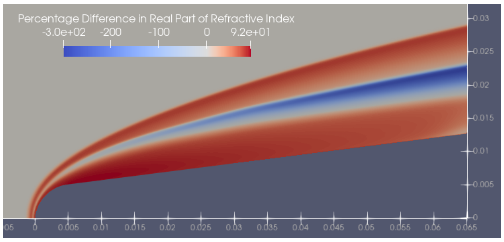

Figure 1: Difference between steady state refractive index plots for 2D Mach 24 simulations.

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Development of coupled fluid / thermal strategies to compute graphite ablation during atmospheric entry

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Abstract

The present work focuses on the numerical prediction of graphite material degradation under severe atmospheric entry conditions. For this purpose, the adopted coupled fluid / thermal approach is presented. In order to fully replicate the ablation mechanism, three different coupling procedures are described, which rely on the heterogeneous reactions of oxidation, nitridation and sublimation that occur on the heat shield of the vehicle. The first ablation paradigm is based on the B' tabulation, which has been historically used to assess the blowing rate of the recessing wall in the framework of a single gas (air) at chemical equilibrium [1,2]. Although such strategy has proven its reliability and efficiency over the past few decades, it suffers from many assumptions that are prone to be broken when applied to realistic descent trajectories. Such hypotheses include the consideration of a chemical equilibrium at the wall, no injection of the ablated carbonaceous species into the flow and the use of convective coefficients that directly depend on the boundary layer location. To overcome these aforementioned limitations, a more relevant nonequilibrium multi-species ablation model has been proposed and implemented. The ablating mass flux and the species mass fractions at the wall, which are the product of finite-rate surface chemistry mechanisms, are performed and updated at each convergence step of the flow [3] (Figure 1). This second method however requires a significant increase of computational time and resources. In order to alleviate such necessary computing memory, a third strategy - a so-called multi-element ablation model that works under the assumption of chemical equilibrium - has recently been developed. For such formulation, the Navier-Stokes equations have been rewritten in terms of chemical elements, allowing the injection of the carbon element during chemical erosion. An external open-source equilibrium solver (Mutation++ [4]) is used to retrieve the corresponding proportions of chemical species that govern the flow properties. As a validating framework, 2D axisymmetric simulations are carried out on two different configurations. The first one relies on the arc-jet test conducted in the Interactive Heating Facility at NASA Ames Research Center [5] and the second one is related to the nosetip of the IRV-2 vehicle [1,2]. Both situations are well-referred test cases that employed a thermal protection system composed of non-charring carbon [6,7,8,9,10,11]. A particular emphasis is made on the generalization to chemical nonequilibrium through the comparison of a large variety of air-carbon ablation models [12,13,14,15]. The presented results will also give the opportunity to tackle broader perspectives such as the influence of exothermic reactions on the wall heat fluxes, as well as the aerothermal interactions with a turbulent flow.

Keywords: Aerothermal Computations; Ablation Models; Nonequilibrium;

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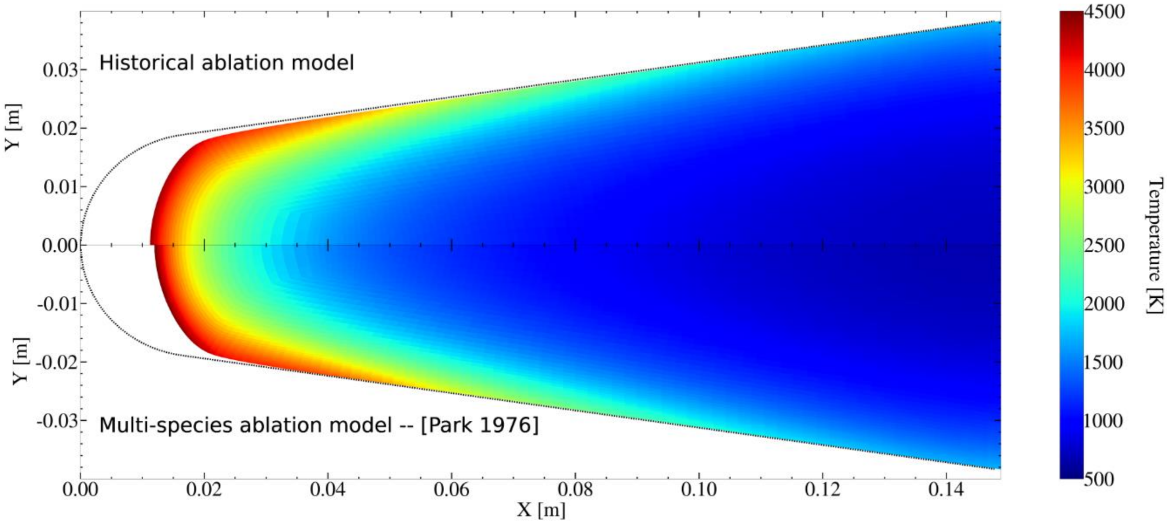

Figure 1: Temperature distribution inside the nosetip of the IRV-2 vehicle at the final trajectory point for the equilibrium historical ablation model (upper panel) and the nonequilibrium multi-species ablation model (lower panel). The black lines indicate the original shape of the vehicle.

Coupled Aero-thermo-chemo-mechanical Analysis of Ablative Thermal Protection Systems

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Abstract

In this work, we present a first attempt of a coupled aero-thermo-chemo-mechanical framework to model the material response of ablative thermal protection system (TPS) materials for hypersonic vehicles, with special emphasis on the effect of coupling the mechanical response of the material. TPS materials exposed to chemically-reacting high-enthalpy flow conditions experience phenomena such as pyrolysis, ablation, deformation, and subsequent material damage. Coupled phenomena have a significant impact on many fundamental quantities, such as the effect of material surface temperatures on the heat fluxes obtained from the flow field. We coupled US3D, a computational fluid mechanics (CFD) solver, with ΣMIT, a material response solver, to perform the coupled aero-thermo-chemo-mechanical analysis. ΣMIT is a finite element code for the bulk material response including heat transfer, chemical degradation, gas transport, thermal expansion, and finite deformation mechanics including damage and fracture. We simulate the thermo-chemo-mechanical material response including mechanical deformations that have been observed experimentally in arc jet experiments of phenolic impregnated carbon ablator (PICA). We then demonstrate the fully coupled capability in a simulation of a pyrolyzing spherical-tipped nose cone following a trajectory at Mach 15 at an altitude of 45 kilometers. Figure 1 shows a snapshot of four fundamental quantities computed in the simulation.

Keywords: Continuum modeling, charring ablator, coupling, fluid-structure interation

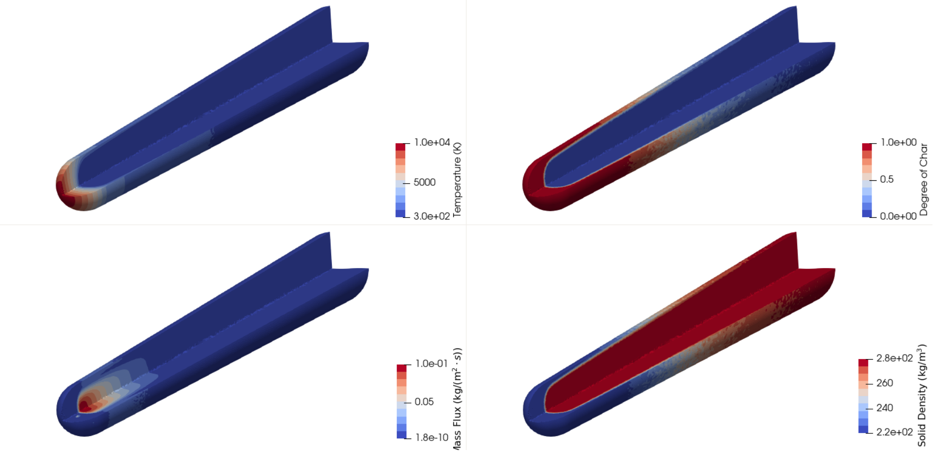

Figure 1: Simulated temperature, degree of char, mass flux, and solid density of an ablative cone subjected to Mach 15 flight conditions at an altitude of 45 kilometers above sea level

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Advancements in Coupled Flow and Material Modeling for Entry Systems

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Abstract

A comprehensive suite of physics-based simulation tools is being developed at NASA Ames Research Center to enhance the predictive capabilities of modeling ablative porous materials exposed to high-temperature flows during atmospheric entry. This effort focuses on the Entry Systems Modeling (ESM) material response tools, integrating both research and mission-critical platforms. The open-source Porous material Analysis Toolbox based on OpenFOAM (PATO) software [1,2] is a modular research platform to develop and validate innovative physics-based models for porous materials. In parallel, the three-dimensional, unstructured, finite-volume Icarus software [3] offers an efficient and robust platform for designing Thermal Protection Systems (TPS) for NASA missions. This work highlights recent advancements and applications in material/flow coupling using these ESM tools at different levels of fidelity. The NuSil-coated Phenolic Impregnated Carbon Ablator (PICA-NuSil) model [4] has been compared to experimental data from a UIUC Plasmatron X test campaign, leveraging a decoupled modeling approach involving HEGEL [5], DPLR [6], and PATO. The updated PICA-NuSil model has been integrated into Icarus for utilization in upcoming NASA missions. Additional decoupled simulation tools, including material response and particle tracking, have been used to analyze aerosol chemistry in planetary missions [7]. The Ares [8,9] multi-physics tool couples Icarus to US3D [10] and NERO [11] to investigate flow-radiation-material interactions [12]. Ares has been used to study coupled ablation under high recession rate conditions, and complex spacecraft features such as cavities, shoulders [13], and enclosures. The impacts of surface gas blowing were analyzed through massive simulations involving flow, radiation, and material response [14]. Finally, simulation results using a unified modeling approach combining fluid and material phases have been compared to flow tube experiments [15].

Keywords: Porous Media, Heat Transfer, Mass Transfer, Material Response, Ablation, Multi-physics Coupling.

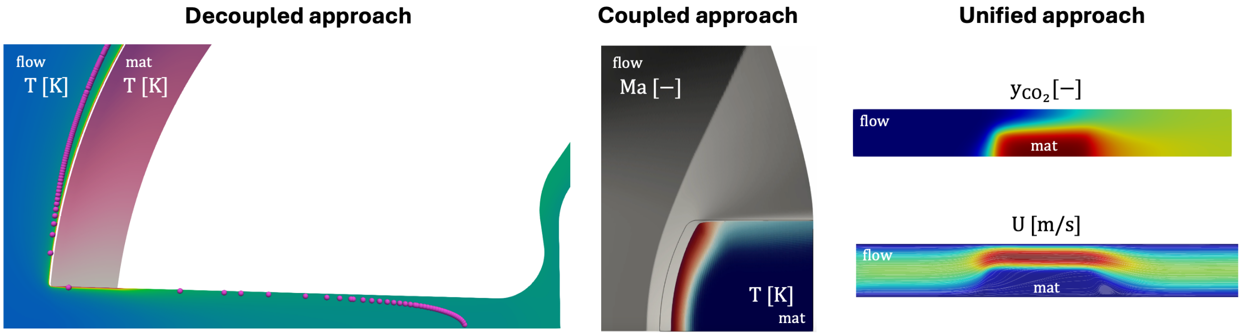

Figure 1: Coupled flow and material modeling strategies: decoupled simulations for aerosol capture analysis in Venus atmosphere (left), coupled simulations of 3MDCP in air flow vs. IHF-385 data (center), simulations of FiberForm using a unified solver vs. flow tube experiments (right).

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Advances on Uncertainty Quantification for TPS modeling

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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 and guide future development.

In this talk, an overview of two novel contributions will be provided. The first work to be discussed entails the development and application of Bayesian inference frameworks to calibrate a finite-rate nitrogen mechanism from both molecular beam and plasma wind tunnel measurements. This multi-scale Bayesian inference framework is capable of learning a kinetic nitrogen ablation model jointly from both experimental facilities. The additional complexity of working at different scales simultaneously must be mitigated through the use of both advanced surrogate models and posterior sampling algorithms. These recent advances will be discussed together with their connection to ablation physics.

The second work is focused on inferring material response models from arc-jet experimental data. The main challenges are related to the experimental data itself, where measured quantities, such as temperatures from thermocouples, change in time while also being distributed in space. Advances related to this work are the development of a reduced-order model capable of capturing space and time correlations, allowing for considerable computational complexity as well as its inclusion in a posterior sampling scheme with delayed rejection. Overall, these methods are being used to provide reliable predictive capabilities for the design of future hypersonic entry systems.

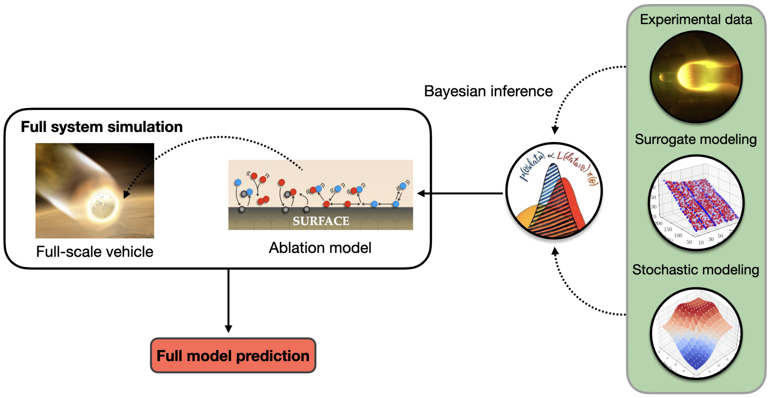

Figure 1: Schematic representation of the statistical learning frameworks used to improve ablation modeling in the context of this work.

Fracture and failure 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 failures, 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. The developed model is applied to a full-scale Stardust TPS geometry, showing that thermal stress and expansion can not only damage the outer surface, but also penetrates the material, causing the interior structure to fail earlier than expected.

Keywords: TPS, crack propagation, failure

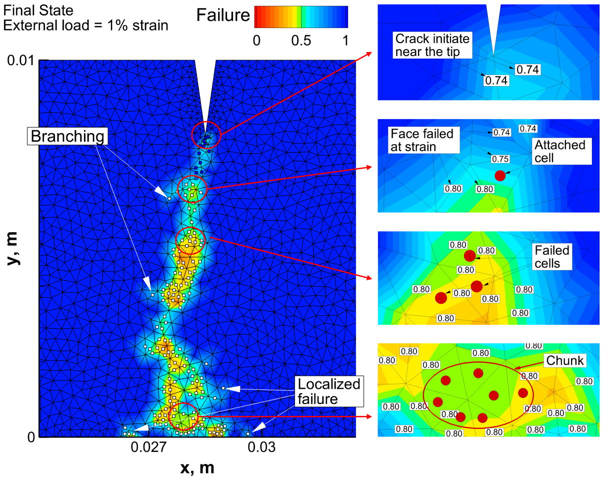

Figure 1: Detailed crack analysis. The developed model can capture crack initiation, branching and failure.

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A mesoscale framework to model the surface recession of ablative thermal protection systems materials

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Abstract

Carbon-carbon composites are used as heat shield materials to regulate the surface temperature of hypersonic vehicles. The thermochemical phenomena experienced by hypersonic vehicles as a consequence of aerodynamic heating have been characterized by physical experiments and detailed flow simulations. However, state-of-the-art flow simulations are unable to resolve the effects of microscale changes occurring in carbon ablators during oxidation. A new coupled mesoscale framework has been developed called Integrated System for Thermochemical Heat transfer, Mesoscale ablation, and Underlying Structures (ISTHMUS) that uses the marching cubes algorithm to enable mesoscale recession of material microstructures directly from x-ray computed tomography (XRCT) scans of heat shield materials. The primary module of ISTHMUS maps the surface mesh obtained from marching cubes algorithm with the voxels representing an XRCT scan. The tight one-to-one mapping of surface mesh and boundary voxels enables a smooth transfer of information across the boundary. ISTHMUS is coupled to the Sparta direct simulation Monte Carlo (DSMC) solver to model gas-surface interactions that occur as a result of diffusion of hot dissociated gaseous atoms and molecules into the microstructure of heat shield materials. The geometry of the underlying material is updated by the geometry modification sub-module of ISTHMUS corresponding to the amount of carbon removed from the material through oxidation. The entire process of voxel representation, marching cubes, voxel-to-surface mesh mapping, DSMC simulations, and geometry modification are automated, allowing for a robust coupled simulation framework to understand recession of microstructures of heat shield materials. A detailed flow chart of ISTHMUS is represented by Fig. 1(a). Figure 1(b) demonstrates the capability of ISTHMUS to model the surface recession of a carbon weave with varying concentration of oxygen atoms and molecules.

Keywords: TPS material, recession rate, gas-surface interactions, DSMC, marching cubes.

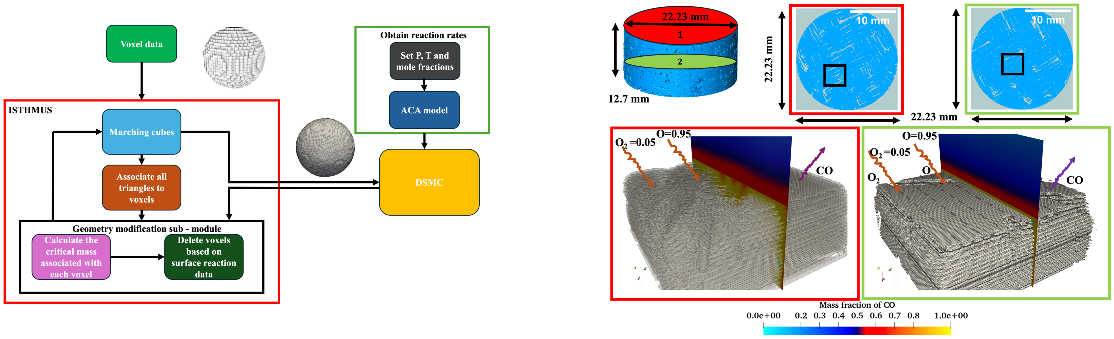

Figure 1: Flow chart of ISTHMUS (Fig. 1(a)) and its capability to model the surface recession of a carbon weave subject to varying concentration of O and O_2 (Fig. 1(b)).

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Towards a physically accurate framework for direct simulation Monte Carlo ablation simulations

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Abstract

Mesoscale ablation models are necessary towards fundamental understanding of the complex gas/surface reactions and interactions. Existing mesoscale ablation models tend to simplify the gas dynamics or employ (either directly or through coupling) computational fluid dynamics (CFD). However, in the context of thermal protective systems, the pore size can be comparable to mean free path, and the CFD approach is questionable. Thus to develop a mesoscale ablation model valid at any Knudsen regime, Borner and coworkers combined the direct simulation Monte Carlo (DSMC) method and the marching cubes algorithm [1]. To expand the usage and improve upon the previous version, we have incorporated two key developments within SPARTA. First, we have incorporated a high-fidelity surface conversion which allows users to convert arbitrary stereolithographic (STL) surfaces into an implicit surface which can then be ablated. The surface conversion algorithm utilizes the new robust multivalues scheme. Second, to remove the bias associated with ablation at the cell-level, a multi-point decrement is implemented. The new ablation framework greatly reduces the numerical artifacts which enables more physically accurate simulations. To demonstrate this, a comparative simulation of an ablating flat plate behind a Mach 5 shock is performed as shown in Figure 1.

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Keywords: Direct simluation Monte Carlo, meso-scale ablation

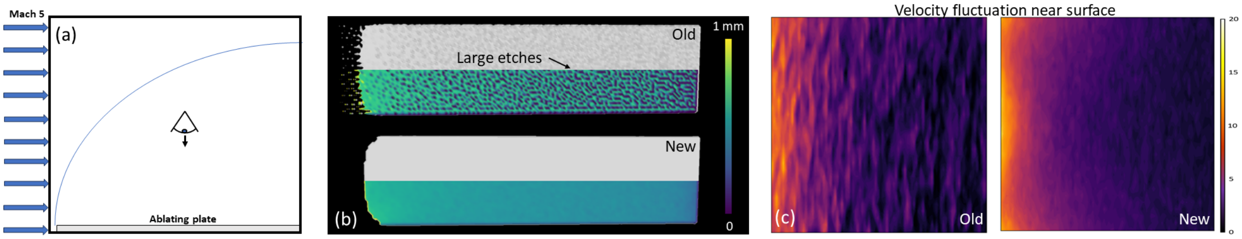

Figure 1: (a) Schematic of ablating flat plate simulations. Blue line represents the shock (not to scale). Eye shape indicates viewpoint for (b) and (c). (c) Bird's eye view of the flat plate after is has ablated. Colors proportional to how far local surface element has receded. (b) Y-velocity fluctuations measured about one mean free path above ablated plate. Color proportional to magnitude

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Drag Model for Non-Spherical Particles and Effects for Hypersonic Flight Through Weather

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Abstract

The non-spherical shape of atmospheric particles is often neglected when simulating particle trajectories through supersonic flow fields. In many cases, such as a hypersonic vehicle flying through a dense cloud of ice particles, it's not computationally feasible to resolve the shape and orientation of each individual particle. Existing methods have simplified the non-spherical shapes based on a sphericity parameter or define an effective diameter based on a sphere with equivalent mass or maximum length. However, these methods do not consider the aerodynamic properties of the non-spherical particle prior to simplification. Incorrectly modeling the drag force may lead to errors in impact locations, induced surface heat flux, and material erosion. Because of this, a generalized drag model is needed that can be used for any arbitrarily defined particle shape independent of orientation. In this presentation, a detailed method of simulating the geometry and aerodynamic properties of non-spherical particles in supersonic flow will be discussed. Comparisons between the new model and orientationally averaged CFD simulations of real geometries will be shown as verification.

Preheated Blunt Nose Wedge Model for Shock Tunnel Testing

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Abstract

Impulse facilities such as shock tunnels and expansion tubes allow the total enthalpy of hypersonic flight to be economically reproduced for test times of the order of a millisecond. Traditionally, these facilities are not well suited to studying ablation, which requires representative flow time scales to be re-created to re-create the total heat load. A technique developed at the University of Queensland (UQ) [1] partially circumvents this by electrically pre-heating the test model to a representative flight surface temperature before the experiment, allowing the interaction of the flow with a hot, ablating wall to be studied. This technique has been used to study ablating flows over fundamental cylindrical [2] and wedge [3, 4] geometries, which are easily amenable to integrating with the hardware required to heat part or all of the test model. To allow the effect of an ablating nose on flow downstream to be studied, this project designed a heated nose for a blunted wedge model. The model was designed using transient heating simulations in ANSYS and CFD. It has been manufactured and will be be bench tested and tested on our X2 facility next year.

Keywords: pre-heated model testing, model design, impulse facility ablation testing, shock tunnel, expansion tube

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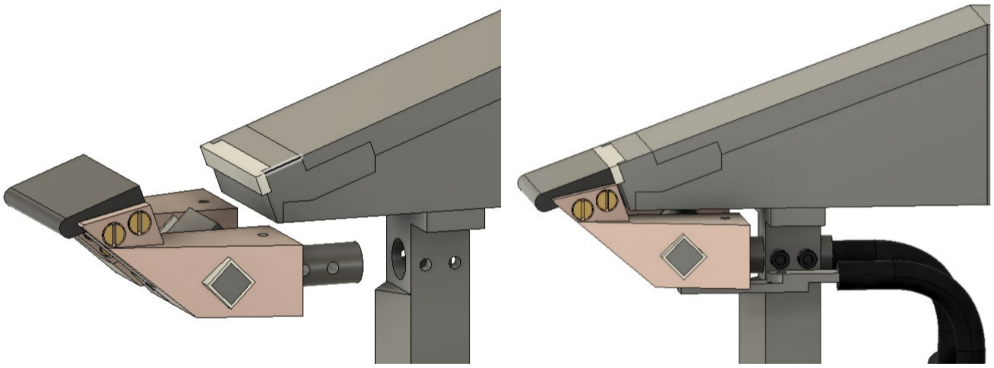

Figure 1: CAD representation of how the heated nose section interfaces with the wedge test model from Scott [5].

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New Tools for Automating Arcjet Sample Recession Tracking and Analysis

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Abstract

Arcjet Computer Vision (arcjetCV) has been significantly upgraded to enhance accuracy and performance in tracking material recession and shock-material standoff in test videos. These improvements include integrating new machine learning models, developing a specialized edge detection class, and incorporating a more comprehensive training dataset. These upgrades have refined the software's ability to automate time-resolved recession tracking, making it more precise and reliable for analyzing complex physical processes.

In parallel, a new tool called STARscan (Spatial Targeting and Alignment Rig for Scanning) is being developed to capture detailed 3D surface data before and after testing. By comparing these pre- and post-test scans with arcjetCV's automated video analysis results, users can achieve a more comprehensive assessment of material recession. This method enables cross-validation of results, improving confidence in the analysis of tested materials.

The expanded capabilities of arcjetCV have been successfully demonstrated on videos from various facilities, including the NASA Ames arcjets, UIUC's PlasmatronX, and the VKI Plasmatron. It has been adopted as a new standard for in-situ recession tracking by the Mars Sample Return Project and Orion. ArcjetCV's improved efficiency and accuracy are critical for reducing testing uncertainties and validating heatshield material performance under extreme conditions. The software's user-friendly graphical interface ensures ease of use, enabling seamless processing and precise analysis of arcjet videos, providing deeper insights into material behavior in hypersonic environments.

ArcjetCV is now available on both PyPI and Conda, allowing easy installation via `pip install arcjetCV` or through the Conda package manager, ensuring broad accessibility and streamlined deployment for users across various platforms.

Keywords: Recession tracking, machine learning, arc jet, porous ablator, open source

Figure 1: STARscan rig

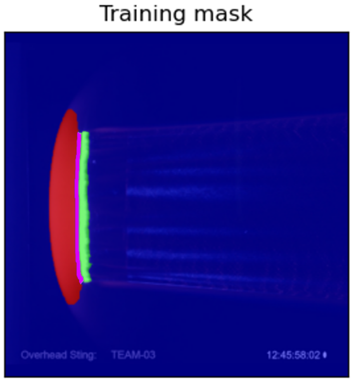

Figure 2: Training mask with sample, shock and edge classes

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Spallation of porous carbon ablators in supersonic air and nitrogen plasma

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Abstract

The phenomenon of mechanical erosion (i.e., spallation) has been recognized as a significant form of mass loss for ablative thermal protection system (TPS) materials for decades [1]; however, the specific contribution of spallation to overall mass loss—a key parameter for accurate predictions with modern ablation codes—remains largely unknown. This gap in understanding presents a challenge to the improvement of spacecraft TPS reliability and safety. Urgency to better characterize the spallation phenomenon has only increased with the recent post-flight analysis of the Artemis I heat shield, which revealed greater than expected char loss. These developments underscore the importance of current efforts to better understand and quantify the mechanisms behind the spallation of TPS materials, such as Phenolic Impregnated Carbon Ablator and its constituent carbon fiber material, FiberForm® [2, 3].

Building on previous study of FiberForm spallation at the Center for Hypersonic and Entry System Studies (CHESS) Plasmatron X facility [3], a total of eight FiberForm samples of varying wedge geometries (Fig. 1a) were subjected to supersonic nitrogen and air plasma at target cold wall heat fluxes of 375 W/cm^2 and 675 W/cm^2 and target stagnation pressures of 4.60 kPa and 6.75 kPa. High-speed image data was collected during each experiment, enabling the use of particle tracking velocimetry to measure particle number density and particle velocity throughout the flow field. From this high-speed imagery, a difference in spallation frequency was observed when comparing air and nitrogen tests (Fig. 1b), with samples in air exhibiting relatively steady particle release over time and samples in nitrogen showing sporadic particle release. Post-test scanning electron microscopy (SEM) revealed the presence of a solid deposition coating fibers exposed to supersonic nitrogen plasma (Fig. 1c), a characteristic not observed for samples exposed to supersonic air plasma. Raman spectroscopy of the solid deposition demonstrates a highly disordered amorphous carbon structure.

Keywords: Spallation, carbon fiber, porous ablator, thermal protection materials, supersonic plasma

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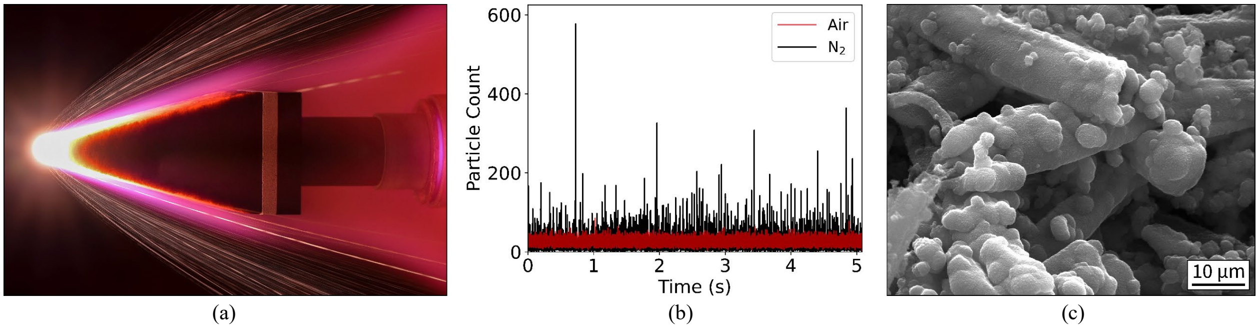

(a) (b) (c)

Figure 1: (a) FiberForm wedge with a half-angle of 15º subjected to supersonic air plasma in the CHESS Plasmatron X. Streaks of light emanating from the nose of the sample correspond to spalling carbon fibers and fiber bundles. (b) Number of detected particles at each time point for tests in air and nitrogen, both conducted at a target heat flux of 675 W/cm^2 and a stagnation pressure of 6.75 kPa. A clear difference in spallation frequency is observed, with steady spallation in air and unsteady particle release in the nitrogen. (c) Post-test SEM image of fibers from a sample exposed to supersonic nitrogen plasma, showing a thick solid deposition coating the fibers. All nitrogen samples exhibit the presence of this deposition, while no solid deposition is observed for cases in air.

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Nanosecond CARS Measurements of Temperature and Relative CO Concentration in the Boundary Layer of a Graphite Ablator

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Abstract

The development of models for the predictive design of heat shields in hypersonic flight and re-entry requires high-quality experimental validation data. Measurements in representative experiments are challenging, due to high temperatures, high background luminosity, and complex chemistry. We present data from measurements with a multiplexing nanosecond Coherent Anti-Stokes Raman scattering system, simultaneously probing CO and N_2 molecules in the reaction layer of a graphite sample exposed to an atmospheric pressure plasma plume. The plasma plume is generated by an inductively coupled plasma torch and temperatures in the plasma are around 5000-7000 K. We discuss measurement challenges and show temperature and relative CO to N_2 concentration profiles at stations 0.2-3 mm away from the graphite surface. Results suggest that CO can reach up to 70% of the N_2 concentration and temperatures change from ~6000 K in the freestream to ~2000 K at the graphite surface over a distance of less than ~3 mm. Moreover, the results indicate a chemical non-equilibrium state near the surface of the graphite sample.

Keywords: High-enthalpy flow, ablation, gas-surface interaction, graphite oxidation, Coherent-Anti Stokes Raman scattering, laser diagnostics

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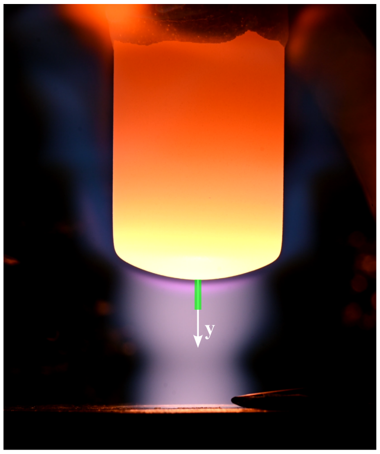

Figure 1: True color image of a graphite sample during testing in the UT Austin ICP torch.

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Current and future capabilities on ablation at NMSU

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Abstract

Research and development (R&D) in hypersonics is progressing at a fast pace. The Department of Mechanical and Aerospace Engineering at New Mexico State University (NMSU) is contributing to R&D in several key areas. At NMSU, we are currently developing new computational and experimental capabilities for flow and material characterization.

New flow diagnostic techniques, such as a Femtosecond Laser Electronic Excitation and Tagging (FLEET) velocimetry system and a Focused Laser Differential Interferometer (FLDI), are evaluated in a Mach 5 shock tunnel. A self-aligned focusing Schlieren system will be available by the end of 2024. These systems are employed for turbulent boundary layer fin interaction research [1, 2]. We are currently expanding this facility to support research in hypersonic boundary layer transition and test sensors for hypersonic flow.

In addition, we have unique capabilities in heat-flux sensor development and characterization with slug calorimetry and thin-film gauges [3, 4]. These sensors have been characterized using a 1.5 kW laser facility and we are currently expanding their usage to support hypersonic environments [5, 6, 7] with particular attention to minimizing their uncertainties.

Furthermore, we are developing new capabilities on material testing and characterization with a combination of several facilities such as a Simultaneous Thermal Analyzer (STA), pycnometry, Reactor Flow Tube Facility (RFTF), Hot Disk Facility. The combination of these facilities at a single location will allow us to carry out a comprehensive material testing to develop consistent material databases [8]. Moreover, we are developing non-intrusiveness lifetime-based thermographic phosphor thermometry using the relationship of phosphorescence and temperature to measure surface temperature distribution.

On the numerical side, we extended our in-house developed LES code to support thermo-chemical non-equilibrium hypersonic flows [9]. For the future, it is planned to link external libraries to support more complex gas-surface interaction chemistry. Moreover, we actively investigate the transition mechanism for the hypersonic boundary layer under non-equilibrium conditions. Furthermore, the usage of Lattice Boltzmann methods to perform fiber scale simulations will be explored with our in-house code [10].

Keywords: hypersonics, ablation, material modeling

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Microparticle Impact Testing of Graphite at Elevated Temperatures

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Abstract

Hypersonic vehicles travel through extreme atmospheric conditions where precipitation and other airborne particulates may impact aircraft surfaces at high velocities and cause spallation damage and erosion of thermal protection system (TPS) materials. These particle-surface interactions occur at high temperatures due to the extreme aerothermal loads of hypersonic flight, where the response of materials tend to be vastly different from their ambient temperature states. To accurately predict and mitigate damage formation under these complex conditions, experimental investigations across a range of impact velocities and temperatures are crucial. This study employs laser-shock-driven particle impact (LIPIT) experiments to study the high strain rate microscale impact damage behavior of POCO ZXF-5Q graphite, a simulant for a TPS material. To assess the influence of elevated temperatures on mechanical strength, spallation, and cratering behavior, a resistive heating system was integrated into the experimental setup. Microparticle impact experiments were conducted on graphite targets by using 60 μm alumina spheres at velocities ranging from 200 m/s to 600 m/s. In these experiments, the target temperatures are varied from 20°C to 1100°C. Fig. 1 shows the impact spallation damage evolution of graphite targets miantained at temperatures 20°C and 1100°C , subjected to similar impact velocities. It is observed that the extent of spallation damage is reduced with an increase in temperature. This is supported by the crater profiles shown in Fig. 2, where the room temperature impact results in a larger crater diameter than that of the case at 1100°C. The crater depth, diameter, and rebound velocities of the particles were used to estimate the damage and strength parameters of the material models. This approach enables the evaluation of material performance under conditions representative of hypersonic flight, providing valuable data for the development of material models to advance predictive capabilities.

Keywords: High temperature, spallation, microparticle impact, LIPIT

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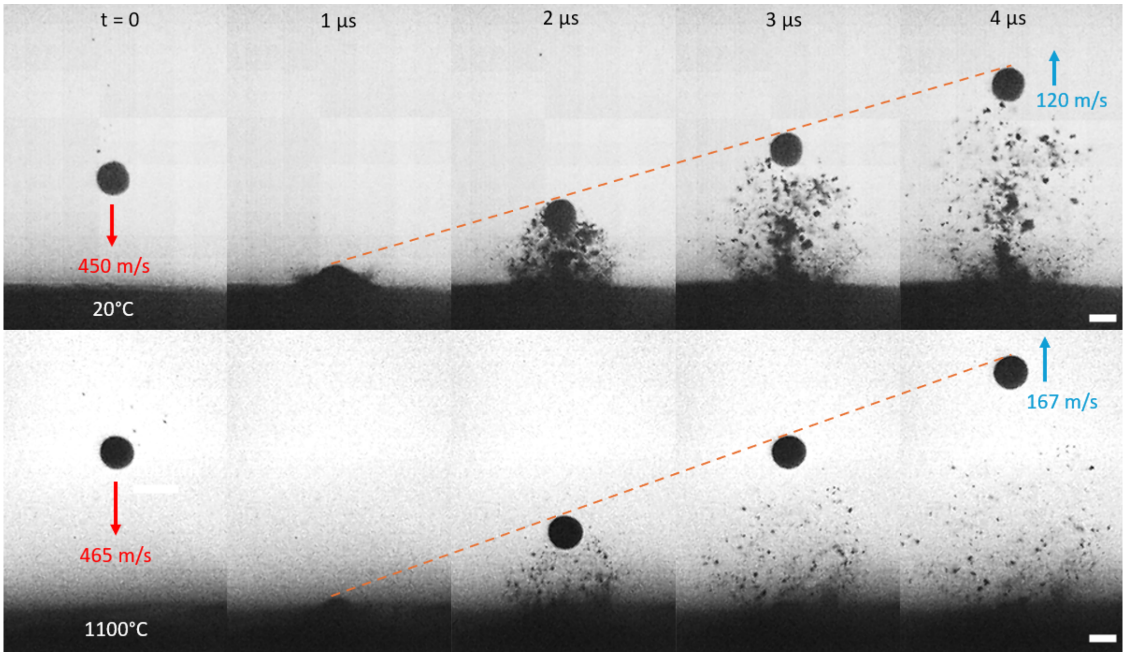

Figure 1: 60 μm Alumina microspheres impacting graphite targets one at room temperature and the other at 1100°C.

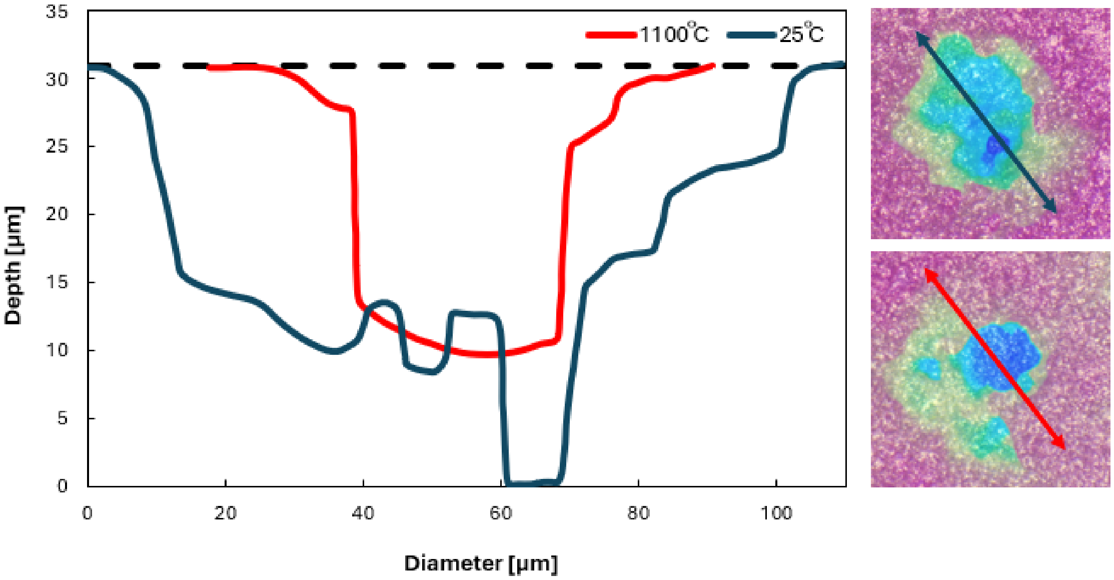

Figure 2: Crater depth profile comparison using confocal microscopy.

Overview of the KREPE-2 Hypersonic Flight Mission

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Abstract

The Kentucky Re-entry Universal Payload System (KRUPS) provides a quick-turnaround, low-cost platform to conduct atmospheric entry experiments. KRUPS is designed to test multiple types of thermal protection systems (TPS) and scientific instrumentation. Five KRUPS capsules were sent to the International Space Station (ISS) via the NG-20 Cygnus resupply vehicle. These five capsules constitute the second Kentucky Re-entry Payload Experiment (KREPE-2) mission, each with a different heat shield TPS material. The data obtained during the mission will help with the reconstruction of the atmospheric entry environment and validation of computational fluid dynamics (CFD) and material response (MR) models developed at the University of Kentucky.

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Data analysis of the Kentucky Re-entry Universal Payload System (KRUPS) hypersonic flights

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Abstract

The Kentucky Re-entry Universal Payload System (KRUPS) is a series of sphere-cone capsules developed at the University of Kentucky. The goals of the KRUPS project are threefold: test novel thermal protection system (TPS) materials in real flight environments, collect valuable re-entry data during missions to validate numerical tools, and develop an effective and low-cost solution for hypersonic re-entry experiments. The data obtained during the orbital flight campaigns of KRUPS, the Kentucky Re-Entry Probe Experiment (KREPE) missions, will be presented. For both missions, although the concept of operations is well defined, the exact breakup location of the host vehicle and the subsequent flight trajectory of the KRUPS capsules remain unknown. Multiple methods are used to estimate the flight trajectory from the received data, focusing on the LI2200 capsule. The methods rely on a trajectory modeling solver called the Kentucky Analysis of Re-Entry Trajectories (KARET) [1], in combination with a one-dimensional material response solver that predicts the wall temperature [2]. KARET is used to simulate the trajectory of the Cygnus vehicle and the KRUPS capsules by starting with the Cygnus vehicle at a known location from its telemetry data and switching to the KRUPS capsules at a chosen ejection altitude. For KREPE-1, a thermocouple-based method is used to reconstruct the flight data [3]. For KREPE-2, the trajectory is reconstructed from the pressure data by comparing the observed pressure to the predicted pressures in the trajectory. A demonstration of the reconstruction process for the KREPE-2 flight using the pressure data is shown in Fig. 1.

Keywords: Re-entry, hypersonics, thermal protection system, trajectory reconstruction.

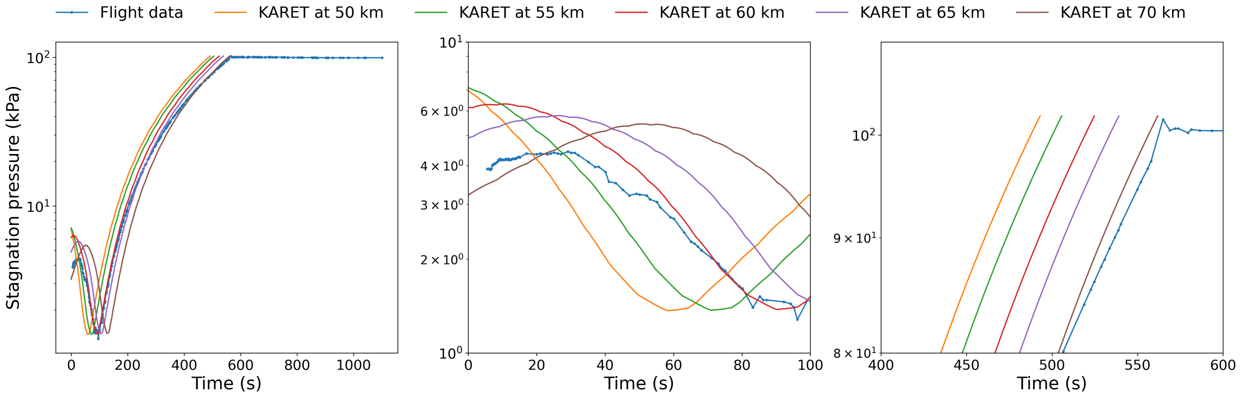

Figure 1: Stagnation pressure comparison between flight data and KARET trajectories for the C-PICA capsule.

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Coking and Oxidation of a Simulated Pyrolyzing Ablator

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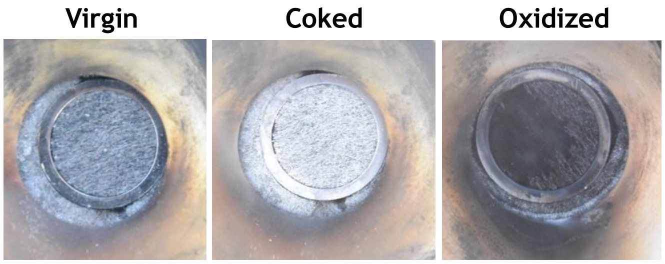
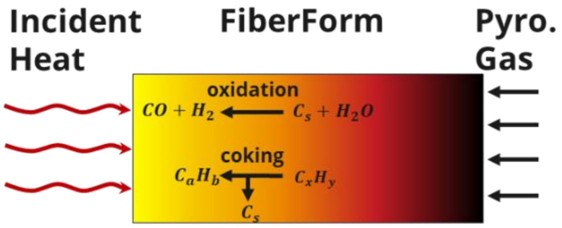
Carbon deposition, i.e., coking, on ablative heatshields was observed during the Apollo program but its importance remains poorly understood [1]. Prior experiments have replicated the coking phenomenon but have not obtained the temperature and flow conditions of planetary entry [2, 3]. Studies of carbon materials synthesis via chemical vapor deposition have explored and characterized relevant reactions [4, 5], but not under entry-like conditions (e.g., porous flow through an extreme temperature gradient).

An experimental test campaign to explore coking in an ablation-like environment was devised. FiberForm specimens were exposed to the concentrated solar irradiation of the Solar Furnace at the National Solar Thermal Testing Facility. These specimens were press-fit into a vitreous carbon crucible, creating a flow-tube reactor withstanding temperatures greatly exceeding 2000 °C. This coking reactor assembly was placed inside an inerted (N_2) vacuum chamber and exposed to up to 335 W/cm2 of radiant heat, while synthetic pyrolysis gases permeated the specimen.

The synthetic pyrolyzate included three gases in isolation and mixtures thereof, which capture the major structures present in pyrolysis-gas mixtures [6]. Methane represented methane, methyl, and methylene groups; Toluene represented aromatic compounds; and water represented oxidizers, such as hydroxyl groups, water, and carbon dioxide.

Reactions observed in prior, lower-temperatures studies (typ. 800-1200 °C) appear to accelerate at the higher temperatures (1800-2200 °C) achieved by our solar-thermal method. Pyrolysis-gas mixtures were capable of both oxidizing and coking FiberForm specimens. In reducing mixtures, coking caused carbon uptake from the gas phase approaching 97%. In oxidizing mixtures, water rapidly oxidized the specimen, resulting in mechanical failure in 10's of seconds. We conclude that pyrolyzate mixtures can be highly reactive with ablator materials, significantly altering macroscale ablator response. These mechanisms may warrant further research to inform the design, modeling, and simulation of decomposing ablators.





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Oxidation of Silicon Carbide with Atomic Oxygen through the Passive-to-Active Transition

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ABSTRACT

We have conducted molecular beam-surface scattering studies to characterize the dynamics of atomic (and molecular) oxygen scattering from SiC as it transitions from the passive to the active oxidation regime. Pulsed beams containing hyperthermal O atoms were directed onto pre-oxidized SiC surfaces at high temperatures, and products consisting primarily of unreacted O atoms were observed to scatter from the surface while the temperature was below the passive-to-active transition, indicating that the passivating oxide layer is highly protective against atomic oxygen. Near the passive-to-active transition temperature, the thin oxide layer decomposes rapidly, leaving behind a graphitic layer on the surface. Inelastically scattered O and O_2, as well as reactively scattered CO and CO_2, from this graphitic surface exhibited dynamical behavior and temperature dependencies that were reminiscent of those observed in an earlier similar experiment with hyperthermal O atoms incident on an HOPG surface. Further investigation into the thermal decomposition of an SiO_2 layer on SiC, without exposure to an incident beam of O (or O_2), revealed products consisting primarily of gaseous Si, SiO, and CO, indicating silicon sublimation from bulk SiC and various reactions at the interface of the SiC and oxide phases; these processes became important above the passive-to-active transition temperature. Active oxidation, evidenced by continuous SiO and CO production through thermal desorption mechanisms, was only observed by exposing SiC to a relatively high-flux, continuous supersonic O/O_2 beam. In this regime, oxidation reactions outcompete Si(g) sublimation and formation of graphitic carbon, leading to significant ablation and roughening of the surface. These results show that multiple mechanisms need to be accounted for when modeling the passive-to-active oxidation transition of SiC with atomic oxygen. Not only must the mechanisms of passive and active oxidation be considered, but mechanisms involving the decomposition of the oxide layer and the sublimation of Si(g) from silicon carbide must also be considered. Furthermore, the flux of atomic oxygen onto the surface plays a key role in modulating the rate of sublimation, and thus the rate of active oxidation. In a practical hypersonic flight environment, the O-atom flux onto a leading-edge surface will always be high enough to "burn through" any incipient graphite layer; however, the underlying mechanisms that may tend to form a graphitic layer under lower-flux conditions may still be playing a role in the outcome of SiC ablation. Thus, the flux of atomic oxygen onto the SiC surface, the active chemical mechanisms, and the detailed reaction dynamics in the complex gas-surface interfacial region must all be considered when modeling the active oxidation regime.

Title: Mo-Si-B Coatings for Enhanced Oxidation resistance in SiC-based Thermal Protection Systems (TPS) for Hypersonic Applications

Authors: Jeff R. Becker, John H. Perepezko

Abstract

One of the most demanding engineering challenges for sustained hypersonic flight is the development of a suitable thermal protection system (TPS) for leading edges that experience high temperatures and low pO_2 environments. While SiC shows promise, it is rapidly consumed in hypersonic operating conditions due to active oxidation – a mechanism that occurs at high temperatures and low pO_2, leading to the production of volatile SiO(g) that breaks down the SiO_2 protective layer. In past work, Mo-Si-B coatings have shown superior ablation resistance in arc jet testing when compared to SiC/ZrB_2 composites. While $MoSi_2$ (a major phase in Mo-Si-B coatings) is known to show active oxidation, it will form Mo_5Si_3 when enough Si is lost. This phase has a lower Si activity allowing for SiO_2 to become the stable oxide again and undergo passive oxidation, allowing for a larger range of oxygen potentials for use with this coating. The compatibility of Mo-Si-B coatings on SiC is evaluated by a diffusion couple experiment. Mo_5SiB_2 (T_2), which is the layer in contact with the substrate for Mo-Si-B coatings, and SiC were placed in intimate contact at 1700°C for 150 hours under pressure. Transmission electron microscopy was used to find that there is no formation of ternary compounds, proving that T_2 and SiC are in thermodynamic equilibrium. This is critical for sustained use of any coating. Isothermal oxidation experiments of Mo-Si-B coatings were also conducted at T=1500°C and $pO_2=10^{-4}$ atm. The Mo-Si-B coatings exhibit robust performance, while SiC which showed significant mass loss under these conditions. The coating protects against active oxidation in a regime where SiC fails. A thermodynamic analysis shows that Mo-silicides can achieve a pO_2 of ~3 orders of magnitude lower than that for SiC, greatly increasing the resistance to active oxidation.

A unifed approach to the active and passive thermo-chemo-mechanical oxidation of Silicon Carbide

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Abstract

Ultra-high temperature refractory ceramics (UHTCs) are one of the most promising classes of materials for use in reusable thermal protection systems and on the leading edges of hypersonic vehicles. In extreme conditions, they may fracture and oxidize according to either passive (mass-adding) or active (ablating) mechanisms. Unexpected transitions between these oxidation regimes can lead to several potentially catastrophic consequences which stem from a complex interplay of thermo-chemo-fracture mechanics couplings and demand unified computational analyses. In this talk, we explore these degradation mechanisms computationally, using the discontinuous Galerkin interfacial multiphysics modeling framework. The approach combines cohesive fracture and rigorous physics-based, chemistry models. We report on recent extensions of the methodology to incorporate the open-source equilibrium chemistry solver, Cantera, in order to naturally capture both the passive and active oxidation modes. Numerical examples are presented that illustrate oxidation and fracture propagation in silicon carbide and other refractory ceramics. The analyses span a variety of temporal scales and environmental conditions, ranging from thermal-shock driven fracture to diffusion-limited, oxide-swelling induced delamination. They unveil a number of important insights into the detailed failure mechanisms and coupled reactions in the vicinity of channeling, kink, and delamination cracks.

Keywords: Continuum modeling, in-depth chemistry, solid mechanics, oxidation, UHTCs, FEM, TGOs, ablation

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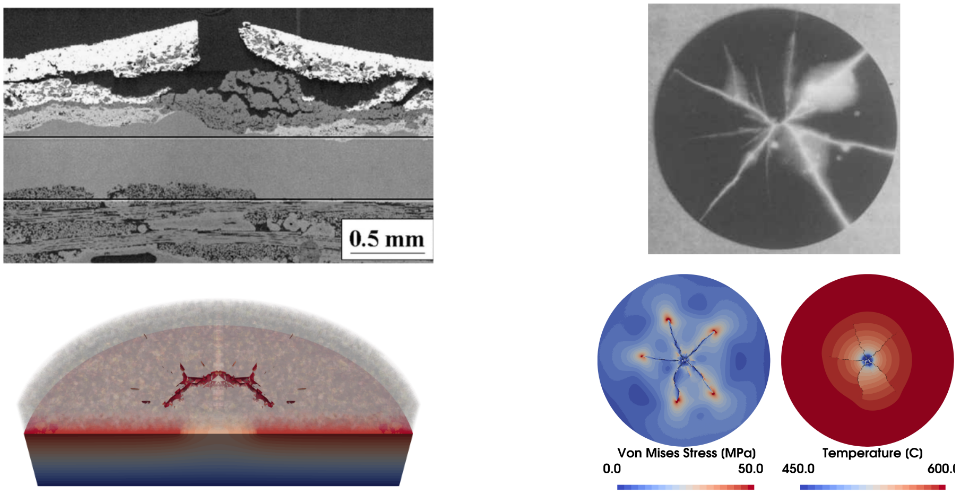

Figure 1: Left: experimental and computational analysis of environmental barrier coating spallation due to oxidation. Right: experimental and computational analysis of fracture propagation in thermally-shocked alumina.

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The Design of Kinetically Limited Subsonic Experiments via Damköhler Analysis

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Atmospheric entry produces intense enthalpy, momentum, and mass transfer due to strong convective forces. The intense boundary-layer mass conductance enhances reactant transfer to the surface, perpetuating kinetically limited ablation to extreme temperatures (>>1500 K). This kinetically limited state is difficult to maintain in many ground test facilities, particularly under atomic oxygen, due to an order-of-magnitude deficit in mass conductance.

The second Damköhler number compares heterogeneous kinetics to boundary-layer diffusion and is deployed here to identify kinetically limited conditions in a variety of traditional configurations for ablator testing. The Damköhler analysis indicates many subsonic experiments encounter diffusion limitations at relatively low temperatures.

The Damköhler analysis also reveals the advantages of non-traditional configurations, such as spinning-disc reactors and microfluidic jets and channels. These enhancements to ground-test apparatuses can intensify mass conductance to transport rates found in a high-speed boundary layer. Experimental ablation rates matching published kinetics models were obtained in multiple configurations to high temperatures. A solar-thermal microfluidic device produced intense spallation of graphite at surface temperatures of only 1000 °C. The Damköhler analysis and approaches deployed appear generally applicable to experiments and modeling by the wider ablation community.

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"Nano" strategies for enhancing carbon-phenolic ablator properties

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Abstract

According to several research activities carried out in the last years[1-3], low density carbon phenolic ablators can be successfully modified at the nano-scale enhancing their performances in terms of ablation rate and thermal insulation. Ceramic nano-particles are able not only to improve some thermomechanical properties of the ablative materials but, when exposed to high heat flux levels, they can coalescence and create an effective ceramic protective shield able to reduce the surface recession rate. Considering previous promising results about nano-ZrO_2 modified carbon-phenolic ablators[2], a new strategy has been developed: a ZrO_2 nano-film was deposited on the carbon fibers of the carbon felt through Atomic Layer Deposition (ALD) technique. The ALD-modified ablators show no significant improvement in terms of thermal insulation or surface recession/mass loss, but their recession was considerably much more uniform. Furthermore, another nano-strategy consists of the addition of thermoplastic polymers, in particular PVP[3] and PEG, allowing to obtain a nano-metric granular-structured morphology of the cured phenolic resin. These nano-structured ablators show improved performances in terms of surface recession and thermal insulation.

The potentialities of the proposed modified carbon-phenolic ablators were assessed by oxyacetylene flame exposure tests, according ASTM E285-08 standard. Virgin and charred samples were characterized through Scanning Electron Microscopy analysis (Figure 1), and by some specific tests selected to investigate specific properties (FTIR, BET, micro-CT, compression tests).

Keywords: Nano-composite ablators, Nano-structured ablators, Oxyacetylene torch test, SEM micrographs.

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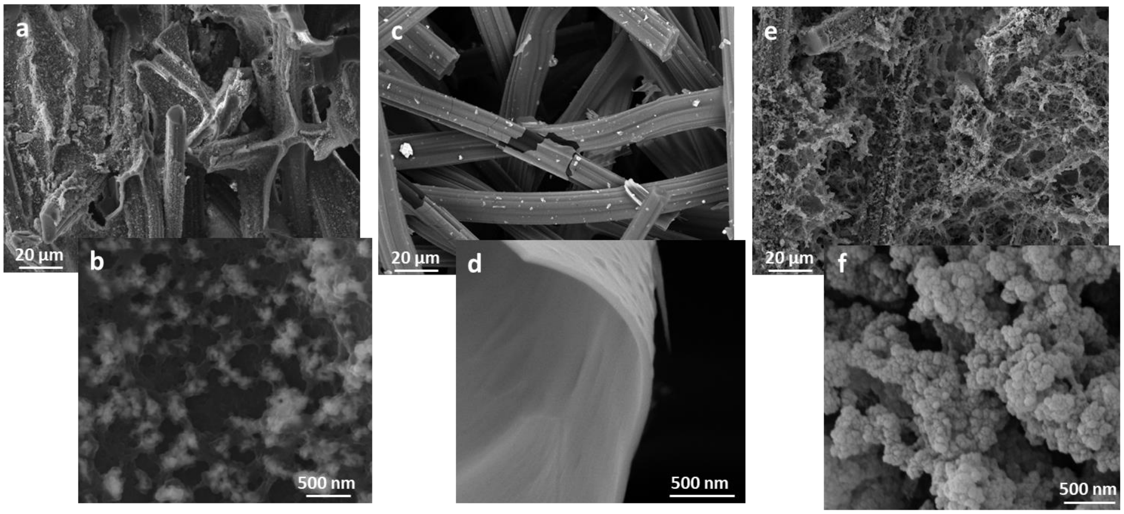

Figure 1. SEM micrographs of modified carbon phenolic ablators with ZrO_2 nano-particles (a,b), ZrO_2 nano-film (only carbon felt with ALD coating) (c,d), PVP (e,f)

Ultra-high temperature thermal characterization of carbon fibers and reinforced composites

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Introduction

Aerospace applications require materials with excellent strength, thermal shock and ablation resistance at temperatures above 1600 °C, and possibly exceeding 2200 °C (ultra-high temperature region).[1] Carbon fibers are characterized by high specific strength and modulus, low coefficient of thermal expansion (CTE) and high electrical and thermal conductivity.[2] Thus, these mechanical/thermal properties make them the best, and currently the only, suitable reinforcement for carbon fiber/carbon matrix (C/C) and silicon carbide-matrix (C/SiC) composites for aerospace applications. Despite the many studies that have been carried out on carbon fiber reinforced composites, only limited thermal characterization results (i.e., CTE, thermal diffusivity and Cp) are available at ultra-high temperatures.[3] In this work, the CTE and thermal diffusivity of various types of carbon fibers and composite materials have been measured up to 2700 °C.

Method

Carbon fibers (IM7, T300 and Mitsubishi Dialead) were uniformly compacted into collimated, cylindrical bundles to known length (25 mm) using a hollow graphite tube. After trimming protruding carbon fibers, cross sectional samples were cut using a diamond Isomet saw to obtain a smooth even surface.[4] Then the fibers were graphitized at the desired temperature (i.e., 1500, 2700 °C). CTE for carbon fibers and composites (cut in-plane and through-plane direction) were measured up 2700 °C by DIL 402 Expedis Supreme HT (Netzsch), whereas the thermal diffusivity for the composite materials were measured by LFA 427 (Netzsch).

Results and discussion

The CTE of carbon fibers progressively increased with the temperature (Figure 1(a)), however the CTE profile for Mitsubishi Dialead fibers, which are derived from mesophase pitches, was shifted to lower values than the ones for IM7 or T-300 (derived from PAN precursors). This suggests the importance of the precursor in the thermal expansion of carbon fibers. The graphitization temperature of the fiber also impacts the CTE (Figure 1(b)), as CTE dramatically decreases after the graphitization treatment temperature is exceeded. However, this behavior is reversible if the fiber is treated at higher temperature in a repeated experiment. A similar effect of the maximum treatment temperature was also observed in the composite materials. Furthermore, a higher CTE was observed through-plane than in-plane direction, whereas the thermal diffusivity was higher in-plane direction in agreement with a higher contribution of the fiber in-plane direction.

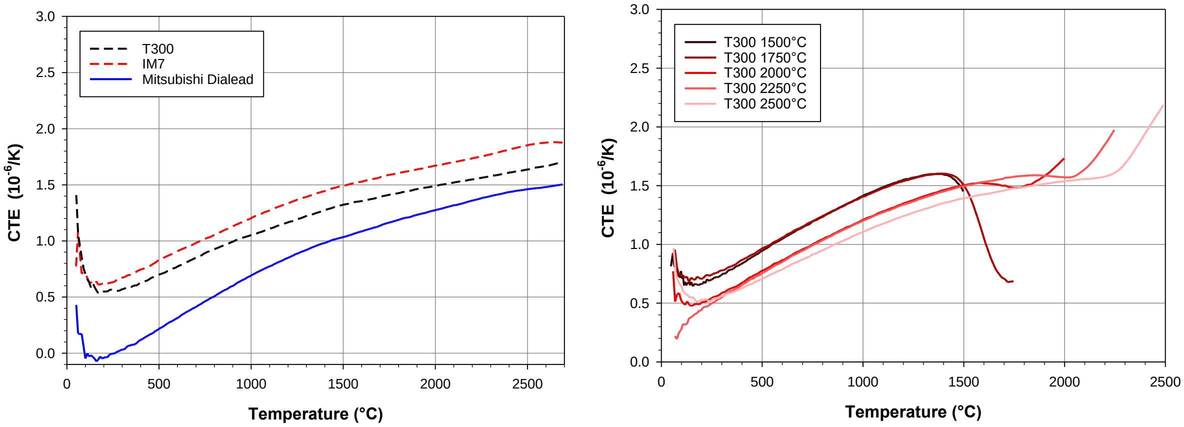

Figure 1: CTE profiles for (a) different fiber type and (b) different thermal treatment on IM7 carbon fiber

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Determination of heat transfer parameters for porous, fibrous insulation materials

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Abstract

Thermal protection systems (TPS) are responsible for protecting vehicles during reentry into planetary atmospheres from the extreme heat fluxes caused by aerodynamic heating. Without TPS, vehicles would inevitably be damaged or burn up during reentry. Therefore, it is of great importance to be able to model the heat transfer in these TPS materials so they can be efficiently designed. Several types of thermal protection systems have been used depending on the expected heat flux magnitude. A common type of TPS material used when reentry vehicles are expected to experience higher heat fluxes are ablative insulation systems. An ablative TPS material that has seen use on several missions is phenolic-impregnated carbon ablator (PICA). A substrate commonly used in the construction of PICA is FiberForm®, a porous, fibrous material. Three primary modes of heat transfer exist in porous, fibrous insualtion materials such as FiberForm®: solid conduction, gaseous conduction, and radiation. Solid conduction occurs due to fiber-to-fiber contact within the fiber matrix. It is a function of temperature and material geometry. Gaseous conduction occurs due to the gases that are present within the pores of the TPS fiber matrix. The gaseous conduction in a TPS is primarily a function of participating gases, temperature, pressure, and fiber geometry. Radiation is emitted from the individual fibers and is dependent on several optical properties of the TPS material such as its extinction, scattering, and absorption coefficients. Other modes of heat transfer such as forced convection are present within these TPS during reentry, but are negligible in the testing conducted in this study. The overall effective thermal conductivity of the TPS material can be found as a superposition of these primary modes of heat transfer. Each of these modes can be isolated by altering the testing conditions of the sample. The contribution from gaseous conduction can be mitigated by bringing the sample environment down to vacuum conditions. Solid conduction and radiation will always be present even at lower temperatures and are more complicated to isolate. Genetic algorithms are used to determine the unknown heat transfer parameters associated with each mode of heat transfer. This requires testing over a wide range of sample surface temperatures in vacuum conditions. An experimental apparatus utilizing the comparative cut-bar method has been developed to measure the thermal conductivity of a sample in different testing environments. Testing has been conducted on FiberForm® to determine the heat transfer coefficients associated with each mode of heat transfer.

Keywords: Fibrous insulation, heat transfer, genetic algorithm

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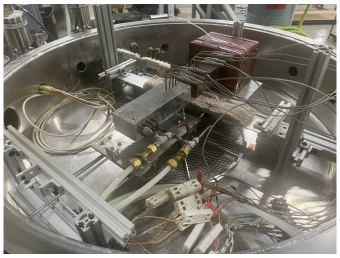

Figure 1: Experimental set-up

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Wavelength and Angle-Dependent Radiative Properties of LI-2200: An Experimental Study.

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Abstract

In any planetary re-entry mission involving hypersonic vehicles, radiative heat transfer may play a crucial role in influencing the thermal response of Thermal Protection System (TPS) materials. While radiative heat load contributes less than 25 – 35% of the total heat flux during Earth's atmospheric entry, it can become especially important in planetary entry missions to other planets in the solar system. This experimental study specifically aims to measure the angle- and wavelength-dependent transmission, scattering, and backscattering properties of TPS samples with varying thicknesses. In our current experiment, LI-2200 samples of varying thicknesses, ranging from 0.4mm to 1.3mm, are encased between two transparent glass slabs, with a fiber-coupled stabilized light source directed at them. Two different types of light sources are employed, with one ranging from 200nm to 1000nm and the other from 400nm to 2500nm. To obtain and collect collimated beams from these light sources, a two-lens tube system is used for the ultraviolet light source and a separate collimator system for the visible light source, both installed at the source and collection ends. The collection end is connected to a high-resolution spectrometer, which ranges from 200nm to 1100nm and is positioned opposite the sample from the light source during the measurement of transmission and scattering through the sample. The transmission beyond 1000nm is below the detection limit of the system. Both the sample and the receiver are mounted on motorized stages that can be rotated to adjust the angles of incidence and collection. Scattering and transmission are measured for collection angle variations of 5° within a range of 0° to 20° from the normal. The sample was also rotated to vary the angle of incidence from 0° to 20°. The sample angle of rotation for backscattering measurements ranges from -20° to 20°. A total of 25 different combinations were identified for transmission and scattering measurements, while 45 different combinations were recorded for backscattering. These measurements were normalized based on transmission through air for transmission and scattering through the sample, and reflection off two different types of mirrors for backscattering from the sample in the ultraviolet and visible spectra, respectively. For these measurements, the heat load on the surface is negligible. Modeling the transmission and scattering response will be utilized to determine fundamental radiative transport parameters, which can subsequently be used to calculate the overall heat load for relevant re-entry scenarios.

Keywords: Radiative heat transport, LI-2200, Scattering, Spectroscopy.

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Overview of Navy Ablation Activities (Part 2)

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Construction of backward rates for the air-carbon ablation model

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[b]*Corvid Technologies, Mooresville, NC 28117, USA*

Abstract

Finite-rate carbon oxidation models are required to understand the behavior of ablative thermal protective systems (TPS) in hypersonic flight. The latest finite rate chemistry model available, the air-carbon ablation (ACA) model, is being widely adopted and is built from molecular beam experiments that probe individual gas-surface collisions. The ACA model only contains forward rates and does not satisfy gas-surface equilibrium [1]. Under equilibrium conditions, for a given temperature and pressure, the ACA model predicts excessive CO and CN. A set of backward rates is constructed to ensure that the ACA model satisfies gas-surface equilibrium and reproduces air-carbon equilibrium compositions. In order to accomplish this task, the equilibrium constants for each reaction are related to the equilibrium constants of adsorption-desorption, sublimation, and gas phase dissociation reactions. In addition to constructed backward rates, scaling functions modify the equilibrium constants of the adsorption-desorption terms based on temperature. Since the goal is to keep forward rates as defined by the published literature, these functions guarantee that mixture composition trends seen at equilibrium occur at the correct temperatures. The comparison of the newly constructed ACA model with backward rates and the equilibrium predictions are shown in Fig. 1. In addition to ensuring microscopic reversibility through gas-surface equilibrium, these additions facilitate choosing appropriate surface chemistry boundary conditions in CFD without prior knowledge of the state near any particular surface. Previously, CFD users would have to choose between applying finite rate or equilibrium models across a surface. With the addition of the backward rates, the newly constructed full ACA model can be used without loss of generality.

Keywords: Air-carbon ablation, oxidation, backward rates, equilibrium, thermodynamics

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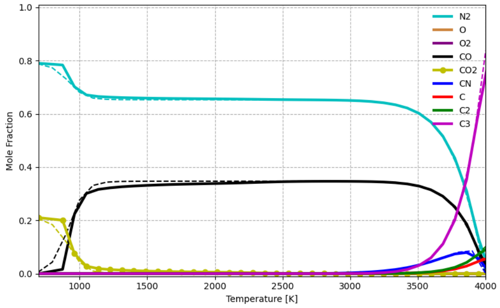

Figure 1: ACA model with backward rates and scaling parameters compared with predicted thermodynamic equilibrium species profiles at 1 atm

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Comparing the thermal response of models made from PICA and 3MDCP when exposed to arcjet test conditions using a coupled CFD-material response approach.

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Abstract

Thermal protection system (TPS) materials that will be considered for future space missions include Phenolic Impregnated Carbon Ablator (PICA) [1] and 3-D Woven Mid-Density Carbon Phenolic (3MDCP) [1]. The heatshield of the Mars 2020 entry capsule was made from PICA [3]. The baseline TPS material for the Mars Sample Return Earth Entry System (MSR-EES) [4] was scheduled to be 3MDCP. The thermal performance of these materials is tested in experiments performed in the NASA Ames arcjet facilities. Figure 1 shows a model made from 3MDCP being tested in the NASA Ames IHF arcjet.

To support the arcjet experiments and to evaluate the performance of these TPS materials under atmospheric entry conditions, a coupled CFD and material response analysis code called Ares [5] has been developed under the NASA Entry Systems Modeling (ESM) project. The Ares framework couples the US3D Navier-Stokes CFD solver [6] and the Icarus material response solver [7]. Ares has been used to simulate arcjet experiments [5] and to simulate the heatshield erosion on the shoulder of the MSR-EES heatshield [4].

This presentation will show and compare the thermal response of 4-inch iso-q models made from PICA and 3MDCP when exposed to arcjet test environments as predicted by the Ares code. Arc heater settings will be selected to approximate the heating rate environments that are expected for Martian and high-velocity Earth entry conditions. The results will include in-depth temperature profiles, surface temperatures, and surface recession at both the stagnation point of the models and at the shoulder.

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

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Figure 1: A 4-inch iso-q model made from 3MDCP tested in the IHF arcjet.

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4D microtomography of Avcoat during heating and decomposition

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Abstract

During heating, ablative thermal protection materials undergo complex thermal, mechanical, and chemical processes. Understanding and characterizing these processes is essential for predictive modeling efforts; however, flight data and traditional experimental methods provide limited insights into the real-time internal behavior of these materials during decomposition.

In this work, we present experimental results and computational analysis of 4D microtomography of Avcoat during heating and decomposition. These experiments were conducted at the Advanced Light Source (ALS) facility of Lawrence Berkeley National Lab [1].

From these time-series images, tools were developed and applied to determine material char progression, shape change, material orientation, and crack behavior. From these data, the frequency, onset, progression, shape, orientation, and spatial distribution of cracks were determined. These experimental and computational techniques provide unique insights into the internal microscale behavior of TPS materials during decomposition, which are used to better understand material performance and inform full-scale material response models.

Keywords: 4D tomography, microtomography, microscale, Avcoat, in-situ

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Experimental investigation of in-depth radiative heating in porous TPS materials exposed to an argon plasma flow

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Abstract

When modeling and designing thermal protection systems (TPS) for entry vehicles, it is common practice to ignore in-depth radiative heating due to emission from the high temperature shock and boundary layer by treating the radiative contribution as part of an effective conductive flux. An experimental arc-jet campaign was conducted to investigate the validity of this approach by comparing the in-depth temperature response of TPS materials subject to a plasma flow supplemented with short wavelength radaition to the response when exposed to only the plasma flow . The arc-ject complex known as the Hypersonic Material Environmental Test System (HyMETS), located at the NASA Langley Research Center, is commonly used for research and evaluation of the physical phenomena experienced during atmospheric re-entry. In this arc-jet campaign, seven candidate TPS materials were evaluade in an argon test condition where each material was exposed to a coupled response from radiative infrared heaters inside the arc-jet chamber and direct interaction the plasma flow. The spectral data, surface temperature, in-depth temperature from an inserted thermocouple, and mass loss data were all recorded for further analysis. These experimental findings will be used to evaluate and extend computational models of TPS materials.

Keywords: In-depth heating, porous ablator, arc-jet

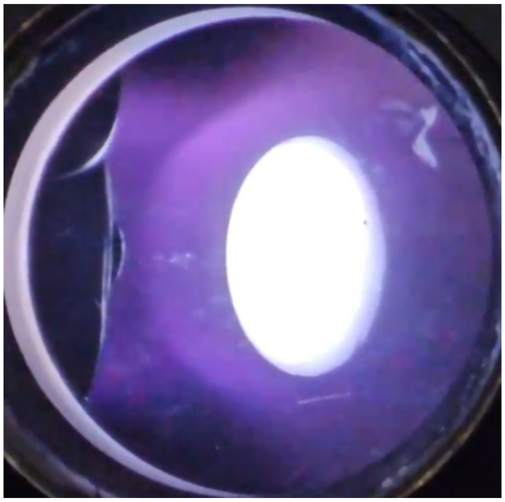

Figure 1: TPS sample exposed to an Argon plasma flow.

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Characterization of carbon-phenolic composite micro- and nano-structure

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Abstract

Low-density carbon-phenolic composites, such as PICA, possess meso-, micro-, and nano-pores making the structure of the resin difficult to characterize. X-ray Computed Tomography (XRCT) is a widely accepted method for characterizing the carbon fiber preform, yet this technique is often insufficient for visualizing the resin because of its minimal attenuation of the incident beam. Phase Contrast Retrieval (PCR) reconstruction considers not only the linear attenuation coefficient, but also the refractive indices of the constituent materials. In a recent effort, phase contrast tomography was leveraged by the authors to visualize the phenolic resin with a voxel resolution of 7 μm. The characterization of the meso- and micro-structure of the porous resin phase is a newly developed capability.

Because standard voxel sizes are on the micrometer scale, the nano-structure of such porous materials cannot be resolved through XRCT. Using focused ion beam (FIB) milling and scanning electron microscopy (SEM), a three-dimensional nano-structure is generated for PICA. Cleaning cross sections expose the interior structure to be captured through SEM. Voxel dimensions of 4 nm x 6 nm x 10 nm have been achieved for the fully automated FIB-SEM method. Charging effects on the non-conductive resin surface during imaging are mitigated through use of a platinum sputter coating sufficient for dissipating the build-up of electrons at the surface. Image registration within the Avizo3D software is used to correct the +52° offset between FIB and SEM. Semantic segmentation of the scans is performed using a developed and trained 2DCNN with a 5-layer U-Net architecture. Deconstructing the high-resolution rectangular SEM scan into patches allows for parallelization of the automated semantic segmentation. Utilization of standard volume generation methods (marching cubes algorithm, Avizo3D, etc.) extend the stack of masks to a three-dimensional surface volume revealing the nano-structure of the phenolic resin and enabling future mechanical and fluid simulations with highly realistic renderings of the material.

Keywords: X-ray computed tomography, Scanning electron microscopy, Focused ion beam milling, micro-structure generation, porous ablator

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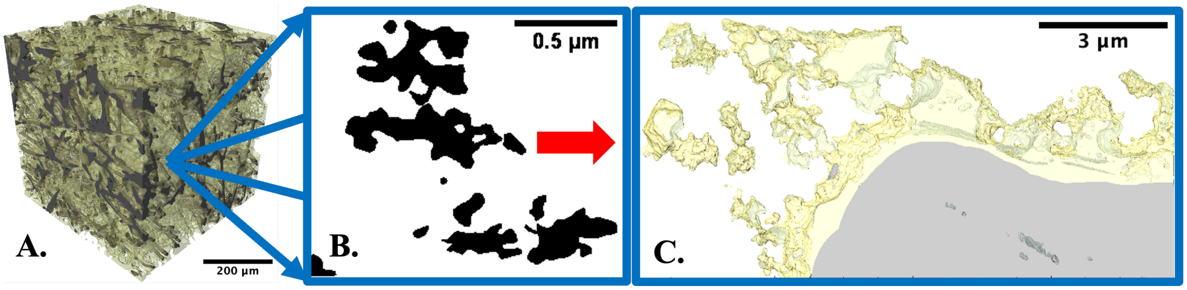

Figure 1: (A) A 500 μm^3 cube of PICA with voxel size of 1.112 μm is depicted. (B) A binarized mask possessing equivalent area to one voxel in (A) is mapped onto the resin structure within the micro-scale rendering. (C) The nano-structure of the carbon fiber and phenolic resin obtained through semantic segmentation of FIB-SEM is visualized.

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A government/industry/academic collaborative research program in accelerating understanding of ablation and oxidation mechanisms in high temperature materials

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Abstract

The DEVCOM Army Research Laboratory leads a collaborative research effort including academia, government, and industry to further understand ablation and oxidation mechanisms in Army-relevant high temperature material systems, including carbon-carbon (C-C) composites. This research focuses on method development for material characterization, high temperature material testing and material response modeling, utilizing commercial-off-the-shelf (COTS) C-C. Efforts are highlighted from university partners including The University of Kentucky (UK), The University of Tennessee, Knoxville (UTK), Rowan University, and The University of Alabama. Leidos Dynetics and Lockheed Martin, as industry transition partners, aim to mature a screening framework where low-cost testing facilities are leveraged in conjunction with high-fidelity modeling tools to significantly reduce the cost burden for evaluation of new and existing high temperature materials. A material-agnostic screening framework will help refine parameters and reduce test condition requirements for high-cost, limited-capacity facilities, thus accelerating and broadening material development activities. Initial efforts are underway to demonstrate the framework through testing materials in UTK's HyperMATE facility, UK's plasma torch, Rowan's McKenna Burner and the Laser Hardened Materials Evaluation Laboratory (LHMEL) system; and through developing associated models using the Kentucky Aerothermodynamics and Thermal-response System material response (KATS-MR) code. Pre- and post-test characterization includes evaluation of material architecture via micro computed tomography, x-ray diffraction, laser heated aerodynamic levitation, electron microscopy, and permeability testing; thermal testing via high-temperature flow tube, plasma jet, and microwave heater; thermo-gravimetric analysis; and numerous other thermal-mechanical test methods.

Keywords: carbon-carbon composites, high-temperature testing, material response modeling, material characterization

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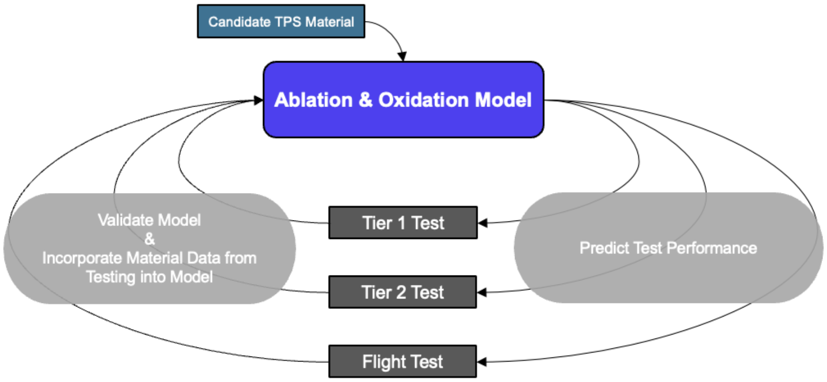

Figure 1: Conceptual model development cycle

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Segmentation Algorithms based on a Vision Foundation Model for CT Scans of Carbon-Carbon Composite Materials

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Abstract

With the rapid advancement of artificial intelligence (AI) and machine learning (ML) in computer vision, new ML models become available to achieve better performance in terms of both accuracy and speed in object detection/classification/segmentation compared with traditional computer vision-based algorithms. Among these new developments, the Segment Anything Model (SAM) is a new vision foundation model developed by Meta (formerly Facebook) for image segmentation. It is based on a transformer architecture that can process both the input image and the user-provided prompts, such as points, boxes, or texts, to achieve excellent results. In this study, we focus on algorithm development based on SAM for computed tomography (CT) scan segmentation to achieve faster and more accurate performance with zero-shot capability. Two approaches were developed from this study. The first approach is built on SAM's automatic mask generation that automatically segments objects or regions in images without any user-provided prompts. The algorithm strives to accurately select the representative masks and classify them into appropriate tow classes (x-tows, y-tows, z-tows, and voids). This method easily handles well-structured carbon-carbon (C-C) composite materials. For other C-C composite materials, another segmentation method based on SAM's mask prediction capability assisted with user-provided prompts. The second algorithm focuses on extract vision features based on preprocessing images to automatically generate point prompts for SAM to properly produce the desired masks for CT scans. The performance of new algorithms is also compared with that of Dragonfly, a software that includes the more traditional ML-based segmentation workflow, which usually requires few-shot supervised training to achieve desired performance.

Keywords: Segmentation, computer vision, machine learning, CT scan, carbon-carbon materials

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Figure 1: Sample tow segmentations using the method based on SAM's automatic mask generation. Images from left to right are original CT scan, X-tow, Y-tow, and Z-tow segmentations, respectively.

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Pyrolysis of Carbon-Phenolics: SC-1008, PICA-D, and 3MDCP-IL

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Abstract

Most pyrolyzing ablative heat shields contain phenolic resin; therefore, a good understanding of the thermal decomposition mechanisms of this material and carbon-phenolic composites provides a foundation to develop improved material 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 materials, molar and mass yields of gaseous pyrolysis products have been determined as a function of sample temperature (room temp – 1200 °C) with five temperature gradients (1, 3, 6, 12, and 25 °C/s), using a method that is based on earlier work by Bessire and Minton.[1] Molar and mass yields for pure phenolic SC-1008 resin, PICA-D (Phenolic Impregnated Carbon Ablator - Domestic), and 3MDCP-IL (3D Medium Density Carbon Phenolic – Insulation Layer) have been collected for each temperature gradient (example **Figure 1**). From the temperature dependent yields, it is clear that, while the underlying decomposition mechanisms are related, the quantitative yields are different. The yields for PICA-D and 3MDCP-IL are more similar to each other than they are to pure SC-1008; however, there are still differences across all three materials. These differences have been studied and are probably the result of differences in phenolic resin density, curing procedures, the presence or absence of carbon fibers, and the polymer from which the fibers where derived.

Keywords: Phenolic resin, carbon-phenolic ablator, pyrolysis, molar yields, mass yields.

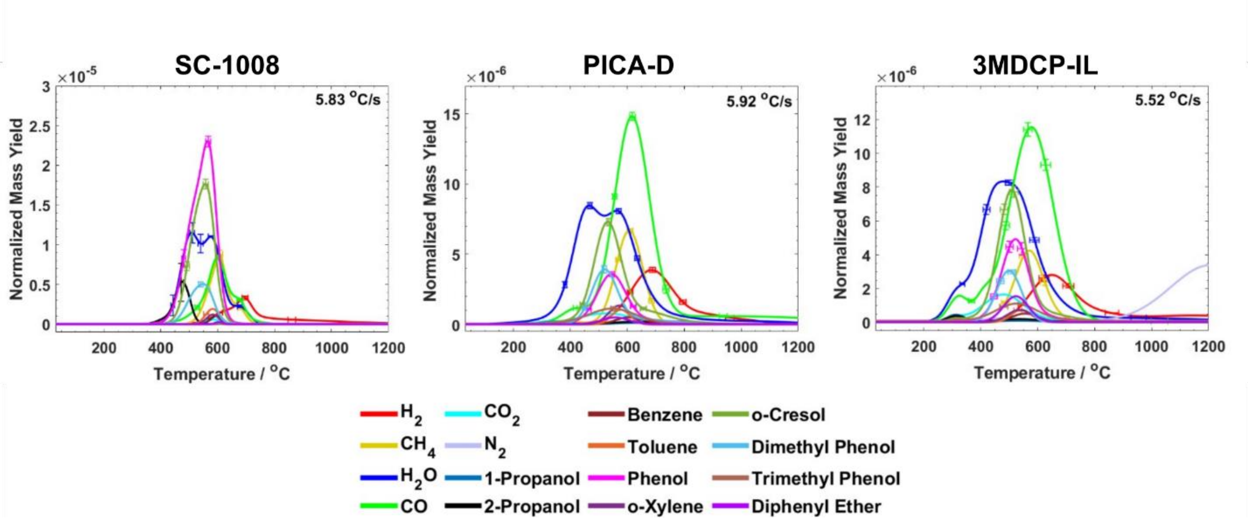

***Figure 1.** Examples of mass yields, normalized with respect to the total mass loss of the 15 dominant gaseous pyrolysis products, for SC-1008, PICA-D, and 3MDCP-IL, with a temperature gradient of ~6 °C /s.*

Reference

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Thermal protective systems modeling in rich-flame combustor environments

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Abstract

Light-weight composite materials for thermal protection systems (TPS) are attractive for withstanding large aerothermal loads of hypersonics flight, particularly in atmospheric (re-)entry where radiative effects and extreme temperatures are present. In many systems, protective insulation is enhanced by endothermic pyrolysis reactions of solid phenolic resin, yielding outgassing flow. This same concept is investigated for air-breathing hypersonic propulsion, where combustor walls must protect against high temperatures of supersonic flow deceleration and combustion. Additionally, the presence of oxygen, essential for combustion, leads to oxidation and recession of the protective carbon fibers, changing the flow path area with impact on the propulsive performance. Thus, material response characterization is a step toward improving the design of high-speed flights systems. The analysis of TPS in such applications is performed with the flat-flame McKenna burner, whose combustion products for different equivalence ratios interact with test materials, as visualized in Fig.1. This setup with its low flow velocities avoids the complexity of supersonic reactive turbulent flows, so it allows for a relatively inexpensive but detailed assessment of flame-wall ablation. An initial analysis is performed with rich flames that suppress sample oxidation and further reduce complexity, focusing on verification of coupled fluid-wall simulations with OpenFOAM-PATO solver [1] as well as conducting sensitivity analysis to identify the most relevant parameters in combustion kinetics, heat transfer and resin pyrolysis degradation models of an in-house carbon-phenolic material [2].

Keywords: In-depth heating, porous ablator, combustion, sensitivity analysis

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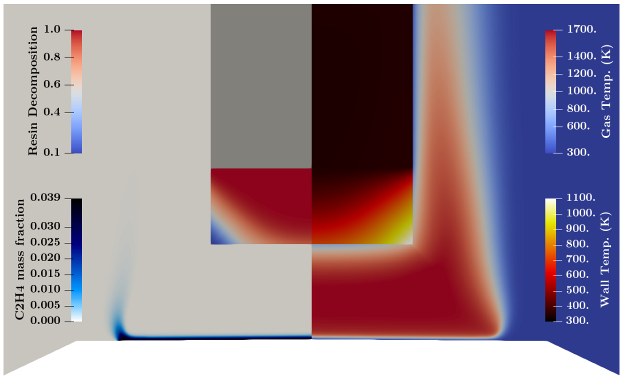

Figure 1: Numerical simulations of an axisymmetric flat-flame McKenna burner.

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Validation of Carbon Ablation Models with density base Navier Stokes solver

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Ablative Thermal Protection Systems (TPS) have been the preferred method of atmospheric reentry in shielding vital components of hypersonic vehicles such as nose tips, leading edges, vehicle acreage, engine inlet cowls, and rocket nozzles. Traditionally, the design of TPS has been through ground and flight test programs.

Ground testing is beneficial in material screening and initial data collection but is unable to replicate real-world flight environments. Flight testing produces the proper environments at the expense of extreme cost and difficult data reduction. The rise of computer simulation has become a key enabling technology in the design and development of hypersonic systems. Once validated, high-fidelity computer simulations can accurately reproduce physical phenomenon and their complex interactions, thus reducing the reliance on ground test facilities.

The present work shows the validation of Ansys Fluent CFD density-based coupled solver in the simulation of graphite ablation comparing to experimental cases performed at the IHF arc-jet facility at NASA Ames Research Center. Two different surface reaction models of air-carbon were implemented, which consist of 11 species, to simulate the ablation of the solid carbon material. This process is coupled with the ablation moving deforming mesh (MDM) implemented in the solver together with conjugate heat transfer (CHT) capabilities. Two geometries are being evaluated with the implemented mechanism comparing with the results of the experimental tests that were performed.

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Phenolic Impregnated Carbon Ablator (PICA) is a thermal protection system (TPS) material that has been successfully used in previous NASA missions to protect from reentry conditions. Predicting the performance and ablation rate of the TPS material allows for a higher probability of success for future missions, but testing can be an expensive and time-consuming process. We built the Macaw application using the Multiphysics Object-Oriented Simulation Environment (MOOSE) to use the phase-field method to model the ablation of both the fibers and char in PICA at the mesoscale while fully coupled with heat transport. We are also adapting Macaw to model the ablation of woven carbon fiber composites. We created a process to import complex woven geometries into Macaw and then model the fiber oxidation process for the outermost layer of the heat shield where the matrix has already ablated leaving just the fibers. This will allow for testing different geometries quickly and affordably before creating samples to test experimentally.

Stochastic reconstruction of TPS material properties

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Abstract

Material response models are used to assess reliability using variances in the bond-line temperature predictions based on uncertainties in trajectory, aerothermal environment, and material properties. A key deficiency in the current approach is that input uncertainties are too often subjective, empirical, or ad-hoc, and are not rigorously linked to the arc-jet test data used to develop the TPS material model. While materials such as PICA are well understood, future missions may require more novel materials such as HEEET where unknown uncertainties have real consequences on the ability to assess reliability.

A quantifiable estimate of reliability requires an iterative methodology where the parameters driving the variance in bond-line temperature (for example) are systematically identified. A test campaign to collect data or develop new models can then be identified to reduce those input uncertainties. A Bayesian inference loop defines these connections mathematically, i.e., prior knowledge about uncertainty is updated based on observation. While these concepts are well known (and often applied intuitively in a non-rigorous approach), only recent advances in reduced-order modelling have made them computationally viable methods for engineering. By replacing deterministic inverse methods with stochastic approaches, the hope is new materials proposed for future missions can more rapidly be developed with a greater understanding of the TPS material reliability.

Two additional steps for the analysis of arc jet test data are discussed. The first is ability to construct a reduced-order model using material response simulations (Icarus/US3D) of the arc-jet test articles, and the second is the inclusion of this surrogate model in the Bayesian inversion process. Both capabilities will be demonstrated using prior PICA arc-jet test data. The quality of a surrogate model will be investigated and the variances on the calibrated material properties will be compared to our current understanding of the PICA material model.

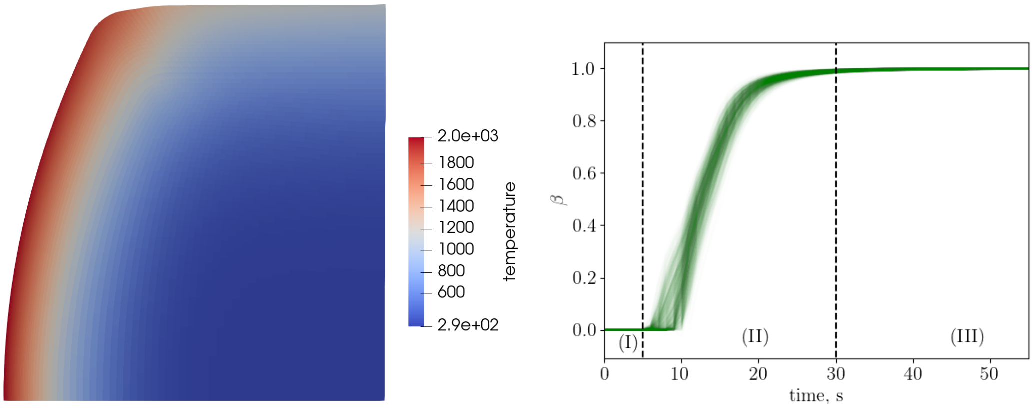

Figure 1: 2D Icarus temperature field for Cases 1 (left) and ensembles of the time evolution of the decomposition parameter as predicted by the surrogate model (right).

Surface Site Density Effects in the Air-Carbon Ablation Model

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Abstract

The Air-Carbon Ablation (ACA) model was developed by Prata et al.[1] to model carbon ablation, but was based on vitreous carbon (VC) experimental data only. Modern ablation materials are more complex, requiring models that are valid for multi-component carbonaceous materials. For example, while the matrix and fibers in Carbon/Carbon (C/C) are both carbonaceous materials, they both have a different reactivity and a different number of active surface sites. This work aims to improve the existing ACA model to account for variations in the number of surface sites as a first-step towards a finite rate model that is valid for arbitrary C/C.

When analyzing the molecular beam (MB) experiments of the oxidation of highly oriented pyrolytic graphite (HOPG) from Murray et al. [2], it is seen that HOPG produces fewer ablation products than VC does. We know that because of its pure, ordered nature, HOPG has fewer active surface sites than VC does. Thus, if we reduce the number of surface sites in ACA, we should expect to see a decrease in CO production. Said another way, we should expect an increase in CO production with an increase in the number of surface sites. However, Figure 1 demonstrates that as we increase the number of surface sites in ACA, there is a decrease in CO production. After rewriting ACA in terms of normalized surface concentrations, it is clear that the Langmuir-Hinshelwood (LH) mechanism in ACA is the cause of this trend. We propose a modification to the LH mechanism in ACA and Marschall and MacLean [3] to have a factor of $\sqrt{B_{ref}^4/B^5}$ instead of $\sqrt{1/B}$ where B is the number of surface sites, and B_{ref} is a constant 1×10^{-5} mol/m^2 (the original value of the number of surface sites in ACA). As shown in Figure 2, the proposed modification gives an increase in the CO production with an increase in the number of surface sites without needing to fully re-fit the ACA reaction rates. This being said, more experimental work needs to be done to solidify these effects and more modeling work needs to be done to fully investigate the relevance of these effects across a wide range of conditions.

Keywords: finite rate modeling, multi-component carbonaceous materials, surface sites, ACA

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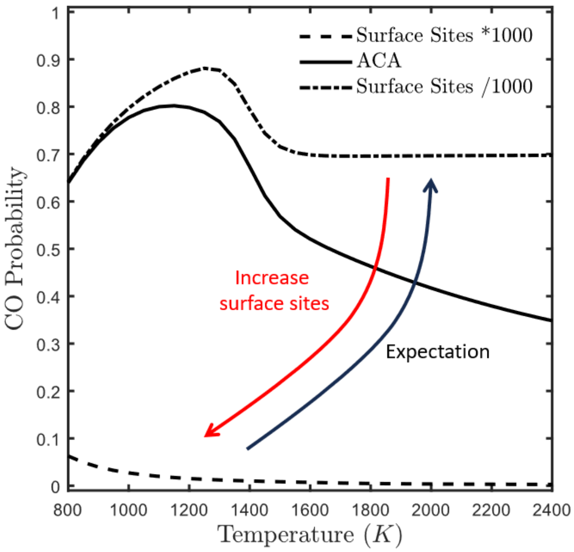

Figure 1: CO probability of the existing ACA model when the surface sites (parameter B) is varied. An increase in the number of surface sites leads to a decrease in the CO probability which is the opposite of what is expected based off molecular beam experiments

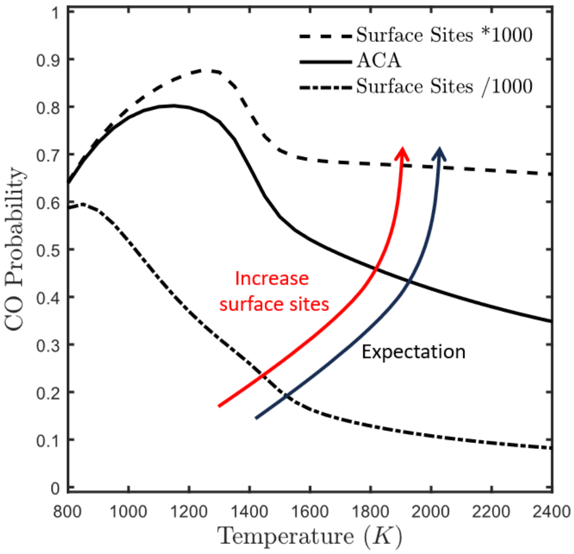

Figure 2: CO probability of the ACA model with a modified Langmuir-Hinshelwood mechanism when the surface sites (parameter B) is varied. An increase in the number of surface sites leads to an increase in the CO probability which is what is expected based off molecular beam experiments

Direct Reconstruction of Ablative Thermal Protection System Aeroheating Using a Green's Function Approach

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Abstract

Reconstructing the heat loads on spacecraft during atmospheric entry is critical to investigate aerothermal phenomena, evaluate the performance of thermal protection systems (TPS), and validate computational models. Current reconstruction approaches rely on the implementation of high-fidelity material response codes in an inverse heat transfer (IHT) formulation to estimate the surface heating conditions from discrete temperature probe measurements. These techniques demand substantial computational resources, however, as they leverage time-marching-based methods and require the whole-domain solution at each time step. In this work, a Green's function approach is used to reconstruct the surface heating conditions on ablative TPS materials from embedded heat flux sensor and temperature probe measurements. The approach models the subsurface temperature time-history at the measurement location as a discrete linear system, allowing for the surface heat flux boundary condition to be recovered directly without the need for time-marching schemes [1]. In the reconstruction algorithm, the effects of material decomposition and pyrolysis gas transport are wrapped into the Green's function formalism using a volumetric energy generation analogue. The performance of the reconstruction approach is analyzed on a 1D computational test case analogous to an atmospheric entry heating scenario with substantial pyrolysis and through-thickness variation in virgin/char composition. Simulated temperature probe measurements are generated via the Porous-material Analysis Toolbox (PATO) [2] using the Theoretical Ablative Composite for Open Testing (TACOT) material database [3]. The reconstruction approach can recover the TPS surface heat flux to within 5% of the input heating condition with a total computation time of 2-3 seconds (over three orders of magnitude faster than current time-marching IHT methods). As a byproduct of the surface heating reconstruction, the algorithm also captures the temperature, material composition, and pyrolysis gas mass flux at multiple through-thickness locations within the TPS, all to within 5% of PATO-generated results. This work demonstrates Green's functions as a more efficient IHT alternative to current methods and more broadly establishes the Green's function methodology as a useful tool for resource-limited analyses such as uncertainty quantification [4] and real-time TPS health monitoring.

This work was supported by a NASA Space Technology Graduate Research Opportunity (grant 80NSSC23K1201).

Keywords: Green's function, inverse heat transfer, thermal measurements, heat flux, material response model, porous material, ablative thermal protection system, pyrolysis

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Plasma testing of woven flexible material for the EARS inflatable heatshield

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Abstract

Inflatable heatshields enable future critical missions to destinations such as Earth, Mars, Venus, and Jupiter. These larger heat shields provide a greater surface area, significantly enhancing the ability to decelerate high-mass entry vehicles by lowering their ballistic coefficients. As a result, the increased drag area allows for reentry missions with heavier payloads while reaching new locations that were previously inaccessible. Conventional rigid TPS exceed their capabilities for such missions, demanding the development of new and more advanced materials. Flexible TPS (FTPS) is one of the key technologies used in inflatable heatshields.

The European Advanced Reusable Satellite (EARS) project, funded under the Horizon Europe program, aims to develop an affordable, flexible and reusable platform for the low-cost SmallSat market, featuring an inflatable heatshield. The FTPS consists of a multilayer structure, including an outer layer exposed to high temperatures, an insulation layer that prevents heat from reaching the internal structure, and a gas barrier to protect the inflatable structure from hot gases. The current material candidates include woven Refrex 1420 for the outer layer and Sigratherm GFA, soft graphite, for the insulative layer.

This study aims to investigate a preliminary approach to employing flexible materials for heatshield applications. These materials must be able to withstand high temperatures, mechanical stress, and pressure during reentry. Therefore, the FTPS stack was exposed to high-enthalpy plasma air in the von Karman Institute for Fluid Dynamics' Plasmatron facility. The tests were conducted at various pressures and heat fluxes. A total of 24 tests were carried out, 12 in the stagnation point configuration and 12 in the flat plate configuration. To investigate a more representative scenario of the heatshield in flight, 6 samples, out of the 12 flat plate samples, included joint seems where the Refrex and/or the GFA were laced together. The flat plate configuration was also tested with different angles of attack.

The materials were evaluated using both intrusive and non-intrusive temperature monitoring techniques. The results showed that the stacking configuration is beneficial and that the Refrex surface remains intact under low heat flux and pressure conditions but loses flexibility when subjected to higher test conditions. Along with the technical knowledge gained from this project, improving the ability to handle flexible systems, specifically at VKI, aids in enhancing the TLR level within the space community.

Keywords: Flexible Thermal Protection System, Plasma Testing, Material Characterization, Material Response

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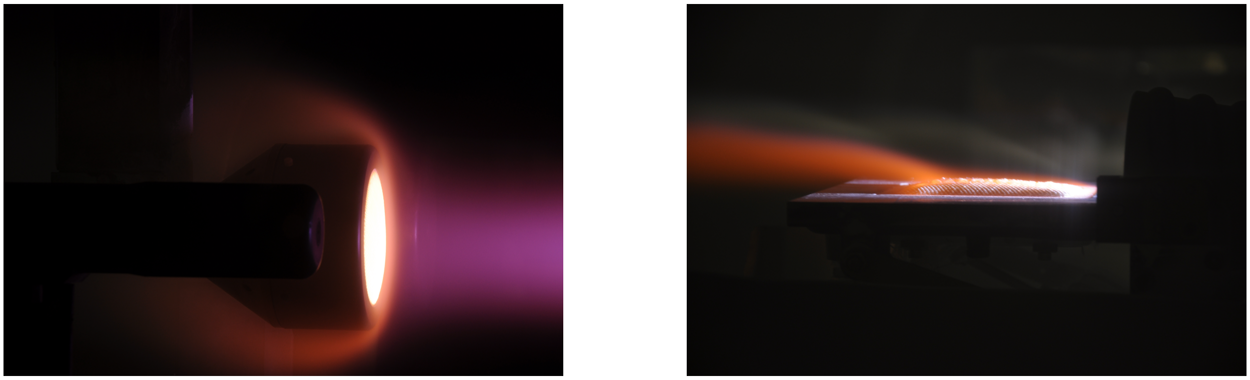

Figure 1: Stagnation (left) and flat plate configuration (right) test of the FTPS stack-up at the VKI Plasmatron facility.

Stagnation line simulations of ablating graphite at 1 atm and comparison to LIF and CARS measurements of species and temperature.

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Abstract

The validation and refinement of surface and gas phase chemistry models for ablative materials requires measurements of species and temperature made in a representative flow environment. In this poster we present comparisons between experimental measurements of multiple species (CO, N, O, CN) and temperature made in the boundary layer of ablating graphite in the atmospheric-pressure UT Austin ICP torch and 1D stagnation line simulations using the von Karman Institute's Stagline solver. Results from two gas surface interaction models, the Park phenomenological and the finite rate Air Carbon Ablation model are shown, while a single gas phase chemistry model, the Olynick air-carbon mechanism, was used for all simulation cases. Good agreement between the predicted and measured thermal boundary layer profiles is seen, however significant discrepancies in chemical species profiles exist.

For both gas surface interaction models considered, the solver overpredicts the production of CO at the wall and higher levels of CO persist through the boundary layer as compared to experiment. Experimentally measured concentrations of atomic oxygen are at super-equilibrium levels in the near wall region, suggesting either that gas phase oxygen recombination rates in the model are too high or that model reaction rates associated with the consumption of CO are too slow. Moreover, computationally profiles of atomic nitrogen are underpredicted with respect to experimental concentrations in the near wall region, again implying modification to the gas phase rates may be required. Finally, qualitative comparison of the CN species distribution shows a shift in the location of peak CN in the boundary layer from computation to experiment.

Keywords: graphite ablation, Stagline, gas phase chemistry, gas surface interaction, phenomenological, finite rate.

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Computational Investigation of Oxidative Etch Pitting in FiberForm and Its Impact on Material Properties

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Abstract

Oxidation-driven carbon erosion does not occur uniformly but rather through the development of localized etch pits at active surface sites [1]. These active sites form due to atomic defects on the carbon surface, making them significantly more reactive than the surrounding, non-defective areas. As a result, these sites are the first to react during ablation, leading to their removal. This process creates new defects in neighboring atoms, increasing their reactivity and causing localized carbon removal around these active sites. In this way, the highly reactive defective areas serve as nucleation points for the formation and growth of etch pits [2], which can have adverse effects on the structural integrity of FiberForm.

To better understand how these etch pits impact the material properties of carbon fiber microstructures, we have developed a new capability within the direct simulation Monte Carlo (DSMC) framework to capture the etch pit formation process. This capability, integrated into the DSMC code SPARTA (Stochastic Parallel Rarefied-gas Time-accurate Analyzer) [3], models material removal in the presence of active sites, leading to the formation of etch pits as shown in Fig.1. The current work focuses on studying the effects of these etch pits on the material properties of FiberForm, a widely used base material in thermal protection systems (TPS). The microstructure of virgin FiberForm, obtained via X-ray microtomography [1], is imported into SPARTA to generate the ablated geometries with etch pits (as illustrated in Fig. 2). These modified microstructures are then analyzed using the Porous Microstructure Analysis (PuMA) software [4] to compute various material properties, including elasticity, thermal conductivity, and permeability.

We investigate the variation of these properties due to the complex surface topology changes caused by etch pit formation. Additionally, we compare the effects of pitting with the conventional model of shrinking fibers, which is traditionally used to simulate the ablation of carbon structures. Significant differences emerge between the two approaches. Consequently, this physically realistic model of material removal through etch pit formation offers improved accuracy in predicting the degradation of carbon-based TPS during oxidation. It also provides insights into other mechanisms, such as spallation, where chunks of material are removed into the flow due to etch pit growth. Ultimately, this model enhances our understanding of failure modes in these materials during ablation.

Keywords: Carbon Ablators, Oxidation, Etch Pitting, Microstructure, PuMA, SPARTA, DSMC.

Acknowledgments

This work was supported by the Entry System Modeling project (J.B. Haskins 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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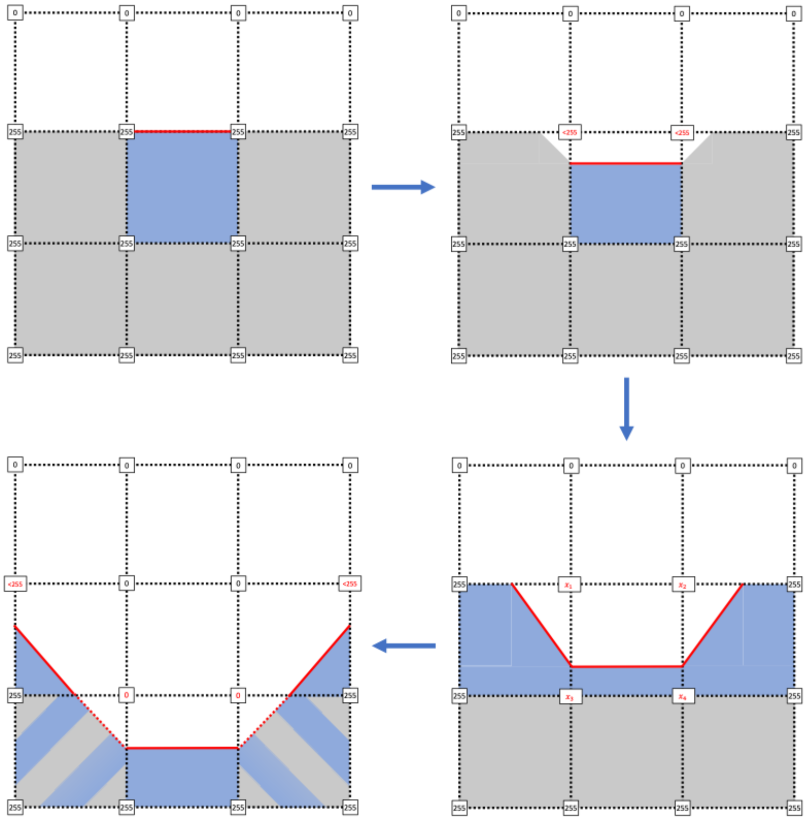

Figure 1: Active-site fraction (ASF) propagation during the ablate step in SPARTA DSMC as solid cell is being consumed in stages.

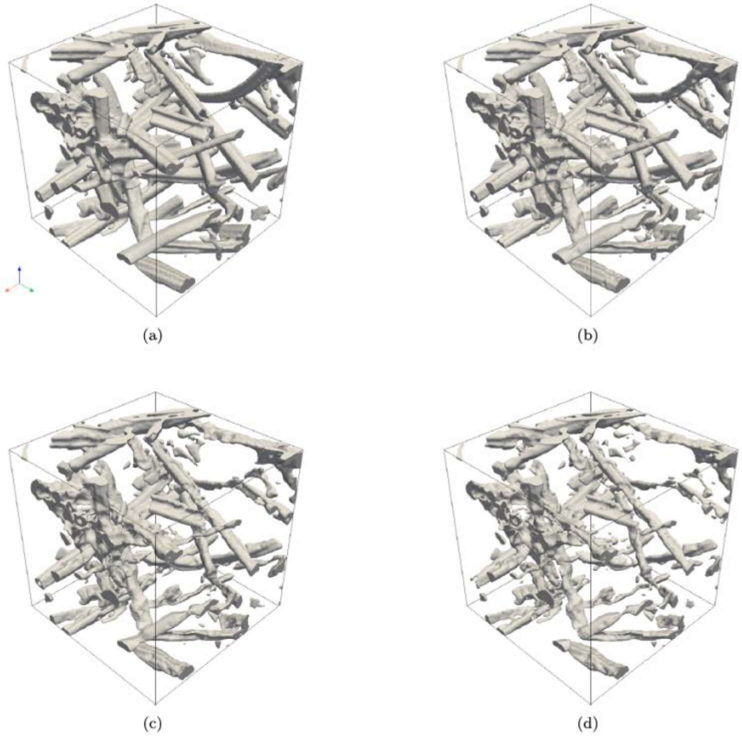

Figure 2: Various snapshots of a FiberForm sample with active sites recessing due to reaction with atomic oxygen obtained from SPARTA and used within PuMA to compute various material properties.

STARscan: Spatial Targeting and Alignment Rig for Scanning

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Abstract

Currently, pre/post-test 3D laser scanning of test samples is a bottleneck in the NASA Ames arcjet testing pipeline. Since it can take up to 15 minutes to scan a single article with a handheld laser scanner and tests have dozens of articles, the scanning process is the single most time-consuming pre-test requirement for principal investigators. Furthermore, a variety of different proprietary softwares are needed to post-process the data for scan alignment, mesh subtraction and analysis, adding additional time and complexity.

The Spatial Targeting and Alignment Rig for Scanning (STARScan) is a 3D photogrammetry system developed in-house at NASA Ames to address this scanning bottleneck and increase 3D scanning efficiency and analysis of arcjet test articles. It addresses key challenges such as scanning speed, scan analysis, alignment of pre- and post-test scans, and secure access to scan data. STARScan reduces the scan time of a single article to under 1 minute, compared to 15 minutes with the current handheld laser scanner, while delivering equivalent accuracy (±0.2-0.5 mm). The system consists of an array of cameras, a simple 3D printed rack, a turntable, and two LED light panels. Most importantly, it features a graphical user interface (GUI) which controls scan hardware and contains various tools for scan visualization, mesh analysis, and data export tools. The analysis tools include measuring the difference between pretest/post-test scans to measure sample ablation, a detailed assessment of surface roughness to quantify changes in texture, and analysis of top surface and shoulder curvature.

This should resolve any bottlenecks in the scanning pipeline by integrating all scanning and post-processing steps into a single efficient scanning station.

Keywords: Recession tracking, photogrammetry, arc jet, 3D reconstruction, open source

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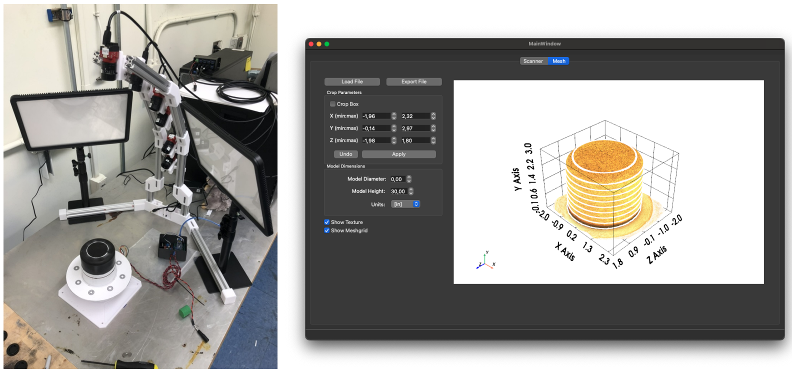

☐ Crop Box
X (min:max) -1,96 2,32
Y (min:max) -0,14 2,97
Z (min:max) -1,98 1,80
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Model Height: 30,00
Units: [in]
☑ Show Texture
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Figure 1: (Left) Image of test rig and (right) graphical user interface

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Transient Pressure-Pulse Decay Method for TPS Permeability Measurements

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Abstract

Predicting the interactions between ablative TPS materials and the outward flow of pyrolysis gasses remains difficult due to their complex microstructure. Permeability measurements give an overall relationship between these materials' resistance to flow, and accurately measuring the value is important to better understand internal pressure and stress during the early stages of pyrolysis. Previously, permeability in TPS materials was calculated by measuring the steady-state mass flow rate and ΔP across a sample at several discrete flow conditions. These discrete measurements can be extremely time consuming; achieving steady flow for low-permeability materials takes multiple hours for each data point with several points required for each sample. Modern TPS materials have even lower permeabilities in the virgin state than legacy materials. We present a transient permeability measurement, similar to some used in petrochemical and mining applications, which allow for much faster characterization of low-permeability materials than methods previously used with TPS materials. This new technique is shown to accurately measure the permeability of several TPS materials where the measured permeability is compared to known values. The test rig is similar to those used by previous, steady flow permeability measurements with two volumes of gas separated by the TPS sample. After an initial pressure pulse on one side of the sample, the upstream and downstream pressures are measured over time. Fig. 1 shows an example of the measured pressures as the two volumes equilibrate through the sample. The decay rate of the pressure difference across the sample is shown to be proportional to the sample permeability multiplied by the Klinkenberg slip factor.

Keywords: Thermal protection systems, Permeability, Pressure Pulse Decay Method, Porous media, Low-permeability

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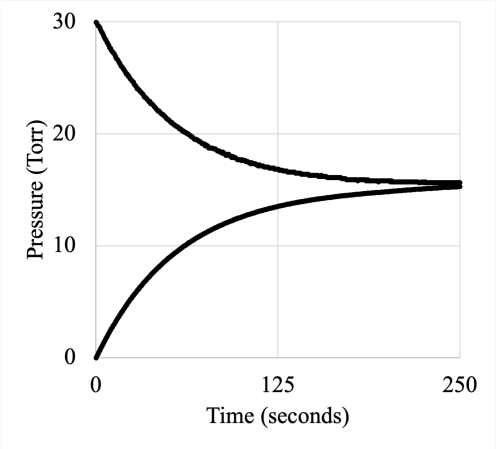

Figure 1: An upstream pressure pulse equilibrating through a TPS sample

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Laser Absorption Spectroscopy Measurements of NO Internal Temperatures and Velocity in a Hypersonic Shock Tunnel and 1D State-Resolved Simulations of Non-Equilibrium Flows

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Abstract

Hypersonic flows produced by reflected shock tunnels are short lived (on the order of 10s of μs to a few ms) and characterized by significant chemical and thermal non-equilibrium. Additionally, the freestream properties of the flow may change during the short operating time. Non-intrusive diagnostics capable of acquiring measurements on short timescales are needed to quantify the freestream flow conditions. This work describes the development and deployment of a laser absorption spectroscopy (LAS) diagnostic for measuring the rotational and vibrational temperatures, partial pressure, and velocity of nitric oxide in the free stream of the Hypersonic Shock Tunnel (HST) located at Sandia National Laboratories. We present 200 kHz measurements for 3 km/s tests and 1 MHz measurements for 4 and 5 km/s tests. The temperature measurements using the LAS velocimetry probe agreed well with measurements taken previously with a larger line of sight. Best practices for hypersonic velocimetry probe designs are also discussed. Predictions from 2D CFD simulations including thermal and chemical finite-rate effects are presented. Also introduced is a multi-species vibronic-state resolved kinetics mechanism. The mechanism is used to run inviscid 1D simulations of the expanding flow in the nozzle using the open-source software Cantera. The 1D simulations can be run on a home computer and can be a useful tool for estimating freestream gas conditions in hypersonic facilities and behind shocks. However, 2D simulations are still highly useful for determining the streamlines of the flows through nozzles, the static pressure, and the thickness of boundary layers.

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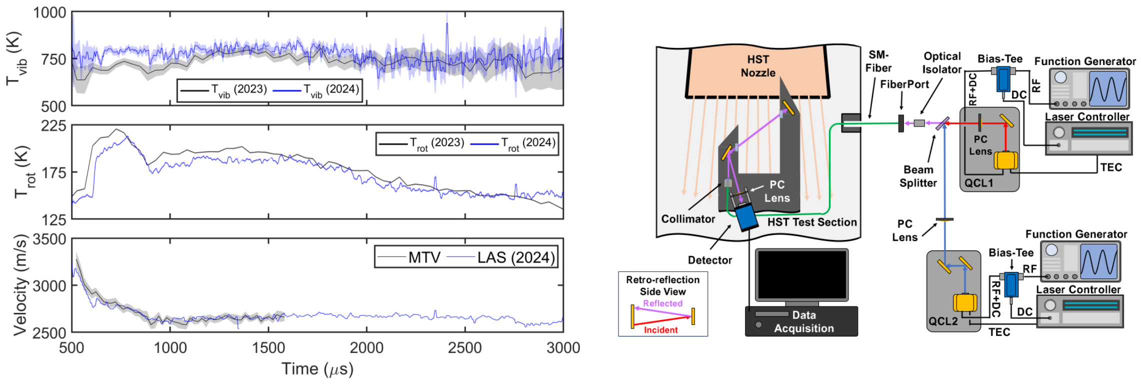

Figure 1: (Left) Time histories of measured vibrational (top) and rotational (bottom) temperatures using the LAS probe deployed in 2023 (black) and more recent velocimetry probe (blue). (Bottom left) LAS velocity results using MTV (black) and recent velocimetry probe (blue). (Right) Schematic of the experimental setup. A cross section of the HST test section with the LAS probe installed is shown on the left. The whole length of the probe is not shown for clarity.

Acknowledgments

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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.

Towards Quantifying and Correlating RTV Intumescence to Entry-Relevant Conditions

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Abstract

Room Temperature Vulcanizing silicone (RTV) is a high-temperature adhesive used as a gap-filler between Thermal Protection System (TPS) tiles for heatshields on numerous missions. It is also adopted to bond instrumentation plugs of temperature and pressure sensors into heatshield's tiles. While RTV has been traditionally assumed to be a non-porous and non-ablating material, numerous experiments have shown that RTV pyrolyzes and becomes highly porous as it is heated. Experimental data has also shown heating rate-dependent swelling (or intumescence) and shrinking of RTV, these volume changes may cause roughness-induced boundary layer transition. Outgassing and surface oxide formation of RTV upon decomposition also occur, which can be sources of contamination of heat shield sensors. This combination of detrimental effects motivates a critical need to develop a high-fidelity model for RTV ablation.

As a first critical step in RTV modeling, a comprehensive material properties database for RTV was collected that account for the lack of data in properties such as pyrolysis char yield, shape change, virgin and char porosity [1, 2]. The next step is to quantify the volume change of RTV as a function of temperature. While this was done in previous campaigns, limited data was collected which showed a possible heating rate dependent intumescent behavior [3, 4].

To further understand the intumescence phenomenon of RTV, numerous dedicated experiments were performed at Beamline 8.3.2 of the Advanced Light Source, where RTV samples were heated while X-ray scans were taken *in situ*. Micro-Computed Tomography scans were taken *in situ* for low heating rates (≤ 60 °C/min), whereas continuous radiography scans were taken for higher heating rates (≤ 1500 ºC/min) [5]. Unconstrained samples and samples constrained in different holders (quartz, graphite, FiberForm and PICA) were tested to determine the change in intumescence due to confinement. Using deep learning techniques, the tomographies and radiographies are segmented to obtain volume change, porosity, pore size distributions and connectivity. From the results obtained, modifications to the previous RTV intumescence model [1] are proposed, along with preliminary comparisons to testing RTV at high-enthalpy facilities [6].

Keywords: RTV, material response, intumescence, in situ MicroCT, TPS

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Preliminary study of implementing surface chemistry model in unified solver

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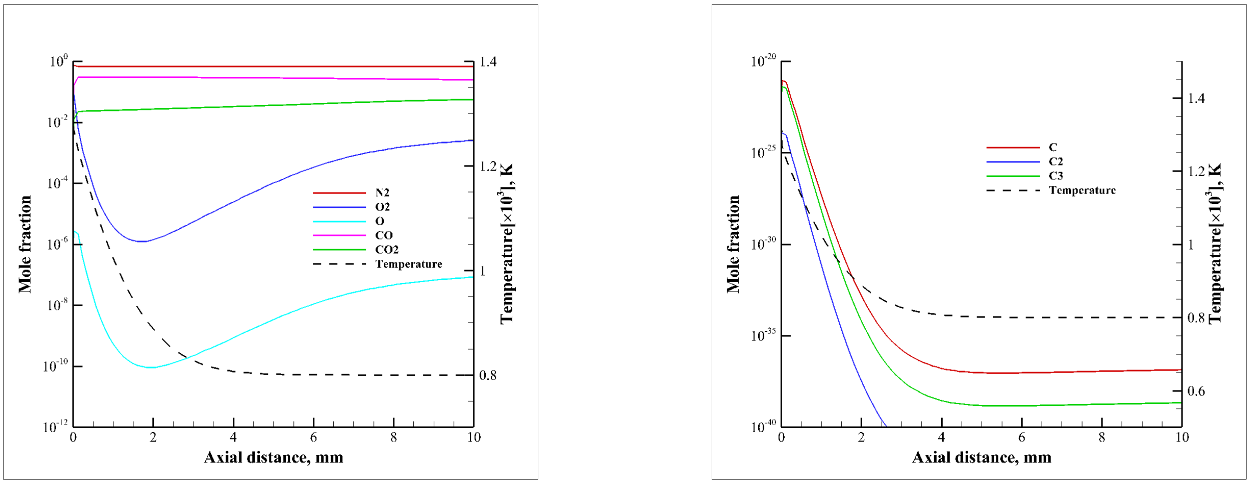
Abstract

Modeling the interaction between the material and gas phase has been the one of the main interests in thermal protection system. The chemical reactions such as oxidation, nitridation, and sublimation at the interface are one of the key phenomenons in the interactions between gas and material. To account oxidation and nitridation, the air-carbon ablation(ACA) model proposed by Prata et al. [1] is implemented. In case of sublimation, the Knudsen-Langmuir formulation for surface evaporation [2] is implemented. In this research, the verification works of ACA model are conducted, and both ACA model and sublimation model on material response are simulated to investigate the surface chemistry. The variations of each gas species and recession of the material are presented.

Keywords: surface chemistry, oxidation, nitridation, sublimation, numerical analysis



(a) ACA model

(b) Sublimation model

Figure 1: Mole fraction profiles.

References

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Permeability distribution function of FiberForm obtained using HERMES

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Abstract

Permeability is an important property of porous heat shields as they dictate the momentum transport of pyrolysis gases ejecting from the material into the flowfield. As part of the ACCESS project, material property distribution functions are being generated to enable stochastic modeling of heat-shield performance. To obtain property distribution functions for permeability, material structures generated from Heterogeneous Effective Representative Multiscale property Extraction Software (HERMES) are used to obtain permeability distribution functions. The direct simulation Monte Carlo (DSMC) solver, Stochastic Parallel Rarefied-gas Time-accurate Analyzer (SPARTA) is used to produce principal permeability distribution functions of FiberForm for all three principal directions. The distribution functions are quantified at scales ranging from a cube of edge length 100 μm to 500 μm, incrementing by 100 μm. To obtain distribution functions, 1000 structures are generated at 100 μm and 200 μm, 500 for 300 μm, 100 for 400 μm, followed by 50 structures at 500 μm. It is observed that the distribution function for permeability converges at 300 μm with a through-thickness permeability mean and standard deviation of $6.63 \cdot 10^{-10}$ and $3.58 \cdot 10^{-10}$, respectively.

Keywords: TPS material, DSMC, HERMES, Permeability

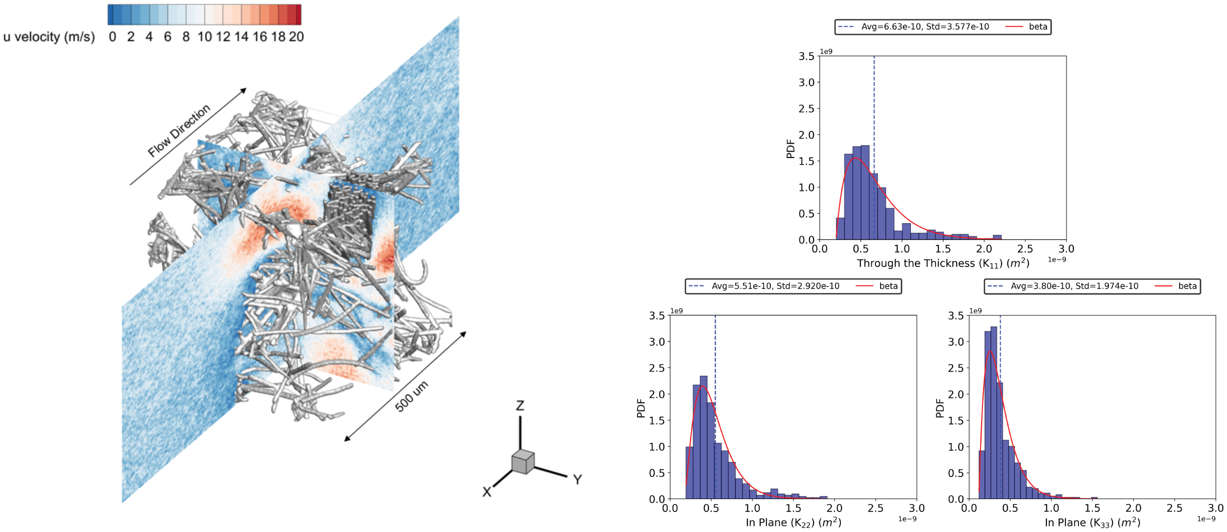

Figure 1: Flowfield visualization of a FiberForm microstructure at 500 μm length scale. Flow simulation is repeated for y and z direction, and the resulting flow properties are analyzed together to compute the principal permeability values (Fig. 1(a)). After the permeability values are computed for all samples, permeability distributions, 300 μm for this case, are generated (Fig. 1(b)).

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Preprint submitted to Proceedings of the 14th Ablation Workshop *October 21, 2024*

Physics-based radiative model and validation with arc-jet experimental campaign

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Abstract

During atmospheric entry, the radiation from shock gases causes in-depth heating and alters the material response of heat shields. Solving radiative transport is computationally prohibitive when considering spectral radiative properties and incoming radiation at each wavelength. A novel radiative model is introduced to offer a reliable and computationally tractable solution for the radiative system. Physics-based radiative relations are obtained by training against various radiative cases simulated by a reverse Monte Carlo ray-tracing (RMCRT) radiative solver [1]. The full-radiative model is divided into three parts. The first part estimates the cooling effect caused by the radiative emission from the medium to the surrounding. The exponential weighted effective temperature (EWET) emission model, published previously, correlates the emission from the medium as a function of its radiative properties and in-depth temperature profile [2]. The second part models the interaction of the medium with the incoming radiative flux from the high-temperature air. This model estimates the radiative exponential decay of the incoming flux caused by radiative absorption and scattering. The exponential decay represents the absorbed radiative energy by each control volume, as shown in Figure 1. The third part models the emission of the medium within itself. The physics-based radiative model will be validated against results from the arc-jet campaign at NASA Langley, which empirically tests the material response of different heat shield samples. The samples are subjected to heat loads from a plasma arc jet and radiative lamps, while the in-depth temperatures will be compared against the model predictions.

Keywords: radiative model, EWET emission model, anisotropic scattering, TPS, RMCRT, radiative transfer equation

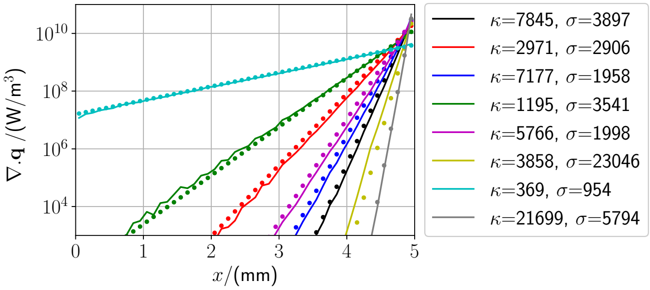

Figure 1: Divergence of heat flux predicted by the exponential model (dot markers) against the RMCRT solution (solid lines) at different absorption (κ) and scattering (σ) coefficients.

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Modelling of NuSil coating using the volume averaging thin-layer approach

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Abstract

Due to the friable nature of PICA, a very thin layer, in order of micrometers, of NuSil coating was applied to the surface of the Mars Science Laboratory (MSL). It was seen that this coating altered the thermal response of the heat shield. The main objective of this study is to capture the behavior of Nusil using a well-known volume-averaging approach without creating extra computational expenses. The Arrhenius rates of NuSil were calculated from the experimental studies of Bessire et al. [1]. Bprime tables were generated with the assumption of no mass loss due to pyrolysis gases. The preliminary results used the RTV properties, but the thermal diffusivity was lowered to simulate the NuSil layer. The applied coating can be seen in Fig. 1(a), and the stagnation point temperature profile in Fig. 1(b). The temperature at the stagnation point is lower than in the pure TACOT case, and the coating removal can be observed. The next step will be to run the ablation workshop case 3.0 with the correct NuSil material properties.

Keywords: In-depth heating, porous ablator, NuSil coating, thin-layer approach

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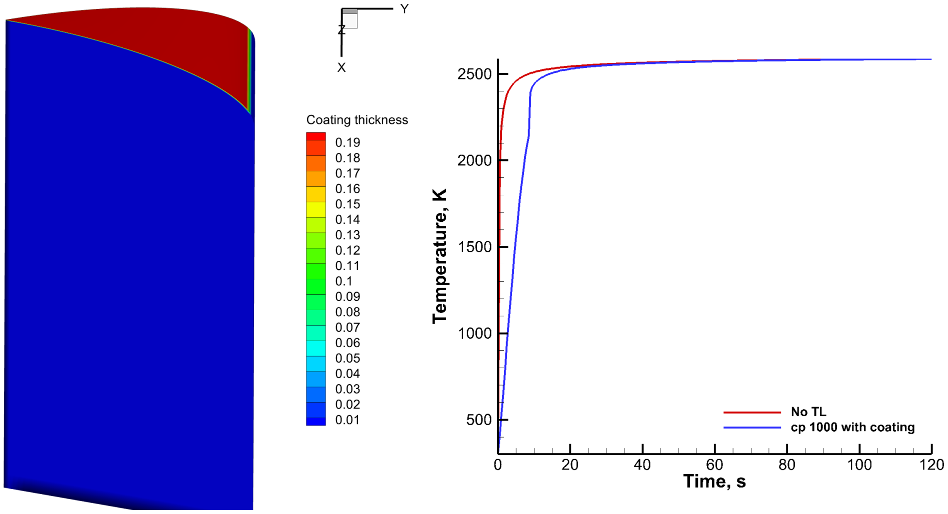

(a) NuSil coating.

(b) Stagnation temperature.

Figure 1: Temperature profile with and without coating.

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Estimation of Muti-Pyrolysis Species' Arrhenius Rate using Curve Fitting Algorithm

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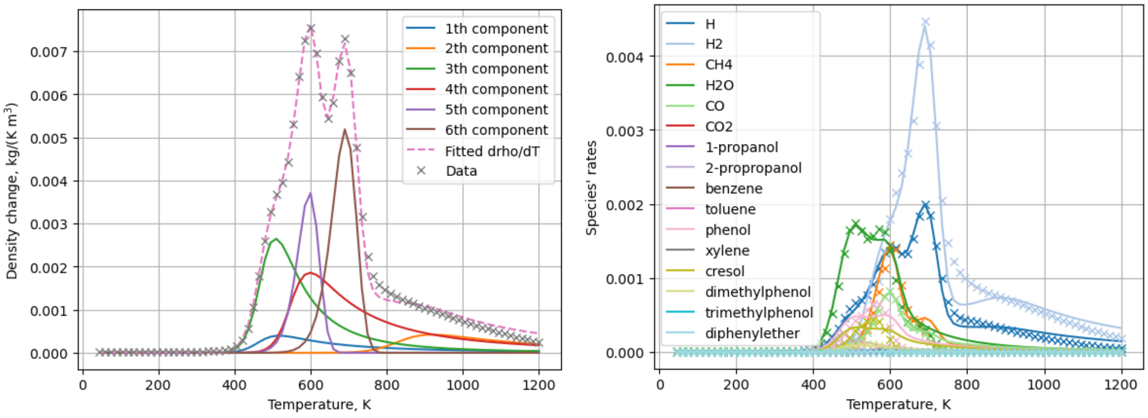
Abstract

Solid decomposition is modeled using a modified Arrhenius rate equation with a given number of equations. Each equation can also be divided into species' reactions. A new solver is constructed to calculate Arhenius rates, and species' molar yield, similar to the work of [1]. The current model uses the least square method to curve fit the thermogravimetric analysis (TGA) curves. Unlike the work of [1], this solver is not coupled with a material response solver to optimize the rates. The solver was tested with the data from [2], and the two have some differences due to the nature of curve fitting. Fig. 1(a) shows the results for reactions and 1(b) shows 14 pyrolysis species' of a phenolic material. These properties will feed into KATS-MR and make it solve multi-pyrolysis gas species.

Keywords: Solid decomposition, Arrhenius rates, multi-species pyrolysis gases



(a) Rates fitting.

(b) Species' fitting.

Figure 1: Results of the curve fitting process.

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An approach to solving enclosure radiation problems in a multi-physics context

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Abstract

Thermal protection system analysis of complex features or damage sites can sometimes require modeling of high temperature enclosures. Implementing efficient and accurate view-factor algorithms required to model such problems is complex [1]. The current work leverages the Non-equilibrium Radiation (NERO) [2, 3, 4] software, which solves the radiation transport equation in a finite-volume scheme, to alleviating challenges often faced with view-factor calculations. By assuming heat transfer occurs only between grey bodies and that the medium is non-participating, computational cost of the method is significantly reduced. The enclosure physics are modeled through emitting and reflecting boundary conditions in NERO. The emitted radiative flux is dependent on the wall temperature which is a solution to the material response, obtained from Icarus [5], in this context. The Ares framework [6, 7] manages the time-advancement and exchange of the necessary data between the solvers. The surface energy balance is modified to account for the enclosure terms within the material response boundary condition. The methodology was verified against analytical solutions including radiating parallel plates, a hollow cylinder (shown in Fig. 1), and a hemisphere. Application of the methodology to inform the design of components of the Dragonfly system will be shown.

Keywords: Enclosure Radiation, material response, multi-physics

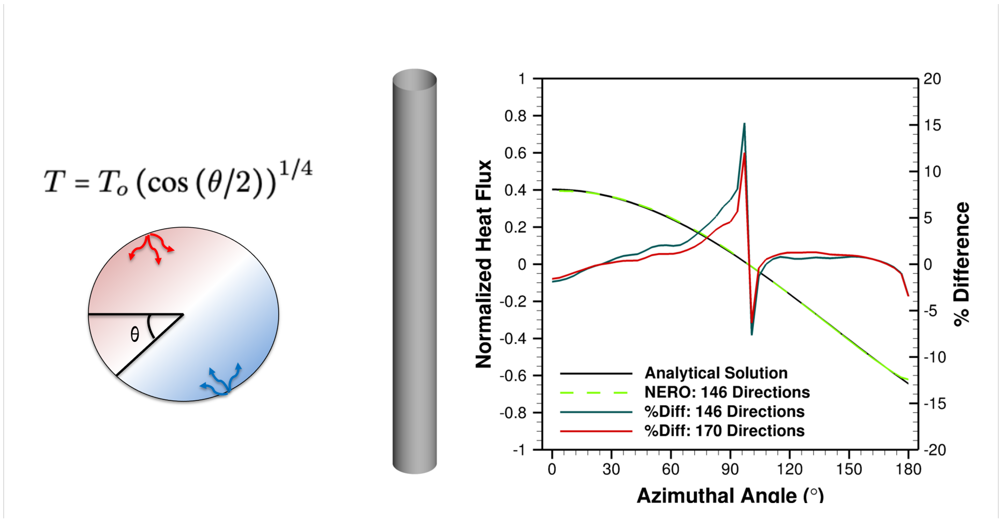

Figure 1: Radiating hollow cylinder analytical solution.

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Generalized Gas-Surface Chemistry and Ablation Modeling in US3D

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Abstract

Recent advances in experimental capabilities and computational chemistry have provided significant insights into the physical processes of gas-surface chemistry at hypersonic conditions. The data from these efforts have been used to develop higher-fidelity surface chemistry and ablation models for use in CFD codes. As these capabilities continue to develop, an easy way of integrating, testing, and evaluating new or improved models is needed. This work demonstrates a generalized framework for finite-rate gas-surface chemistry and ablation modeling in the US3D flow solver [1].

The generalized surface chemistry architecture developed as a US3D plugin by VirtusAero extends the capabilities of US3D to allow for advanced surface chemistry modeling with parameters configured entirely in an input file. Select examples of models integrated into US3D using this plugin are the Air-Carbon Ablation (ACA) model [2] and the Park model [3]. Illustrating the capability to easily test new materials, a recent study also modified the ACA model to investigate the effects of trace ablation products on free electron density and the resulting wake [4]. The generalized framework allows for easily adding or removing reaction mechanisms, tuning existing ablation models, or implementing new gas-surface chemistry models through an external gas-surface chemistry file. Additionally, surface recession can be modeled when coupled with a grid deformation engine. The US3D plugin architecture also allows for coupling this capability with other extensions for high-fidelity multi-physics CFD simulations. Predicting ablation products and conjugate heat transfer over vehicle trajectories, optimizing gas-surface chemistry models to experimental or flight data, or performing uncertainty quantification analysis of ablation models are a few examples of these capabilities.

Keywords: ablation, multi-physics, gas-surface chemistry, CFD

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Updates to PATO's Thermo-Mechanical Model

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Abstract

The solid mechanics module within the Porous material Analysis Toolbox (PATO) material response code [1] was updated to model the stress contribution from both internal pressure and pyrolysis shrinkage as function of material's decomposition. Incorporating these physical phenomena, alongside the previously included temperature dependent mechanical properties, thermal expansion, and aerodynamic loads [2], allows for a more accurate thermo-mechanical behavior modeling of Thermal Protection System (TPS) materials, which is critical to assess spallation risks during atmospheric entry [3]. This poster outlines the workflow for obtaining the necessary PATO inputs, derived from dilatometry experiments, which are used to model the stress field in TPS materials due to thermal expansion and pyrolysis shrinkage. Furthermore, to analyze the relevance of the stress contribution from the internal pressure, a study was conducted using TACOT [4] with different permeability values.

Keywords: TPS, *Stress Analysis*, *Thermo-Mechanical Response*, *Spallation*, *Pyrolysis Shrinkage*, *Thermal Expansion*

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A Mesoscale Toolkit for Quantifying Variability of Material Properties in Thermal Protection Systems

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Abstract

Thermal protection system (TPS) is a critical component of space vehicles, safeguarding them from extreme heat loads during flight. Variability in TPS material properties, caused by morphological differences from manufacturing processes, can impact their performance during hypersonic flight. To quantify this variability, property distribution functions are derived by integrating x-ray computed tomography (XRCT) with a newly developed mesoscale property toolkit called Heterogeneous Effective Representative Multiscale property Extraction Software (HERMES). HERMES efficiently processes hundreds of structures from primary XRCT scans and provides the corresponding geometrical properties of the material. As a demonstration, HERMES is used to generate property distribution functions of FiberForm as seen in Fig. 1. Ten primary volumes of FiberForm, a fibrous carbon-based ablative TPS material, were scanned using XRCT to generate the data for analysis. Each scanned volume length was ~2 mm. The toolkit was designed to extract, clean, and repair these volumes, generating material property statistics. Additionally, a novel algorithm for calculating fiber diameters was developed. The property distribution functions were calculated over a range of extracted cubic volumes. Notably, it was observed that the geometric material properties did not converge to a single value, even when the extracted cubic volume reached the representative elementary volume (REV) of FiberForm. Instead, the properties converged to a distribution function. Property distribution functions for surface area, closed volume, porosity, volume-to-area ratio, as well as the mean and standard deviation of fiber diameters, were fit to various standard statistical distribution functions. These distribution functions provide a more accurate representation of the effective properties of the material, capturing variability that a single bulk value would not capture. The resulting distribution functions can be used to enhance the understanding of material performance and improve the accuracy and reliability of numerical simulations for the design of TPS materials.

Keywords: XRCT, Material statistics analysis, Mesoscale property toolkit, Property distribution functions (PDF)

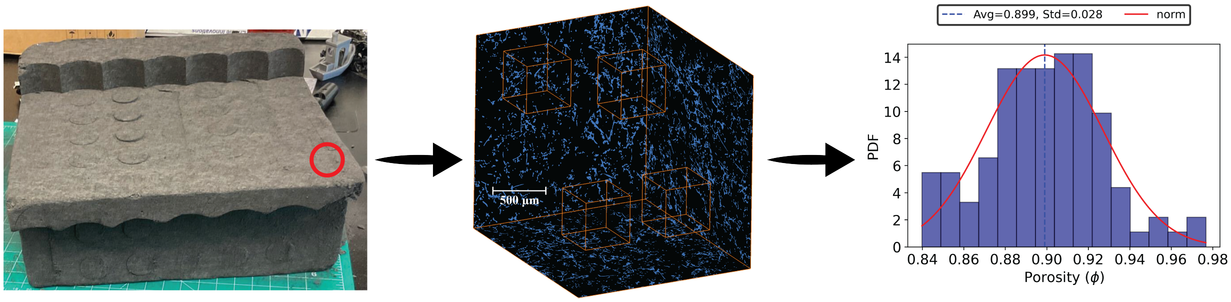

Figure 1: Overall workflow of property distribution generation from raw material to binary TIFF stack and generation of PDF.

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Characterization of volumetric ablation through plasma facility experiments

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Abstract

Volumetric ablation is a process in which material is removed from thermal protection systems (TPS) beneath the surface of the material [1]. A recently revived plasma torch referred to as the High Enthalpy Low-cost Multi-Use Torch (HELMUT) is capable of providing information regarding volumetric ablation, due in particular to the configuration of the upward-facing sample. The observation of a layer of carbon fibers remaining on a FiberForm® sample during early HELMUT experiments demonstrates the existence of volumetric ablation. Thus, a test campaign is underway using the HELMUT plasma facility at the University of Kentucky to quantify this in-depth region. Preferential binder ablation is theorized to produce this layer of detached fibers on the surface of the sample. These weakened fibers could also heavily contribute to spallation, a process in which particles are ejected from the bulk material [2]. These tests aim to measure the thickness, profile, and quantity of the remaining fiber layer after exposure to the plasma torch. This information is predicted to provide insight into the repeatability and extent of the observed volumetric ablation in a plasma environment.

Keywords: Volumetric ablation, spallation, plamsa experiment

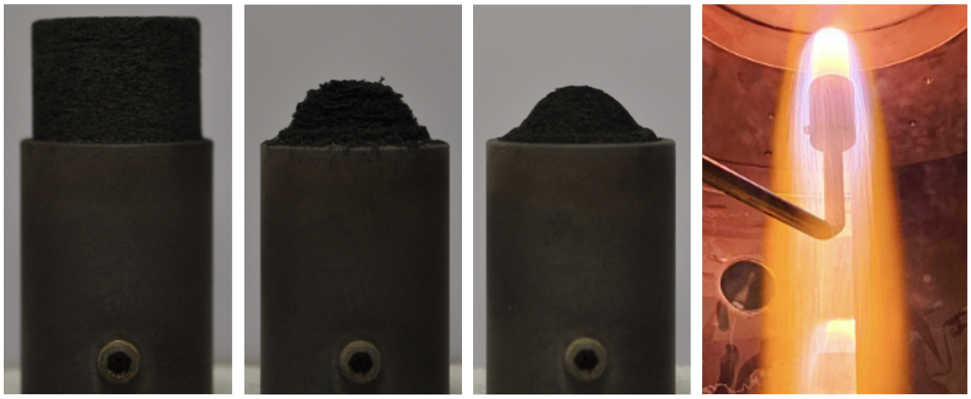

Figure 1: Preliminary results showing a layer of fibers remaining on a FiberForm® sample after plasma exposure, indicating the potential for structural changes beneath the surface during atmospheric entry.

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Numerical reconstruction of spalled particle trajectories in an arc-jet environment: Evaluation of ejection frequency

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Abstract

Spallation, a form of thermo-mechanical ablation, is a mass removal mechanism of the material in the form of particle ejections into the flow field when subjected to intense heat. In order to evaluate the effectiveness of the spallation phenomenon, numerical reconstruction of particle trajectories was performed recently on the spallation experimental data conducted at NASA HyMETS arc-jet facility [1]. Several numerical models were developed, which included a Lagrangian particle trajectory code that accounts for the particle's chemical reactivity, a drag coefficient model, a non-sphericity model, a back-tracking model, and a data-driven adaptation technique that assisted in accurate predictions [2]. The reconstruction results provide the particles' size and ejection parameters for every trajectory. In this work, the reconstruction results are analyzed to evaluate the ejection frequency of the phenomenon. The spallation frequency would assist in further explaining the mechanisms leading to ejections [3, 4].

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

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Comparison of Interaction Potentials for N_2 Recombination During Nitrogen Impingement on Graphene

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Abstract

Understanding gas-surface interactions is essential for thermal protection systems, particularly during spacecraft reentry. Dissociated oxygen and nitrogen atoms from the post-shock flow recombine on surfaces, a process known as catalytic surface recombination [1]. This process involves complex atomic-scale mechanisms such as adsorption, diffusion, and desorption. Given this complexity, making accurate predictions is challenging yet crucial for effective thermal protection systems [2]. To model these complex atomic-scale interactions, advanced computational methods like Molecular Dynamics (MD) simulations with reactive potentials are required [3]. Previous MD studies on carbon surfaces have primarily focused on interactions with oxygen, including adsorption, oxidation, catalysis, and desorption [4, 5, 6, 7, 8]. Despite progress in understanding carbon-oxygen interactions, carbon-nitrogen interactions at the molecular level remain largely unexplored.

This study explores carbon-nitrogen interactions on graphene using MD simulations to understand catalytic recombination mechanisms and reaction products, focusing on the influence of interaction potentials. A classical trajectory approach is applied with the LAMMPS [9] solver to model the interactions between a carbon-based surface and atomic nitrogen. Four interaction potentials are considered: RDX [10], ReaxFF-CHON-2010 [11], ReaxFF-lg [12], and ReaxFF-CHON-2019 [13]. A pristine graphene structure is generated, with nitrogen atoms introduced at 1 ps intervals over a 500 ps period. Six nitrogen incident energies (*i.e.,* 0.1, 1, 2, 5, 8, and 10 eV) are examined, monitoring species formation and surface evolution over time.

Figure 2 presents the N_2 recombination over time for RDX and ReaxFF-CHON-2019 potentials. The RDX potential shows an increase in N_2 production over time at all incident energies, followed by a sharp drop in each case. This drop coincides with surface fragmentation, indicating that the surface facilitates N_2 recombination. ReaxFF-CHON-2019 exhibits steady N_2 production across all incident energies with no surface fragmentation observed. Lower energies (0.1 and 1 eV) result in higher recombination rates, while higher energies lead to surface instability, indicating that catalytic recombination dominates at lower energies.

Our results demonstrate the impact of four interaction potentials—RDX, ReaxFF-CHON-2010, ReaxFF-lg, and ReaxFF-CHON-2019—on modeling carbon-nitrogen interactions during atomic nitrogen impingement on graphene. The rapid surface fragmentation observed in RDX aligns with the potential's role in modeling high-energy reactions involving quick bond breakage. ReaxFF-CHON-2010 struggles with complex gas-surface interactions, while ReaxFF-lg faces short-range interaction issues. ReaxFF-CHON-2019, trained for C-H-O-N systems with nitrogen corrections, shows a clear relationship between energy and N_2 recombination, favoring recombination at lower incident energies. Of all the potentials examined, ReaxFF-CHON-2019 shows the greatest promise in maintaining surface integrity and promoting catalysis; however, experimental validation of adsorption and reaction energies is necessary to confirm these findings. Future efforts will incorporate experimental techniques to gain atomic-level insights and investigate N_2 recombination on complex carbon fiber surfaces, focusing on parameters like surface coverage and temperature.

Keywords: Catalytic Surface Recombination, Interaction Potentials, Molecular Dynamics

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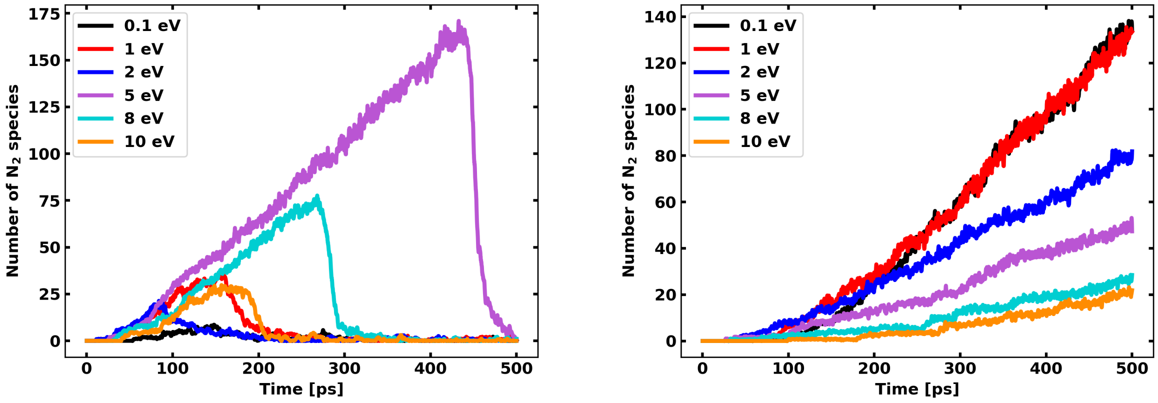

(a) RDX

(b) ReaxFF-CHON-2019

Figure 1: N_2 production on graphene over time

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