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Summary of Dragonfly's Aerothermal Design and DrEAM Instrumentation Suite

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An overview of the Dragonfly aerothermal environments and simulations performed will be presented. Titan's atmosphere predominantly consists of nitrogen (~98% by mole) with small amounts of methane (~2% by mole) and other trace gases. CN is a strong radiator and is found in nonequilibrium concentrations for Titan entry, and is of particular importance on the backshell, where radiation dominates the heat flux.

The presentation will discuss the simulation methodology and assumptions, as well as the margin process in determining the aerothermal environments for Dragonfly's entry at Titan. A relatively new methodology, known as shock tube informed bias, based on experiments performed in the NASA Ames shock tube, EAST, are used for assessing design margins for Dragonfly's radiative heating. Open questions regarding reconstruction of the Dragonfly entry, such as understanding the free-stream methane abundance will be discussed.

NASA Ames and Langley are partnering with DLR to propose a comprehensive instrumentation suite known as the Dragonfly Entry Aerosciences Measurements (DrEAM). Dragonfly will be the first competed mission to fly EDL instrumentation as part of NASA's Engineering Science Investigation (ESI). DrEAM will provide key aerothermodynamic data and performance analysis for Dragonfly's forebody and back-shell Thermal Protection System (TPS), and includes a DLR-provided Data Acquisition System (DAS).

The accurate modeling of nonequilibrium CN radiation has proven to be a difficult task. Prompted by the Huygens mis-sion, many experimental campaigns and analyses were per-formed to better understand the aerothermal environments experienced by the probe during Titan entry [1]. However, the Huygens probe carried no heatshield instrumentation. There-fore, the DrEAM instrumentation suite will significantly ad-vance the state-of-the-art not only by documenting the environment and performance of Dragonfly's entry system but also by making key measurements in Titan's atmosphere for the first time.

Aerodynamic and aerothermal environments and TPS response will be measured using sensors similar to the Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2) Instrumented Sensor Plug (MISP) and the COMbined Aero-thermal and Radiometer Sensor (COMARS) suite [2], with the latter supplied by DLR. For MEDLI2, MISP used em-bedded thermocouples (TCs) to directly measure in-depth temperature of the TPS at several locations, which can also be used to infer surface environments via inverse analysis. For DrEAM, the MISP style plugs will be known as Dragonfly Sensors for Aero-Thermal Reconstruction (DragSTR) plugs. Atmospheric density measurements and capsule aerodynamic data will be obtained through the onboard Inertial Measurement Unit (IMU), supplemented by hypersonic pressure transducers similar to those used by the MEDLI Mars Entry Atmospheric Data System (MEADS). The DrEAM pressure sensors will be known as Dragonfly Atmospheric Flight Transducers (DrAFT) On Schiaparelli, the COMARS suite included three total surface-mounted heat flux sensors, three pressure sensors, and one radiometer. For DrEAM, the CO-MARS package will be known as COmbined Sensor System for Titan Atmosphere (COSSTA).

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2. A. Gülhan. et al. "Aerothermal Measurements from the ExoMars Schiaparelli Capsule Entry," Journal of Spacecraft and Rockets, 2018.

Summary:

Provide an overview of the aerothermal environments used in the Dragonfly design and the entry instrumentation known as, Dragonfly Entry Aerosciences Measurements (DrEAM).

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Prediction of MEDLI2 Radiometer Signal Loss from Ablation Product Thin Film Deposition

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I. Introduction

On February 18, 2021, the Mars 2020 Perseverance rover successfully entered the Martian atmosphere and landed safely on the surface. During entry, the Mars 2020 aeroshell was outfitted with a sensor suite, known as Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2), which measured pressures, in-depth temperatures, and surface heat fluxes at various points on the forebody heatshield and backshell [1]. The integrated sensor plug subsystem included two total heat flux sensors and one radiometer which was used to directly measure the radiative and convective heating on the backshell of the vehicle. The radiometer and one total heat flux sensor were located on the leeside shoulder of the backshell near the predicted peak radiative heating location while the other total heat flux sensor was located at a similar radial location on the windside shoulder of the backshell. A detailed analysis of the measurements recorded by these three sensors are reported by Miller et al. [2].

Prior to flight, an experimental campaign in the NASA Ames Research Center's miniature arc jet (mARC) facility was performed in order to assess the possibility that ablation products from the forebody thermal protection system (TPS), convected downstream to the radiometer location, could deposit on the sapphire window of the radiometer and lead to a loss of the radiation signal [3]. These tests demonstrated signal losses of around 20 %, though questions remained about the applicability of the results to flight. In particular, while the expected heat loads on the forebody and aftbody TPS samples were nearly matched during the tests, the heating profile and length scales were very different from the flight conditions. Moreover, due to limitations on the mARC facility, the composition of the test gas contained significantly more nitrogen than the Martian atmosphere. Subsequent test campaigns performed in the NASA ARC's Panel Test Facility arc jet demonstrated signal losses as high as 76 % [2]. Post-flight analysis of the measured total and radiative heat flux measurements suggest an actual signal loss of around 50 %, assuming the predicted convective and radiative heating rates are correct (total predicted heat flux varied by about 12 % from flight data) [2]. Based on these results, the largest uncertainty in the radiometer measurement is the change in the radiometer window transmissivity due to ablation product deposition, and more work is required to fully understand the flight radiometer measurements.

II. Methodology

In this work, we present a methodology for numerically predicting the MEDLI2 radiometer signal loss due to ablation product deposition, taking into account the actual time and length scales seen during the flight. The overall strategy is based on coupled ablation, radiation, and flow field solutions for the Mars 2020 vehicle over the Best Estimated Trajectory (BET). As a post-processing step, the film growth on the radiometer window is estimated using a detailed surface chemistry model, accounting for the key processes believed to be important for the change in transmissivity of the window. The predicted signal loss is then obtained from predicted irradiance on the vehicle surface at the radiometer location and the computed optical properties of the deposited film.

The coupled ablation, radiation, and flowfield solutions are obtained using the LAURA/HARA code [4], assuming two-temperature thermochemical nonequilibrium with the following 16 species: CO2, CO, N2, C, O, N, CN, O2, C2, C3, C5, H, H2, CH, C2H, and C2H2. The ablation rates are computed using locally 1D in-depth material response solutions based on the methodology of [5] for a PICA TPS, where the elemental composition of PICA is taken to be [C,H,O,N] = [0.403, 0.144, 0.435, 0.018] for the pyrolysis gas and 100 % carbon for the char. Only the forebody surface is modeled with an ablating boundary condition. The backshell is modelled using a fully catalytic wall, which is appropriate for SLA-561V insulation on the backshell.

The simulation framework for ablation product deposition compiled in this work is based on existing vapor deposition models developed for carbon nanotube growth [6, 7], silicon carbide coating [8, 9], petrochemistry [10], and the production of thin solid films for electronic devices [11, 12]. These diverse applications consider essentially the same fundamental process, although each with different chemical species. The model utilizes a detailed surface chemistry mechanism which describes the transition from ablation products in the gas phase to adsorbed surface species, and then the deposition of these surface species to the solid film. The total number of available surface sites is modeled as a conserved, material-dependent value, taken to be 1 × 10−9 mol/cm2 for the sapphire window as suggested by Zhluktov and Abe [13]. The surface site compositions are determined using a steady-state approach which allows for the determination of the deposition rate for the bulk phases.

Using the detailed surface chemistry model, the film deposition rates are integrated over the BET to yield an average film composition and thickness. The transmissivity of the film is then determined at each time point through exponentiation of the negative product of the film thickness, density, and absorption cross-section. Where possible, the spectral absorption cross-sections for each bulk phase are taken from relevant literature sources. For the dominant contribution of OH(b), we have utilized the cross-sections from Goullet et al. [14]. Once determined, the film transmissivity is then coupled with the measured transmissivity of the pristine window and the predicted incoming irradiance and integrated over the spectral range of the radiometer to determine the signal loss. The presentation will provide comparisons between this predicted signal loss with the rebuilt flight data and discuss how further improvements to the modeling framework could reduce uncertainties of future radiometer signal loss predictions.

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Summary:

We present a numerical methodology for predicting the MEDLI2 radiometer signal loss due to ablation product deposition on the radiometer window. The model uses a finite-rate gas surface interaction mechanism to predict the deposition rate of ablation products, coupled with an optical model of the resulting film to determine the spectral transmissivity of the radiometer window, contaminated with the ablation products, over the best estimated trajectory of the Mars 2020 atmospheric entry.

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Fast-response measurements of shock layer radiation in the High Enthalpy Shock Tunnel Göttingen (HEG)

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Background of the study

The development of reentry aerodynamic configurations requires examination of surface heat flux. Reentry-relevant freestream conditions are suitably generated by shock tunnels such as the High Enthalpy Shock Tunnel G{\"o}ttingen (HEG). Surface heating due to radiation at high-enthalpy stagnation conditions has been shown to comprise a significant portion of the total measured surface heat flux on reentry configurations [1,2]. Earlier studies of surface heat flux at or near the stagnation region on blunt sphere-cones [3] and capsules [4] indicated substantial underprediction of surface heating by numerical calculations compared with what was measured in experiments. The conclusion of recent tests in the HIEST at JAXA was that this extra heating component measured in shock tunnel experiments was due to radiation within the shock layer [1]. \\\\

Previous observations made at the HEG of stagnation point flows have demonstrated fluctuations within the radiating shock layer. The objective of the current experiments is to probe the shock layer and thereby investigate the fluctuations of radiation heat flux within the shock layer. This will be combined with synchronised imaging of the shock front to correlate fluctuations of the shock front geometry with fluctuations in measured heat flux due to shock layer radiation.

Methodology

The HEG will be used to generate reservoir stagnation pressures of approximately 44~MPa and stagnation enthalpies of up to 12 MJ/kg. A flat-faced cylindrical probe has been designed to generate a bow shock layer upstream of the model face. The probe houses an array of surface-mounted sensors including a radiative heat flux sensor, pressure sensors, temperature sensors, and fibre optic components for measurements within the shock layer.\\\\

Preliminary studies and in-situ calibration of the radiative heat flux sensor with a measurement frequency range on the order of 1 MHz will be described. This sensor will thereby enable fast-response measurement of radiation heat flux fluctuations within the shock layer, for a given transmission wavelength band. This will be complemented by fast-response pressure measurements in the stagnation region. Furthermore, installation points for fibre optic cables are available which enables calibrated in-situ emission spectroscopy measurements for further insight into shock-layer radiation and comparisons with similar measurements of the freestream flow. \\\\

Optical diagnostics include high-speed schlieren for imaging the shock front and assessing fluctuations within the shock layer.

Results

Preliminary results of the measurement campaign will be presented. The focus will be on the time-resolved measurement of radiation heat flux within a specific transmission wavelength band. The use of the radiation heat flux sensor for shock layer heat flux fluctuations in the $\mathcal{O}(MHz)$ frequency range will be additionally demonstrated. The synchronisation of these measurements with high-speed schlieren images of the shock front will be elaborated.

Conclusion

The full presentation will discuss the applicability of the above-mentioned methods to the development of fast-response measurements of radiation heat flux within the shock layer.

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Summary:

The experimental setup for fast-response shock layer radiation measuements in a shock tunnel will be discussed.

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MARS 2020 BACKSHELL RADIATIVE HEATING MEASUREMENT AND SHOCK TUBE VERIFICATION

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In February 2021, the Perseverance rover was brought to the surface of Mars by the Mars 2020 mission. A feature of the Mars 2020 capsule was instrumentation to measure its entry, descent and landing (EDL) with the so-called Mars EDL Instrumentation 2 (MEDLI2) [1]. The MEDLI2 introduced, among other things, backshell instrumentation, including a broadband radiometer. The radiometer was mounted on the leeside of the vehicle next to thermocouple plugs and a heat flux gauge. The data returned by the leeside MEDLI2 heat flux gauge is largely analogous to that measured by the COMARS gauge flown on the ExoMars Schiaparelli [2] entry in that it is measuring heat flux in an area that is entirely dominated by radiative heating. The COMARS measurement provided excellent validation of backshell radiative heating models for Mars entry, albeit at a limited number of points [3]. The MEDLI2 heat flux gauge measurement effectively confirmed the quality of the prediction, extended over the full trajectory, as will be presented in this paper. The MEDLI2 radiometer,however, was blocked by ablation products and suffered a loss of half of its signal. The second backshell heat flux gauge installed on the windside of the vehicle was also well predicted, although the heating had both radiative and convective contributions.

It was desired to reproduce the conditions of the Mars 2020 entry via ground testing in the Electric Arc Shock Tube (EAST) at NASA Ames. Tests to verify stagnation line heating were previously reported in EAST, confirming the presence of shock layer radiation as the major discrepancy in heatshield temperature modelling [4]. Therefore, tests for stagnation line heating were not repeated. Instead, the shock tube informed bias method [5, 6] was used to identify test conditions that may produce similarity to streamlines that pass around the backside of the vehicle and are responsible for the radiation observed at the two heat flux gauge locations. This method was used to identify a range of velocities and densities in the shock tube that are relevant for confirming the radiative environment encountered.

This paper reports the results obtained in the 10 cm diameter EAST shock tube, corresponding to later trajectory points at ambient pressures of 1.1-2.0 Torr and velocities from 1.2-3.5 km/s. The test series employed two primary diagnostics: emission spectroscopy and tunable diode laser absorption spectroscopy (TDLAS). The emission spectroscopy performed broadband measurements of the radiative emission of the 4.3 and 2.7 μm bands of CO2 at flight similar conditions, obtaining both spectral and spatial data corresponding to the relaxation behind the shock front. The TDLAS measured the absorption of several lines of CO and CO2 and obtains species number densities and temperatures as a function of time behind the shock front. This paper will review highlights of this test series and analyses of the emission and absorption data. While the datasets generally show good agreement with predictions, a few discrepancies and items for additional investigation are identified and will be discussed.

Summary:

Report on flight heating data obtained for Mars entry and subsequent similarity condition testing in the EAST facility.

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Mars Sample Return Flow Condition Design and Pitot Rake Testing in T6 Stalker Tunnel

Auteurs: Eric Won Keun Chang[1]; Tobias Hermann[1]; Matthew McGilvray[1]; Chris James[2]

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Please find the abstract attached.

Summary:

This work outlines a design process of high-speed and high-density expansion tube flow conditions for future Mars Sample Return missions. The expansion tube must attain 10 km/s or above shock velocity through denser gas fills in shock/expansion tubes to produce higher freestream density for the subscale test models. An experimental investigation was carried out in the T6 Stalker Tunnel at the University of Oxford to examine the feasibility of generating such conditions. The experiments showed that these conditions obtained desired flow velocity and steady test-time.

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Extension of PARADE with MgO molecule (B-X and B-A systems)

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The recording of meteor spectra allows a better understanding of meteoric composition and in doing so, also the composition of the parent body [1-2]. The composition of a meteoroid is measured by analyzing the measured radiating species with a simulation software for emission spectra. One software is PARADE (Plasma Radiation Database), a line-by-line emission calculation tool [3]. This software was originally developed for the analysis of re-entry radiation of spacecraft. Recently, atoms and molecules (Na, K, Ti, V, Cr, Mn, Fe, Ca, Ni, Co, Mg, Si, Li, AlO, TiO) commonly found in meteor spectra have been added to PARADE [4], therefore enabling a more precise assessment of the observed spectra. Molecules such as MgO, also observed in the radiative cloud of meteor [5], are still missing in the database. This work presents the extension of PARADE with the MgO molecule.

The PARADE data base is extended by the electronical, vibrational and rotational energy levels of MgO (X1Σ+, A1Π, B1Σ+) [6-10] and the transitions between them (B1Σ+⟶X1Σ+ and B1Σ+⟶A1Π) [11-14]. Moreover, the Franck-Condon factor, r-centroids and complete transition moments of the two transitions were interpolated and extrapolated to fill in a comprehensive MgO data file. The spectra computation is operated by the PARADE software for given plasma temperatures and yields the emission coefficient of the molecule [3-4]. Preliminary experiments have been conducted to validate the emission spectra of MgO, and further experiments are planned to improve the recorded spectra by optimizing the conditions used in the plasma wind tunnel facility.

The final paper will present the computed spectra of MgO from PARADE, the comparison to experimental data and a discussion on the improvement possibilities.

Summary:

The final paper will present the computed spectra of MgO from PARADE, the comparison to experimental data and a discussion on the improvement possibilities.

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CFD/Radiation analysis of the Chelyabinsk and St Valentine meteoroids

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This contribution focuses on the numerical analysis of large meteoroids during their entry into Earth atmosphere. After a survey of the available flight data, two entries of meteoroids have been reconstructed: the Chelyabinsk event that occurred in 2013, and a meteor, which felt in the Atlantic Ocean in February 2016, the Saint-Valentine day. For both meteoroids, the most likely trajectories have been computed with a three-degree-of-freedom trajectory tool. Computations have been then performed using a non-equilibrium Navier-Stokes solver at specific points of the trajectories to determine the temperatures and the composition of the mixture around the meteoroids, as well as the surface heat-flux. The flow-field distributions of Mach number predicted at 31 km of altitude for the St Valentine meteoroid is shown in Figure 1 (Left), while the corresponding VUV spectrum is shown in the right part.

Fig. 1: Left: Mach number distribution at 31 km of altitude for the St Valentine meteoroid; Right: Corresponding VUV spectrum
Then, the SPARK line-by-line radiation code has been selected to post-process the CFD results for predicting the radiative heating. It has to be noted that SPARK capabilities have been extended via an updated database capable of reproducing VUV molecular radiation. The spectra obtained for the St Valentine meteoroid at 80 and 31 km of altitude, highlight the strong contribution of molecular VUV radiation at high altitude as shown in Table 1. Then, comparisons have been carried out between the radiative heating calculated using engineering correlations and the CFD/radiation computations at the different altitudes. The comparison put in evidence the lack of reliability of usual stagnation point correlations particularly at low altitude and high level of stagnation pressure.

Table 1: Part of VUV contribution as function as altitude for St Valentine meteoroid
Finally, the last part of this work focuses on the meteoroid demise. Firstly, a qualitative analysis of the thermal response of the meteoroid accounting for the available element on material opacity for the incoming radiation wavelength range has been conducted, in a second step the radiative and convective blockages have been estimated. The final point is to propose a scenario corresponding to the meteoroid demise and supported by the outcome of this work.

Summary:

This contribution focuses on the numerical analysis of large meteoroids during their entry into Earth atmosphere.

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CHARACTERISATION OF A SPATIALLY RESOLVED VUV SPECTROSCOPY SYSTEM FOR SHOCK TUBE FLOWS

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Please see attached PDF.

Kind regards,

Maïlys

Summary:

The T6 Stalker Tunnel shock tube was previously used to perform emission spectroscopy in the wavelength regime of 350-850 nm to measure radiation in the shock layer. A VUV emission spectroscopic system is currently under development to use on T6 in its steel shock tube mode, with the goal to perform spectroscopy for shots in the speed range 10-15 km.s−1 and for various gas densities. This system was designed to offer fast turn-around, easy calibration and ensure repeatability between experiments. It comprises a telecentric optical system developed using an optimisation approach, and ray tracing simulations were run to observe, quantify and correct optical aberrations.

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Measurement of Aeroheating of Satellite Components at True Flight Total Enthalpies

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At end-of-life, satellites must be de-orbited to comply with guidelines laid out by the Inter-Agency Space Debris Coordination Committee (IADC). Disposal by direct re-entry into Earth's atmosphere is preferred. The IADC guidelines also state that undue ground risk to people and property must be avoided, and environmental pollution should be minimised. These guidelines are intended to prevent over-crowding of the LEO region, which has accumulated a significant amount of orbital debris since the advent of the space age. Aerothermal heating during re-entry causes satellites to burn up in the Earth's atmosphere. Occasionally, re-entering bodies fail to burn up completely leading to Earth impact events. One such event occurred in 2001, when a 70 kg tank from a Payload Assist Module - Delta (PAM-D) rocket stage crashed into the Saudi Arabian desert.

Computational models have been developed by space agencies and private corporations to predict re-entry trajectories. Accurate prediction of aerothermal heating in the rarefied slip-transition regime is difficult, particularly when coupled to the high temperature gas effects generated by entry speeds over 6 km/s. There is also a distinct lack of experimental data to verify and improve these models. Most of the re-entry literature focuses on aerodynamically optimal geometries at low total enthalpies and continuum. Very few studies have gathered data at conditions where density and enthalpy are matched to flight.

This paper describes heat transfer experiments in the Oxford T6 Stalker Tunnel, configured in expansion tunnel mode. A new rarefied flow condition was commissioned with a freestream Knudsen number of 0.011. Flow enthalpies in the range 19-22 MJ/kg were achieved, corresponding to flight velocities of 6100-6500 m/s. Post-shock conditions were matched to those expected at altitudes in the range 81-90 km. Scaled flat-faced cylindrical models with a diameter of 10 mm were used to represent satellite tanks. The Macor models were instrumented with platinum thin film heat transfer gauges and coated in a thin silicon dioxide film to insulate them from electrons in the ionised flow. A novel mounting method was developed using a ring to allow mounting of up to 12 models at the same radius in the nozzle, avoiding particulate damage caused in the operation of the expansion tunnel. This ring also allows for variation of angle of attack of the model set, as well as the flexibility to mount models in different orientations. Heat flux measurements are compared to those numerically predicted using the Eilmer 4.0 solver.

The test bed described in this work provides a novel capability in Europe to provide further validation data for satellite demise.

Summary:

This work was undertaken by the main author during a Master's project. The co-authors, all based at the Oxford Thermofluids Institute, provided guidance and assistance throughout the project. The main author is returning to the Oxford Thermofluids Institute after graduation to pursue research into aero-heating of satellite components during re-entry. More experiments using the test bed developed in this study will be conducted to provide a reference dataset for aerothermal modelling.

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NEW FEATURES OF THE NEQAIR RADIATION CODE

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The longest-lived code for predicting shock layer radiation, NEQAIR, is now in its 5th decade of service. Substantial changes to the code have been made over the previous decade, the most recent report of which was at the 5th Workshop on Radiation in High Temperature Gases in 2014, for the version referred to as NEQAIR14. This paper will review some of the improvements made to the NEQAIR code since then, which is now at v15.2. Some of these features are discussed briefly below.

NEQAIR15 and subsequent versions have enabled parallel evaluation of multiple lines of sight. This is accomplished by utilizing the HDF5 file format and placing multiple lines into a single file, LOS.h5, which is used for both input and output. This approach enables straightforward parallel execution both over the number of lines of sight and the number of points per line. For large problems, run-time reduces linearly with the number of nodes deployed since each line is processed independently by a subset of MPI ranks.

Three applications of the multi-line solver are discussed. The first has to do with performing loosely coupled radiation-flowfield solutions. In this case the computed absorption and emission coefficients are used to evaluate the total energy absorbed or emitted at each point, allowing evaluation of the volumetric source term in the flowfield. The second computation is for obtaining heat flux from non-uniform flows, which require integration over spherical co-ordinates. These are of particular interest for evaluating radiation on the vehicle backshell. This 3D option improves the angular integration scheme and allows adaptive line selection that together reduce the number of lines required by about an order of magnitude. The final application is for remote observation, which is essentially the 3D integration problem over a small solid angle. For all three of these computations, data can be stored in the HDF5 file which allows a NEQAIR run to be restarted when it times out, or to add atmospheric absorption or instrument scan functions.

An additional level of parallelism is enabled in NEQAIR15.2 using GPU routines. The GPU parallelism has realized up to 8x speed-up when running on a single core but diminishes as CPU parallelism is increased. For running multi-line simulations, it may be easier to reserve a large number of CPU nodes than to obtain the number of GPU nodes required for similar performance.

A GUI, known as NEQTPY, allows for reading and creating input files, running NEQAIR, and displaying results. A significant feature of NEQTPY is the ability to perform spectral fits to data. The fits can operate on a single line spectrum (radiance vs. wavelength) or a 3D input file with multiple columns of data.

Other new features include improved constants, additional species, more detailed non-Boltzmann modelling, advanced user controls, the ability to read and calculate spectra from HITRAN datafiles, photodissociation and photoionization cross-sections. A "fast" automatic grid option may reduce the size and time of spectral calculations while still maintaining good accuracy for total heat flux.

Summary:

Summary of updates to NEQAIR code since last report at 2014 workshop

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Plasma Ball Formation: an experimental technique to test radiative models in non-equilibrium plasmas

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Background
In hypersonic flights, the energy transfer between the atmosphere and the vehicle depends greatly on gas kinetics, in particular on nonequilibrium vibrational kinetics as well as on dissociation and recombination processes which are similar in many aspects to those met in electric discharges in gases [1]. As mentioned in [1], "the main difference is that in the latter case the vibrational quanta are primarily pumped by electrons while during reentry they are pumped by recombination processes…" This difference may however be suppressed in our setup, thanks to the plasma ball formation (PBF), an acoustic plasma confinement mode we have recently discovered during the development of a pulsed sulfur plasma lamp [2], also observed by a team at UCLA [3]. Indeed, the molecular dissociation is then governed by the pure vibrational mechanisms [2], i.e. by the collisions between vibrationally excited molecules, rather than by electron impacts [4], p. 228. Another similarity between hypersonic plasmas and the sulfur plasma in our device is the radiative energy transfer that arises from the relaxation of excited electronic states of molecules formed in recombination processes, resulting in optical emission spectrum (OES) that does not follow the Planck's law. Moreover, in our device the chemistry is dominated by two-atom dissociation-recombination processes (S2), as in a hypersonic plasma of Earth's atmosphere (N2, O2). In both cases, the chemical kinetics are determined by the excitation-relaxation of vibrational states.
The objective here is to study the non-equilibrium vibrational aspects involved in PBF. This phenomenon is obtained by pulsing the input microwave power with a short duty cycle, at a repetition rate of the order of 30 kHz, providing spherically symmetric compression-expansion cycles for the plasma. During PBF, the plasma is confined at the center of the spherical bulb, extending to half radius. From the measurements of the acoustic resonance frequency, the average sound velocity as well as the average pressure and temperature inside the bulb were found to be 0.60 km/s, 0.52 MPa and 2.2 kK, thanks to a one-node-lumped model [2]. The acoustic waves are necessary for the PBF to take place. However, the exact force balance during the confinement is not yet completely understood, a crucial question this study opens a way to answer by analyzing digital photographs as well as OES. The final goal of this project is to provide physics basis for the design of an experimental device to ease the costly calculations [5, 6] required to simulate atmospheric reentry in hypersonic shockwave conditions. For instance, the bulk viscosity is still a topic of investigation as this property of nonequilibrium gases is extremely difficult to measure [7] and is therefore often neglected, as in [8] for instance. Yet, it introduces a dispersion effect resulting from velocity divergence and in hypersonic reentry it can have an influence on the shock wave structure [9, 10]. This paper shows there are reasons to think that the bulk viscosity plays an important role in the PBF. Moreover, the possibility of it becoming negative does not seem to be considered in the western aerospace community as we only found publications from Russia mentioning "Negative bulk viscosity" in a literature study. Evidence for this sign change, however, could be obtained from the amplification of sound waves that occurs during PBF, as shown in this publication.
Methodology
In this work, we concentrate in two experimental observations of the PBF as follows:
1) Shape analysis for understanding the convective cells and heat transfer inside the bulb.
Digital photographs have been analyzed in order to reveal the exact shape of the plasma ball. The camera was a Panasonic DMC-FZ8 placed behind a green solder filter. The contrast between the plasma ball and the background was increased by digital treatment. The plasma ellipticity was determined by manually fitting an ellipsoid in the high contrast image.
2) Spectral analysis for estimating the vibrational temperature of the S2 molecules.

The OES, emanating from the plasma, was recorded with a CAS 140CT array spectrometer in the wavelength range of 300−1100 nm. The average photon energy was integrated from the spectra. This value was then used as the LHS of the equation (9) of [11] in order to find the corresponding values of the vibrational quantum numbers and the energies of the excited and ground electronic states of the S2 plasma molecules, taking into account their anharmonicity. From the Frank-Condon factors given in [11], the most and second most likely transitions were associated with the peaks in the OES for a discussion of vibrational pumping [12, 13] and its role in the PBF phenomenon. Particular attention is paid to the effect on sound velocity in view of the application to modeling hypersonic plasmas.

Results

The plasma ellipticity was found to be close to one. No expected concavity was observed at the bottom of the ball, due to possible inward mass flow from the peripheral zone to the plasma, like seen in flames. A dissipative structure composed of two convective cells could explain this unexpected observation, as we show in this publication. A non-equilibrium thermodynamic modeling is proposed for the interpretation of this dissipative structure, based on the vibrational excitation gap between the plasma and the surrounding gas. Our analysis of the OES shows that the S2 ground state mean vibrational energy, for a plasma in the spherical mode (PBF), is 1.97 eV, whereas it is at 1.81 eV in the case no PBF, consistent with the observed redshift of the emission peak. This result, the increase of the sum of vibrational quanta in the plasma, suggests that the PBF enhances the vibrational pumping mechanism. The cause of this effect could be related to the sound dissipation due to the bulk viscosity.

Conclusion

This additional vibrational pumping could explain the observed features according to the presented non-equilibrium thermodynamic model. Complementary experimental investigations should make it possible to measure the bulk viscosity. The plasma translational and vibrational temperatures are of particular interest because, being modifiable thanks to the input power control parameters (mean value & modulation), it is possible to study the effect of varying plasma state. Thus, in addition to providing an experimental technique for testing radiative models in non-equilibrium plasma, PBF could open a way to measure the bulk viscosity under controlled conditions, in addition to the sound velocity, so offering an opportunity to improve the models used in numerical simulations of hypersonic flows.

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Summary:

This article shows that a recent discovery in the field of molecular plasma, called Plasma Ball Formation (PBF), could provide a new experimental technique for testing collisional radiative models in non-equilibrium plasmas. Moreover, PBF could open a way to measure the bulk viscosity under controlled conditions, in addition to the sound velocity, thus providing an excellent opportunity to improve models used in numerical simulations of hypersonic flows.

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Experimental Simulation of a Galileo Sub-Scale Model at Ice Giant Entry Conditions in the T6 Free-Piston Driven Wind Tunnel

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Uranus and Neptune, known collectively as the Ice Giants, are the only two planets in the solar system that are yet to be explored with a dedicated mission. Planetary entry probe missions to the Ice Giants were proposed in 2010 by NASA and ESA which prompted a resurgence of interest in experimental simulation of the aeroheating environment that would be encountered by such a spacecraft. The Oxford T6 Stalker tunnel is the only facility in Europe capable of replicating the high speeds required for Ice Giant entry and is therefore a key stepping stone on the path to realising the goal of an Ice Giant mission.

Although significant progress in Gas Giant entry research has been made in the last ten years, many studies have neglected the influence of trace components such as CH4 on the aeroheating environment. Such trace components are negligible for Jupiter and Saturn, but may exist in much greater quantities on Uranus and Neptune - CH4 is what is believed to give the Ice Giants their distinctive blue colour.

In the present work, a 1:10 scaled model of the Galileo probe has been tested at Ice Giant entry conditions. Conditions for nominal composition (85%H215%He), Stalker substituted, and nominal composition with methane (0.5% and 5% CH4) gas mixtures have been developed and validated for use with a new expansion nozzle via a pitot rake survey. Test flows with flight equivalent velocities greater than 22 km/s have been produced with test times on the order of 30 ⊠⊠. Heat flux into the model for the developed conditions has been inferred from temperature measurements with a series of coaxial thermocouples. High speed video has been captured to allow for measurement of the shock standoff distance during the test time.

This work provides the first ever experimental dataset for Ice Giant entry conditions with CH4 addition and demonstrates a unique capability to simulate Ice Giant entry conditions in Europe.

Summary:

A 1:10 scaled model of the Galileo probe has been tested at Ice Giant entry conditions. Conditions for nominal composition (85%H215%He), Stalker substituted, and nominal composition with methane (0.5% and 5% CH4) gas mixtures have been developed and validated for use with a new expansion nozzle via a

pitot rake survey. Test flows with flight equivalent velocities greater than 22 km/s have been produced with test times on the order of 30 ⊠⊠.

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Numerical investigation of hypersonic aerothermodynamics over a double-cone

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Space exploration has become a stronghold in aerospace engineering. Understanding the dynamic behind hypersonic flows is crucial for the design of thermal protection systems of space vehicles. The extremely high flight velocities of such bodies while entering in the atmosphere induce the formation of strong shock waves in front of them: in the downstream region, non equilibrium takes place due to chemical activity and vibrational excitation. One of the most interesting aerodynamic shape object of current efforts is the double-wedge or the double-cone. These shapes present two wall deflections that promote a complex shock structure, resulting in a complicated shock wave/boundary layer interaction. The attached shock generated near the leading edge interacts with the detached shock propagating in front of the second wall, inducing the boundary layer separation near the compression corner. By the years, these geometrical configurations got interest since they represent simplified models of more complex aerodynamics components (wings or fuselage) and their study is currently a major topic.

Given the chemical activity occuring in hypersonic flows, the problem is stiff: at high enthalpy regime, the assumption of perfect gas deteriorates due to molecular dissociation induced by the strong shock waves forming near the body. Also, most of the kinetic energy is converted into internal energy (translational, rotational, vibrational and electronic), leading to thermochemical non equilibrium. In this work, electronic contribution is neglected since the temperature does not exceed 9000 K, threshold value for ionization phenomena. In order to properly treat the non equilibrium, the multitemperature Park model (mT) is employed: it accounts for 5 species neutral air mixture and 17 chemical reactions; furthermore, a Boltzmann distribution governs the population of the vibrational levels. This approach is an affordable compromise between computational cost and accuracy. Nevertheless, when dealing with strong non equilibrium phenomena, the assumption of a Boltzmann distribution is not acceptable and one should reformulate the problem accordingly. In this view, a detailed state-to-state model (StS) is employed. It takes into account all the vibrational levels for molecular oxygen and nitrogen: since each of them is treated as a single species, this model leads to a relevant increment of the total number of species. To overcome such an issue, an MPI-CUDA approach is implemented in the solver to allow for multi-GPU executions.

In order to simulate the hypersonic flow around a double-cone, 2D axis-symmetric Navier-Stokes equations are solved for an oxygen reacting mixture. Steger-Warming flux vector splitting is employed for inviscid fluxes, along with a MUSCL reconstruction ensures second order accuracy; diffusive fluxes are discretized through the generalized Gauss' theorem. Finally, time integration is performed through an explicit third order Runge-Kutta scheme, such that potential unsteady behavior is well captured. Source terms are evaluated through a splitting approach. In the first step, homogeneous equations are solved; in the second step, source terms are computed through an iterative Gauss-Seidel scheme to update the mixture composition. In such a way, the overall time-step size preserves reasonable values and is not affected by the stiffness of the chemistry terms.

In this work, two different flow regime are investigated. The first one presents a low free stream enthalpy value (4 MJ/kg): indeed, it is found that non equilibrium phenomena are not relevant. Also,

the flow reaches a steady state. The results obtained through the simulations are in a good agreement with those reported in literature and with experimental measurements in terms of surface heat flux and pressure.
On the contrary, when dealing with a higher enthalpy regime (10 MJ/kg) non equilibrium becomes relevant. Chemical phenomena are very strong since oxygen dissociation starts occurring for temperature values above 2000 K. Numerical results have shown a poor agreement with experiments, as also found by other researchers: in particular, the predicted separation region is much smaller than those evinced during the experiments. In order to assess possible influence of wall chemical activity, a fully catalytic model has been also implemented: the results are still in poor agreement with experimental measurements.
However, it is evident from the simulations that the computed wall pressure presents an important deviation from experimental measurements also downstream of the attached shock generating near the leading edge, where the calculation should be straightforward. This led the authors to investigate the influence of non equilibrium in the free stream conditions: for this reason, simulations of the flow expanding through a nozzle have been performed. It has been found out that the mT model provides different conditions at the exit of the nozzle (namely the free stream conditions of the double-cone flow) with respect to those calculated through the StS model. The new simulations performed starting from the mT nozzle conditions and the StS nozzle conditions highlighted a different shock wave/boundary layer interaction over the double-cone. Specifically, the wall quantities computed through the StS simulations predicted a larger separation region, as expected from the experiments, leading to consider that a StS calculation of the free stream quantities (nozzle expansion) would bring the results much closer to experimental measurements.

Summary:

This work deals with numerical simulations of hypersonic flows and thermochemical non equilibrium modeling. The hypersonic flow over a double-cone is investigated.

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EMISSION SPECTROSCOPY OF LOW DENSITY AIR SHOCK TUBE FLOWS ABOVE 10 KM/S

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Please find the abstract in the attached pdf.

Summary:

Please find the abstract in the attached pdf.

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Spectroscopic Signatures of Common Spacecraft Materials under Representative LEO Re-Entry Trajectories

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Introduction

The missing understanding of the disintegration of spacecraft structures during the atmospheric entry flight is the main driving parameter for the calculation of ground impact risk. Additionally, the full demise of the spacecraft becomes increasingly important, because of the rapidly increasing number of Low Earth Orbit (LEO) which undergo uncontrolled entry after the mission. The recently launched satellite systems such as Starlink and OneWeb with thousands of satellites have furthermore only short lifetimes of 3-5\,years which again increases the amount of entering space debris. It is of utmost interest for the space industry to predict the re-entry and demise accurately and space debris problems are a main topic of the European Space Agency under the Space Debris Initiative.

One option for the analysis of re-entry processes is the observation of spacecraft during re-entry which gives insight into the processes that dominate fragmentation and ultimately the demise of spacecraft. Another option is to fly on-board systems which analyze the entry in-situ. However, this requires a comparably complex system and the hardware has to be sent to space. Four Re-entry Break-up Recorders (REBR) were flown aboard Japanese and European Spacecraft, of which three acquired data. Finally, the experimental simulation of re-entry demise can be realized in ground testing facilities. In comparison with flight observations, this method allows investigating the particular features of an atmospheric entry leading to the full demise of spacecraft structures.

The High Enthalpy Flow Diagnostics Group participated in almost all airborne re-entry observations using different spectroscopic instrument. We develop diagnostic methods to be applied in ground testing experiments allowing us to assess the material processes in-situ. With a recently installed load cylinder, the simulation of mechanical forces during the aerothermal testing becomes available. Mechanical forces have been largely discounted and thus not included during re-entry simulations aside from a few case-specific, high-level codes.

In this study, material samples of the main structural components used in spacecraft were tested under combined aeromechanical and thermochemical loads. During testing the emission spectra of the stagnation point were observed by an Echelle spectrometer in 250-880nm. The results of the present study show that depending on the mechanical stress and the aerothermal situation, the materials show different features in the spectral data.

Experimental Arrangement

Experiments were conducted in the plasma wind tunnel facility PWK4 at the Institute of Space Systems - IRS at the University of Stuttgart. The facility consists of a cylindrical vacuum vessel with a diameter of 2m and a length of 6m, connected to the central vacuum system with a four-stage pump system that allows static pressures in the range of 1Pa-50kPa. The plasma is generated by the thermal arc-jet plasma generator RB3, allowing for high local specific enthalpy at sufficiently high total pressures. The material samples are 20mm x 5mm flat bars or 10mm diameter round bar samples with a length of 90 mounted between a 5kN electro-mechanical actuator and the movable PWK test platform.
Material samples were prepared from 4 common structural spacecraft materials (Al6060,Al7075,A316,TiAl6V4). The samples were tested at conditions corresponding to the re-entry of CYGNUS OA-6 with trajectory points mathed between 90km and 60km altitude. During testing the samples were observed with still frame and video imaging, thermal imaging and an echelle spectrometer. The forces and generator conditions were synchronized with the instruments allowing for a time resolved interpretation of the data.

Results

Prior to the material failure the bulk material was not visible spectrally in any of the experiments. However all of the materials showed chracteristic and unique spectra. Aluminum samples were chracterized by the emission of Alkali metals with Lithium lines being unique to Al6060. Chromium lines were the strongest radiator in the A316 stainless steel sample while TiAl6V4 is chracterized by the emission of Vanadium. The surface temperature, oxidation state and force dependent emission of these samples will be shown and discussed in the final paper.

Conclusion

The characteristic spectral features of common spacecraft materials can give insight into the failure modes of re-entering spacecraft. This can further the understanding of the processes governing fragmentation and allow the reconstruction of the break-up from spectroscopic data.

Summary:

Destructive experiments of common structural spacecraft materials were conducted in the plasma wind tunnel facilities of IRS Stuttgart. The spectral features allow a distinct differentiation between materials even among different aluminum alloys. This can give insight into the failure modes of re-entering spacecraft.

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Comparison of Equilibrium Radiation Between Shock Tube and Plasma Torch Spectroscopy for Atmospheric Pressure Air

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As a vehicle re-enters the Earth's atmosphere, it will be travelling at hypersonic speeds through the quiescent atmospheric gas for the majority of its journey. Consequently, a bow shock forms ahead of the vehicle, creating a sudden temperature and pressure increase. The post-shock temperatures are high enough to excite internal energy modes of the gas particles and promote dissociation and ionisation reactions. Radiation is then emitted as the high temperature gas tries to attain a new state of thermodynamic equilibrium.

High enthalpy ground testing facilities play a pivotal role in the advancement of understanding shock layer thermochemistry and subsequent radiation emission ahead of an entry vehicle. These effects are critical to understand the convective and radiative heat loads during planet re-entry. Two types of such facilities are shock tubes and plasma torches. The Oxford T6 Stalker Tunnel [1, 2] is a transient facility, able to recreate both the high temperature and aerodynamic environment of the shock layer flow field, though limited to test times on the order of micro-seconds. A recent study by Glenn et al. [3] has acquired data in synthetic air for shock speeds from 5.5 to 7.2 km/s while operating in Aluminium Shock Tube (AST) mode, with post-shock pressure close to 1 bar. Simulations run using NASA's NEQAIR radiation code [4] underpredict the experimental data. This discrepancy is identified to not be a result of shock deceleration effects, which is fairly minimal for the considered test cases.

In contrast, the École Centrale inductively coupled plasma (ICP) torch is another type of ground test facility capable of reproducing the high static enthalpies experienced in the shock layer of an entry vehicle, though is restricted to subsonic flows and atmospheric pressure. The continuous operation allows for extremely long camera exposure times, ideal for high resolution spectral data [5]. Previous studies have shown the ICP torch to be in a state of local thermodynamic equilibrium [6], making it a good comparison for equilibrium radiance data at atmospheric pressure. Simulations using the SPECAIR radiation code [7] generally show very good agreement to the high resolution spectral radiance data after reconstructing the line of sight across the plasma diameter.

The post-shock temperatures of the 5.5-7.2 km/s T6 AST shots are in the range of temperatures present across the ICP torch plasma diameter. Thus, the same radiating species will be present. Direct comparison between the two facilities can not be made due to the different thermodynamic and aerodynamic environments. Instead, comparisons are performed using the NEQAIR and SPECAIR radiation codes after reconstructing the line of sight through the centre of each facility. Comparison

of spectra from each facility to NEQAIR/SPECAIR predictions in the ultraviolet/visible range will provide valuable insight to both the thermochemical processes occurring within air shock layers ahead of entry vehicles, the performance and characteristics of data obtained from each facility type, as well as the capabilities of the two radiation codes.
The full paper will present experimentally attained spectral radiance from both facilities in the UV/Vis range, along with NEQAIR and SPECAIR simulation results.

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Summary:

Equilibrium radiance spectra from the Oxford T6 Stalker Tunnel and École Centrale inductively coupled plasma torch are compared to predictions from NEQAIR and SPECAIR radiation codes

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ADVANCES IN THE EXPERIMENTAL SPECTRAL EMISSIVITY DETERMINATION BY DUAL-COLOUR PYROMETERS IN MATERIALS FOR SPACE VEHICLES TPS APPLICATIONS IN ATMOSPHERIC RE-ENTRY

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Background of the study
Thanks to the improvements performed in the application of the dual-colour pyrometers for the temperature measurement of the exposed surface of the samples at the hot hypersonic plasma, now it is possible to analyse qualitatively the trend of the material surface spectral emissivity of a sample or an assembled model during the development of a test run carried out in a hypersonic plasma ground facility.

Methodology
Such type of analysis is at present carried out at CIRA in both the SCIROCCO and GHIBLI plasma facilities. It is executed by using dual-colour pyrometers operating simultaneously in single-colour and two-colour modes. It is possible to get from each dual-colour device measurements of the two temperatures, one detected in single colour mode and the other detected in two-colour mode. By combining such temperatures, it is possible to determine the trend of the spectral emissivity of the material surface of the sample tested during the test run.
The use of pyrometers let to measure the temperatures achieved on specific parts of samples or model assembly, also at their stagnation point.

Results and Conclusions
The trends of the spectral emissivity obtained show that the model surface changes during the development of the test. In some cases, there is the occurrence of little variations, but in other cases emissivity changes strongly. Such kind of behaviour can indicate variations in the chemical composition of the surface due to chemical reactions between the material surface and the gases of the hot plasma, or can be due to change of the state of the material surface, like melting, sublimation, etc. The results obtained with the application of such analysis are very interesting, but they are always limited by the assumption of the hypothesis of grey-body behaviour of the material surface.

Summary:

The experimental analysis of the spectral emissivity of a material surface may be performed by the deep use of a dual-colour pyrometer. It is a qualitative characterization only, because of the very strong hypothesis of gray material surface behaviour when the two-colour temperatutre is measured.

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EMISSION SPECTRA OF ABLATING METEORITES AT 1 KILO-HERTZ FRAME RATE

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Plasma wind tunnel PWK1 at the University of Stuttgart has been used for testing the ablation of various types of meteorite samples. Radiation of the ablating meteorites provide useful information to identify the elements present in them and to compare that with the meteor spectra recorded during ground observation. Recently, emission spectra of the ablating meteorite samples have been recorded at frame rates as high as 1 kHz for the first time in a ground testing facility [1]. Radiative emission from the atomic lines of iron (Fe), chromium (Cr), and sodium (Na) have been captured by using an image intensifier coupled with a high-speed camera. A horizontal slice in the ablating flowfield was investigated by aligning it with the entrance slit of the spectrometer using a periscope. This arrangement resulted in a field-of-view of 142 mm that covered the freestream, ablating meteorite sample, and detached droplets flowing away downstream.

This high-frame rate emission spectral arrangement provides data sets with simultaneous spatial, spectral and temporal resolution. The spatial distribution/evolution of radiation from the atomic species can be studied from the calibrated spectral images. A significant advantage offered by the high frame rate spectral data is the information on the time history of integrated radiance of the atomic emission lines. The time history of radiance of various meteorites recorded from our experiments show significant differences between test cases. The distribution of peaks in the time axis is an indication of the frequency and also of the size of the detaching droplets from the meteorite sample ablating in the plasma flowfield. Detailed analysis of the spectral data for various test cases will be discussed in view of spatial and temporal evolution of radiation emission of selected atomic species and its implications on the fragmentation/melting behavior of the meteorites during ground testing.

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Summary:

The abstract discusses about the experimentally recorded radiation emission spectra of ablating meteorites tested in plasma wind tunnel facility. High frame rate emission spectral data of various types of meteorites have been recorded for the first time in a ground testing facility at 1 kHz frame rate.

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Numerical Model for Non-Equilibrium Shock Tube Flow

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Background of the Study

Non-equilibrium phenomena can significantly change the heat transfer and aerodynamic characteristics of hypersonic vehicles. Consequently, the design of vehicles entering planetary atmospheres relies heavily on numerical calculations, and in turn these require accurate estimates of physical quantities such as rate constants and intra-molecular interaction parameters. The intra-molecular parameters and rate constants for transport quantities used by numerical solvers for hypersonic flow draw from a range of sources [Par90]. Experimentally generating the flow conditions typical of planetary entry is unattainable in continuous flow facilities, and must be studied using shock tube facilities. Shock tube facilities are comprised of several compression stages using shock heating processes to generate the required flow [MDMG15]. The spatial and temporal variation of the test gas properties are in turn determined by the processes taking place in a shock tube. These processes make the characterization of the test gas state in a shock tube a non-trivial exercise, requiring assumptions about the test gas condition when analysing spectroscopy data. As an example, assumptions about the test gas pressure and temperature were required to determine rate coefficients for high-temperature reactions from spectroscopic data generated by shock tubes [FD61, DL70, Byr59, Par88b]. When radiation measurements in shock tubes are gathered, it is commonly assumed that the test gas has a uniform temperature profile corresponding to the nominal shock speed just upstream of the optical measurement station. However, even during an experiment where the shock is propagating with constant velocity,the growth of the boundary layer on the tunnel wall causes the gas conditions to change along the length of the test slug. Park estimated boundary layer effects by assuming a linear increase of density and both temperatures behind the shock [Par88a]. Recent results have illustrated the importance of shock trajectory on the temperature profile of the test gas,and subsequently the impact on prediction of radiation spectra for equilibrium conditions [SGC + 22]. It has been shown that the flow is in a state of thermal and chemical non-equilibrium [DMG + 12] in many tests performed in high-speed expansion tube experiments. This paper introduces a new method to account for the effect of non-equilibrium phenomena on spectroscopy data in shock tube experiments. The method is demonstrated for experiments in synthetic air using Park's two temperature model and second-order approximation Chapman-Enskog transport properties.

Methodology

The method applied in this study has two key components, the thermodynamic model, and the numerical model of the shock tunnel.

The thermodynamic model considers thermal and chemical non-equilibrium according to Park's two temperature model [Par90] with rate-coefficients set by NASA-RP-1232 [GYTL90]. The model assumes the rotational and translational temperatures of the heavy molecules are matched at temperature T . The model also assumes that the vibrational temperature of the molecules, the translational temperature of the electrons, and electronic excitation of the atoms and molecules are equal and are at temperature T_v. This assumption is made on the basis that the transfer of energy between the translational motion of free electrons and the vibrational motion of N_2 and is very fast, and low-lying electronic states of the molecular species equilibriate quickly with the ground electronic states [Lee84, Lee86]. The dissociation rate coefficients are determined as a function of the geometric mean of the two temperatures $T_a = \sqrt{TT_v}$. Chapman-Enskog theory is used to evaluate the transport properties of the test gas as a multi-component gas mixture [CC70]. Collision integrals requiredfor calculation of these properties come from a variety of sources [HBC64], including intermolecular potential functions such as the Tang-Toennies potential [LW04], differential cross sections [SMI + 95, NMKM88, LKZ04, SGGB95, TN75] and tabulated datasets of ab-initio calculations [LPS90, PSL91, SPL91, SPL00, SPL01]. The tabulated collision integrals are evaluated at the electronic-vibrational temperature T_v for any interactions involving electrons, and at the translational temperature T for all other interactions [GYTL90].

The shock tube flow is modelled as a compressible, one-dimensional unsteady flow. The conditions of the test gas around the centreline are described using the parabolised Navier Stokes equations in cylindrical coordinates. The parabolised equations are simplified by separation of variables, due to the centreline being a streamline. Further simplifications are made exploiting the symmetry conditions around the centreline itself, which require scalar variables and the radial velocity to have zero gradient. Symmetry and separation of variables allow the parabolised Navier-Stokes equations to be written as a set of coupled one-dimensional equations by expanding the solution near the centreline with respect to a small parameter, which represents the distance from the centreline itself. The equations describing the test slug are found to be formally similar to the equations ruling stagnation line problems. Mass continuity requires the centerline derivative of the radial velocity to match the radial velocity at the edge of the boundary layer. The boundary layer at the wall of the shock tube can be determined by using a self-similar solution which matches the local streamwise pressure gradient and centerline scalar quantities to the growth rate of the boundary layer at the wall. The useful test time of the test slug can then be determined by the radial velocity at the edge of the boundary layer. The flow equations, closed by the thermochemistry model equations, are discretised using a second order accurate finite volume method and cast as a large system of coupled algebraic equations. By considering experimental shock trajectory and pressure traces, the system of equations becomes a boundary value problem. The system is then solved using Newton iterations using exact Jacobian matrices.

Conclusion

An numerical method has been presented to calculate the non-equilibrium properties of a shock tube test gas. The method, formally similar to a stagnation line problem with Park's two temperature model, is based on a version of the parabolised Navier-Stokes equations in cylindrical coordinates. Second-order approximations of the non-equilibrium gas transport properties are evaluated using Chapman-Enskog theory. The centreline solution is coupled to a self-similar boundary layer solution which determines the radial velocity and the test time. History effects on the test slug are simulated using a method based on [SGC + 22]. Therefore, this work allows consideration of shock trajectory effects for a non-equilibrium flow within a shock tunnel.

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Summary:

A numerical method is developed to calculate non-equilibrium properties of shock tube test gas. Parabolised Navier-Stokes equations provide the basis for the method, analogous to a stagnation line problem. Gas properties are determined by incorporating Park’s two temperature model with transport properties evaluated using second order Chapman-Enskog theory.
The centreline solution of the shock tube is then coupled to a self-similar boundary layer solution, thus determining the radial velocity and the test time.

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Emission Spectroscopy of Plasma Flows for Ice Giant Entry

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Uranus and Neptune are the only two exemplars of ice giant planets in the Solar System. This planetary class is currently not well understood, as the models for their interior structure cannot be fully explained by observations. As opposed to planets classified as gas giants, ice giants are mainly composed of volatile substances heavier than hydrogen and helium, called \textit{ices}, in their bulk. Such unique composition suggests that their formation is rather a rare event, which contrasts with their abundance in our galaxy. An exploration of Neptune and Uranus, the ice giant planets of the Solar System, involves entries at high velocities into atmospheres consisting of H_2, He and CH_4. Experiments in plasma wind tunnels at the Institute of Space Systems of the University of Stuttgart have been conducted to investigate the behavior of this plasma. Two emission spectrometers were set up to characterize the free-stream plasma and optical filters were used to avoid the prominent H lines of the Balmer series. The final paper will present free-stream spectra measured in the wavelength range from 250 to 880 nm during experiments of ice giant entries. A series of optical filters will be used to block the most prominent H lines, which will allow for more detailed analyses of the CH and the C_2 molecular radiation in the plasma. In addition to the Echelle spectrometer used in the previous campaign, a second spectrometer will be set up to record emission spectra from 280 to 433 nm. To resolve the temperatures and number densities of the produced species, the spectra will be fitted to simulations

Summary:

The exploration of Neptune and Uranus, the ice giant planets of the Solar System, involves entries at high velocities into atmospheres consisting of H2, He and CH4. Because these entries may produce radiative heat fluxes not yet fully understood, arcjet experiments to simulate them were conducted at the PWK1 facility of the Institute of Space Systems at the University of Stuttgart. Two emission spectrometers were set up to characterize the free-stream plasma and optical filters were used to avoid the prominent H lines of the Balmer series. The final paper will show a spectrum from 250 to 880 nm acquired during ice giant atmospheric entry experiments. Additionally, the measured spectra will be fitted to simulations to resolve the temperatures and number densities of the produced species.

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Locally-resolved optical emission spectroscopy of supersonic inductively-coupled air plasma jet and comparison to radiative transfer simulations

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Background
The VKI Plasmatron facility is the world's largest Inductively Coupled Plasma (ICP) torch, providing a chemically pure plasma flow for material response studies in atmospheric entry conditions. Three supersonic nozzles have been recently designed and commissioned, including both conical and semi-elliptical exit geometries. The test-envelope of the facility is largely increased, reaching higher flow

Mach numbers, heat fluxes, total pressures and surface shear stresses on the test articles.
Free-stream characterization is a critical task to provide precise information about the experimental conditions. This, in fact, is required by numerical simulations, including both CFD and material response, to study the material interaction with the chemically-reacting plasma flow and to provide insights into the complex multi-physics environment. In this regard, cold-wall heat flux and stagnation pressure are traditionally measured by means of intrusive probes. Pressure taps, placed in the convergent and divergent parts of the nozzle, provide information about the expansion behaviour. Shock stand-off distance is measured by conventional camera imaging, thanks to the bright emission of the plasma after the shock.
In the context of this work, we provide an additional mean of characterization of the supersonic plasma flow by measuring the radiative signature of the emitting species in the UV-NIR wavelength range and comparing to radiative transfer computations, starting from CFD simulation of the flowfield.

Methodology
We used the Acton Series SP2750 spectrograph, featuring a Czerny-Turner configuration, with a 150 grooves/mm grating and a 750 mm focal length, to resolve the spectral emission of exited species in the plume along the orthogonal direction to the jet axis. The system is mounted on translating rails, also allowing different axial distances from the nozzle exit. Due to the strong expansion, the plasma flow cools down significantly and the Princeton-Instruments PI-MAX3 intensified CCD camera, with additional pixel binning, allows to measure the faint emission with enough signal to noise ratio. The spectrograph uses a double mirror imaging system to avoid chromatic aberration and it is precisely calibrated to achieve absolute intensity measurements.
Starting from the measured values of gas mass flow rate and nozzle inlet pressure, the steady flowfield is simulated numerically using the ARGO software, developed at CENAERO. The solver is based on a Discontinuous-Galerkin (DG) approach and an axi-symmetric formulation, using a 7 species air mixture and adaptive meshing. Temperature, pressure and species number densities are then extracted from the simulation at the corresponding measurements locations. A ray-tracing tool is used to build the line-of-sight (LoS) profile of the aforementioned quantities, replicating the side view of the spectrograph. Finally, the line-by-line code NEQAIR is used to compute the radiative transfer along the LoS for each probing volume along the radial coordinate. The simulated spectral image is then compared to the locally-resolved measured radiance.

Preliminary experimental results and future work
We applied the proposed methodology to an experimental test case on a conical nozzle featuring a 60 mm dimeter exit, with the following conditions: 410 kW generator power, 180 mbar nozzle upstream pressure and 5 mbar chamber pressure.
The measured spectra at 50 mm and 90 mm from the nozzle exit show a narrow emission profile within 20 mm from the jet axis. Radiative emissions for atomic oxygen and nitrogen dominate the emission spectra. Molecular rovibronic transitions of N2+ and NO are also detected in the ultra-violet band. Preliminary numerical simulations have shown a frozen chemical composition downstream of the convergent part of the nozzle, with little concentration of diatomic molecules, which would explain the absence of significant radiative contributions from N2.
The final paper will show a detailed comparison of the calibrated spectra to the simulated emission at different probing locations from the nozzle exit, thus providing additional insight in the characterization of the supersonic plasma jet.

Summary:

Free-stream characterization is a tedious task in supersonic plasma flows. On top of traditional intrusive measurements of cold-wall heat flux and total pressure, we perform locally-resolved emission spectroscopy by means of a spectrograph and an intensified camera. The CFD simulation of the flowfield is post-processed with a radiative transfer code, allowing to compare the simulated radiance to the measured one. The technique aims at providing additional validation of the simulations tools, thus improving the characterization capabilities.

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Multi-Fidelity Modeling Framework for High-Temperature Gas

Radiation

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Introduction
During atmospheric entry flights, a substantial amount of radiative heat transfer occurs around surface of spacecraft and this affects the success of designed mission. The radiative heat transfer roughly depends on the fourth power of governing temperature which implies the accurate representation of it is one of the crucial components to design a thermal protection system (TPS).

Depending on purposes, radiation analysis requires a wide range of fidelity in its numerical approach. For example, to identify stagnation point heating during an atmospheric entry flight, the radiative transfer equation (RTE) can be integrated using quasi-one-dimensional approximations, such as the tangent-slab and the spherical-cap methods, without significant loss of accuracy. However, to identify the radiative heat flux incident to the afterbody of a spacecraft by including the radiative cooling effect, a flow-radiation coupled approach to multi-dimensional spatial grid topology is inevitable. This aspect requires the development of a numerical framework that can manage the radiative heat transfer problem accurately and efficiently with variable levels of numerical fidelity.

To this end, this work aims to develop such an improved numerical toolbox for the high-temperature radiation analyses, currently targeting applications to hypersonic aerothermodynamics study. This abstract summarizes the modeling framework with selected results of applications.

Overview of Radiation Modeling Framework
In this work, a numerical toolbox MURP (MUlti-fidelity Radiation Package) has been developed to encapsulate various kinds of radiation analysis strategies required for high-temperature aerothermodynamics and astrophysical studies. It provides a flexible, efficient, and accurate numerical framework and this has been achieved by integrating the following three key components.

a. Radiative Transport
The MURP supports integration of the radiative transfer equation (RTE) in one-, two-, and three-dimensional spatial grid topology that includes absorbing, emitting, and scattering non-gray medium. For one-dimensional cases, either SHOCK-TUBE or HEATING modes can be used. The former provides a spatially-resolved intensity profile that can be compared against shock-tube measured data. The latter can be used to compute wall-directed radiative heat flux based on the tangent-slab or spherical-cap methods to integrate the RTE.

In multi-dimensional grid cases, the MURP supports two-dimensional, which includes axisymmetric, and three-dimensional RTE solvers. In these cases, the RTE is integrated by applying a finite-volume method (FVM) for both spatial and angular discretizations. The parallel I/O and distribution of the spatial mesh along the multiple processors are performed using a DMPlex object within the open-source library PETSc.

b. Spectral Property
A line-by-line (LBL) radiation module is employed to simulate detailed non-Boltzmann spectral properties at a given thermodynamic condition. This model includes bound-bound, bound-free, and free-free transitions from atomic, diatomic, and triatomic species. The non-Boltzmann electronic populations of upper and lower states of radiating species are computed based on the concept of non-Boltzmann correction factor. The radiation spectra emitted from species that can exist in the atmospheric compositions of Earth, Mars, Titan, Jupiter, and other kinds of ablative gaseous species from meteorite can be simulated to estimate spectral properties.

Several kinds of reduced-order modeling strategies have been implemented in the MURP to reduce computational costs required for radiative heat transfer simulations. In this study, we demonstrate the multi-band opacity binning (MBOB) approach, which guarantees accuracy and efficiency for analyses of the diatomic molecular band systems.

c. Coupling
Coupling with other numerical codes, for example, the one between flow and radiation fields, is achieved through a volumetric coupling strategy. An open-source library preCICE is used to take care of the description of the coupler environment along with data exchange. A flow field solver

HEGEL (High fidElity tool for maGnEto-gas-dynamics simuLations) developed at the University of Illinois is employed to obtain temperature and species number density distributions including thermochemical nonequilibrium effects. The MURP then determines the amount of radiative cooling by solving the RTE and feeds it back to the energy source term of HEGEL until the temperature field is frozen. The present study demonstrates a flow-radiation coupling for Titan atmospheric entry flight conditions.

Applications to Hypersonic Non-Boltzmann Radiation Analysis
In the present study, electronic non-Boltzmann radiative heat transfer has been analyzed for Titan atmospheric entry flight conditions. First, we have studied features of electronic non-Boltzmann radiation by simulating the test campaigns measrued from NASA Ames EAST facility. The EAST shot 61-19 is considered benchmark data. The condition of shock is 0.1 Torr and 6.1 km/s with composition of 98% of N_2 and 2% of CH_4. From the present analysis, it has been found that not only the CN Violet and Red bands but also contributions from N and N_2 from the vacuum ultraviolet range are significantly affected by the radiative heat flux.

Second, a Titan atmospheric entry flight trajectory(t=211 s) of Dragonfly is simulated in a flow-radiation coupled manner. This second part of the analysis is ongoing work and improvement of physical model's accuracy has been achieved by modifying chemical-kinetic parameters for the Titan mixture. Through sensitivity analyses, the most influential reaction processes are determined and calibrated against shock tube measurements. Then they are employed to investigate hypersonic flow and radiation fields around the Dragonfly entry capsule. The radiative cooling effect from Deep VUV to infrared is considered via efficient spectral data management by the MURP that identifies individual contributions from several different spectral ranges.

Concluding Remarks
In the present study, a multi-fidelity modeling framework for high-temperature gas radiation has been developed and applied to hypersonic atmospheric entry conditions. For accurate and efficient analyses of radiative heat transfer, spectral, radiative transport, and reduced-order modeling framework have been integrated into a single numerical code, MURP. Applications to hypersonic aerothermodynamics study for the Titan composition have been performed to demonstrate the capability of the MURP. This investigation first revealed the additional influential radiators in the high-energy spectral region in addition to the well-known strong radiator in the ultraviolet. Then the massive flow-radiation coupling analysis has been carried out and will be refined through future investigation to thoroughly identify the mechanism of radiative heat transfer in the Titan atmospheric entry conditions.

Acknowledgement
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Summary:

During atmospheric entry flights, a substantial amount of radiative heat transfer occurs around the surface of the spacecraft and this affects to the success of designed mission. Depending on purposes, radiation analysis requires wide range of fidelity in its numerical approach. This work aims to develop an improved numerical toolbox for the high-temperature radiation analyses, MURP (MUlti-fidelity Radiation Package), currently targeting applications to hypersonic aerothermodynamics study. The MURP encapsulates various kinds of radiation analysis strategies required for high-temperature aerothermodynamics and astrophysical studies. It provides a flexible, efficient, and accurate numerical framework and this has been achieved by integrating the three key components; (1) radiative transport from one- to three-dimension, (2) spectral modules from LBL to order-reduction approaches, and (3) coupling approach with other numerical codes. This abstract summarizes the modeling framework with selected results of applications to the hypersonic Titan atmospheric entry conditions.

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NASA's Entry Systems Modeling Project Investment For Entering H2-He Atmospheres

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Introduction:
The Giant planets are key destinations of interest to the planetary science community for their potential to provide insight into the formation and evolution of our Solar System, as well as extrasolar planetary systems. To date, the Galileo atmospheric probe is the only purpose-built entry probe to a Giant planet. Post-flight analysis of Galileo's performance showed that there was significant recession of the thermal protection system (TPS), well beyond what was predicted on the flank, and this was due in part to insufficient modeling capabilities for estimating the flight environment and TPS response. While Galileo ultimately survived its flight, the example serves to highlight the great challenge of designing successful missions for environments that are poorly understood or where models have not yet been validated. NASA's Entry Systems Modeling (ESM) Project is tasked with investigating such considerations for planetary science missions across the Solar System, and in recent years has begun to do so for Giant planets. This talk provides an over-view of the ESM project and highlights the impact of ongoing and future investments.
The ESM project is leading efforts to develop accurate thermochemical databases based on state-of-the-art measurements in the Electric Arc Shock Tube and detailed computational chemistry. The large heat fluxes anticipated by mis-sions has driven interest in new TPS materials, in particular woven materials, which may be enabling but have never been flown before. Consequently, multiscale models are in development to describe properties and performance of the materials from micro- to system-scale. The goal is to not only provide accurate thermal response but also to inform thermostructural reliability predictions for extreme entries. Additionally, new computational models have been developed to evaluate performance of non-destructive evaluation techniques which are vital to establishing acceptance of systems to be free of manufacturing faults like material cracking, voids, and debonding. In the area of guidance and control, aerocapture has been shown conceptually to provide a number of mission benefits, including reducing transit time and increasing payload frac-tion. The ESM project is building a launch-to-landing trajec-tory simulation capability to enable detailed studies of aerocapture maneuvers in the context of Giant planets mis-sions.

Galileo Probe Revisited:
To assess the impact of previous
ESM investments, several state-of-the-art modeling approaches were applied to an evaluation of the Galileo Probe entry. These included coupled ablation modeling, TPS recession due to ablation, full angular integration of radiation, high-fidelity diffusion modeling, ionization potential lower-ing of H, state-specific H modeling, and precursor absorption in the freestream. Results of this study are shown in Fig. 1. This figure shows a comparison with flight data and preflight predictions [1]. This analysis provides the most accurate re-cession prediction for the Galileo Probe TPS material to date. Although a Jupiter probe will experience a much different environment compared to a probe entering the other gas giants, this work highlights not only the impact of ESM project investments, but also, as part of the uncertainty analysis per-formed, identified areas of investment to reduce risk for future gas giant probes.

Summary:

Overview status of EDL research relevant to H2-He destinations

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Simulation of radiating non-equilibrium flows during atmospheric entries using a gas kinetic simulation code

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To protect space vehicles of the extreme heat loads during atmospheric entries, appropriate heat shields are necessary. For the higher entry speed class of missions, their design requires the characterization of the both the incident radiative heat flux and associated uncertainties, as well as the impact of radiative cooling in the flow field. An accurate prediction of these properties is also needed for ground testing, since radiation measurements offer a good accessibility to characterize flow fields. Experimental measurements have shown that thermal and chemical non-equilibrium effects can be crucial for the correct prediction of radiative heat fluxes and interpretation of spectrometric measurements. Computational Fluid Dynamics (CFD) methods, which are typically used for these kind of flow field simulations, are based on Navier–Stokes equations. These equations are physically correct only in a certain range of gas and plasma flows. Strong thermal and chemical non-equilibrium effects found in the region surrounding a bow shock lead to locally high gradients in the flow field. In addition, the backshell protecting the payload from the recirculating flow is subject to rarefaction effects in the wake of the capsule, where continuum assumptions break down. These effects lead to increasing errors in Navier–Stokes-based CFD results and alternative modeling approaches become necessary. The Direct Simulation Monte Carlo (DSMC) method has proven to be an efficient method for calculating these types of flows. Using this well-established approach, it is possible to calculate detailed information about each flow species. Additionally, it is possible to calculate electronic excitation temperatures directly.
In this work, the open source plasma suite PICLas is bidirectionally coupled with a radiation solver. A line-by-line method is implemented to calculate radiative properties in the flow field, a photon Monte Carlo approach is used to calculate the radiative energy transfer. Models to overcome the downsides (computational costs, statistical fluctuations, memory requirements) of the used methods are implemented. Different test and application cases have been simulated and will be shown.

Summary:

See content

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An investigation into the role of measurement uncertainties and models' assumptions in the enthalpy rebuilding procedure of Inductively Coupled Plasma facilities through a Bayesian formulation of the inference problem.

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Ground testing has always been essential for aerospace development. As an example, they are a key component in the design process and qualification of thermal protection materials for re-entry systems. They also have a crucial role to tackle the problem of space debris for which the end-of-life disposal through aerothermal demise in atmospheric entry is largely promoted. In such context, plasma wind tunnels are required for the validation of the design-for-demise (D4D) tools. Their testing conditions (e.g., free-stream enthalpy) must be accurately known to offer flight-relevant test conditions for material testing and precise database generation. Unfortunately, they cannot be directly measured and must rely on empirical formulas or rebuilding procedures. These methodologies couple numerical models and experimental data increasing the total uncertainty of the envisaged quantities due to inaccuracies in the selected models and errors in the measurement chain.

The overall objective of this work is to assess the impact of measurement uncertainties and some model assumptions on the enthalpy inference of Inductively Coupled Plasma facilities through a Bayesian formulation. We have recently presented three different enthalpy rebuilding procedures with application to the VKI's Plasmatron at the FAR conference held in Heilbronn that is, the ASTM method, the standard VKI rebuilding procedure, and a stochastic approach based on the Bayes theorem. While the former employs an empirical formulation of the enthalpy, function of heat flux and dynamic pressure measurements only, the VKI procedure includes the effect of the catalysis phenomena described by the catalytic coefficient, γ, assumed known from the literature. Conversely to deterministic approaches resulting in a point-estimate, the stochastic method provides a full probability distribution of the inferred quantity due to measurements' uncertainties and models' inaccuracies. A normal distribution with a 2σ confidence level set to 10% uncertainty range for the experimental data and a (log) uniform distribution for γ was considered based on the conclusions of previous works. This paper aims to extend the previous results by computing the actual uncertainties of the experimental data, and to investigate other models' assumptions hereafter presented.

The Bayesian formulation requires the solution of the forward problem thousands of times to correctly predict the statistics of the quantity of interest. The forward problem is based on the heat flux computation that is then compared with the experimental counterpart through the evaluation of the likelihood function. The heat flux computation is performed with two CFD codes that are, the ICP solver and the Boundary Layer (BL) code. The former simulates the plasma jet in the Plasmatron chamber under the LTE assumption. The ICP reference conditions are the mass flow rate supplied to the torch, $\dot{m}$, the static pressure of chamber, p_s, and the effective power supplied to the plasma by induction. For low subsonic, low Mach number test conditions, $\dot{m}$ and p_s are considered constant, as verified by the results of numerical simulations and dynamic pressure measurements, and therefore set equal to the experimental values. As far as P_{el}^{eff} is concerned, it is exact value is still unknown and efforts are underway to overcome the problem. Today, a power efficiency $\eta = \frac{P_{el}^{eff}}{P_{el}^{eff}}$ = 50 % is accounted for with P_{el} the electrical power supplied by the VKI's Plasmatron generator to the coil. The ICP provides the boundary layer edge quantities, in terms of five non-dimensional parameters, to the BL code that solves the flow around the testing sample, with catalytic coefficient γ, under chemical non-equilibrium conditions. One of the outputs of the BL code is the heat flux at the wall.

This paper proposes to investigate the assumptions of η = 50% and the definition of the non-dimensional parameters in enthalpy inference. For instance, the fifth parameter is defined as the ratio of the normal component of the velocity with respect to the probe at the boundary layer edge dimensionalized by the free-stream velocity. However, the choice of the free stream point may differ among the authors (e.g., half at the distance between the probe and the torch exit section or the point where the velocity gradient of the tangential component along the tangential direction has an inflection point, etc). Preliminary studies have shown a negligible effect on the heat flux estimation, but further investigations are necessary to better assess the role in the inference problem. Furthermore, the chemical non-equilibrium in the boundary layer employs chemical models such as Park's Gupta's or Dunn-Kang's, that provide the coefficients of the Arrhenius law modeling the formation/deprecation of the species which may significantly impact the heat flux computation. Such coefficients are affected by significant inaccuracies being calibrated more than 20 years ago and validated with experimental data available at that time. We, therefore, propose to extend the stochastic approach to study the Park's coefficients uncertainties in the enthalpy estimation.

Summary:

The Bayesian formulation of the enthalpy rebuilding in Inductively Coupled Plasma facility is here presented with application to the VKI's Plasmatron. The procedure compares experimental data and its numerical counterparts through the evaluation of the likelihood function. The paper focuses on the role played by measurement uncertainties and some model assumptions in the inference of the quantity of interest.

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Ab-initio Based Kinetics and Model Reduction for Application to Computational Hypersonics Aerothermodynamics

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See Attached File.

Summary:

This talk outlines a new paradigm for constructing predictive modeling and simulation tools from a fundamental physics perspective, rejecting the empiricism that has prevented progress in modeling hypersonic flows for decades. Inspired by model reduction strategies developed in statistical physics, this work addresses the challenges of the combinatorial explosion of the possible configurations of the system, obtaining new governing equations by projecting the master equation onto a few lower-dimensional subspaces. The distribution function within each subspace is then reconstructed using the Maximum Entropy Principle, thus ensuring compliance with the Detailed Balance. We will cover the critical aspects involved in model development, namely: (1) using direct numerical simulation to study the fundamental physics; (2) derivation of a reduced-order set of equations that give an accurate and physical consistent description of the physics at a much-reduced computational cost; (3) validation and uncertainty quantification. Applications discussed include hypersonics and discharge-induced plasma flows.

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PHOTON MONTE CARLO TRANSPORT COMPUTATION FOR ATHMOSPHERIC (RE-)ENTRY

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Reentry into Earth's atmosphere and entry into the Martian atmosphere can yield to significant radiative heat loads experienced by the flight configurations. For an Earth-atmosphere, the gas is normally considered optically transparent, but very high temperatures behind the shock will radiate, especially in thermodynamic non-equilibrium conditions. CO2 is the main constituent of the Mars atmosphere and a complex molecule. This molecule and its dissociative products have the ability to strongly emit and absorb radiative heat loads. In fact, previous investigations [1] revealed radiative heating to be crucial not only for the stagnation point region but also from the wake flow. The shock layer is optically denser compared to a shock layer produced by an earth entry. Therefore, a precise radiative transport computation is necessary to capture the extreme gradients of radiative heat loads in the shock layer.

In [2] early results for the reentry of the Fire II flight experiment in air are discussed. Use was made of the k-correlation method, and the results were validated against the flight measurement and different numerical results. [3] applied a further development of this method for Martian flows. In [1] Navier-Stokes fluid flow computations for the 2D axisymmetric test case TC3 are presented. Here, thermal equilibrium and a mixture of perfect gases were assumed. They use a Photon Monte Carlo Method for radiative transport computation initially developed for turbulent sooty flames. The solver was modified to feature not only a correlated-k but also a statistical narrow band model.

They found significant radiative heat loads at the rear part of the entry vehicle mostly due to CO2 infrared radiation. Similar results were obtained in [4] by using a axisymmetric Navier-Stokes non-equilibrium flow computations together with a radiative transport ray-tracing discrete ordinates method.

For this investigation, an efficient Euler-Boundary-Layer method [5, 6] for entry flow computations is used. It features equilibrium and chemical non-equilibrium computations for earth atmosphere and equilibrium computations for a Martian atmosphere. The latest development is the inclusion of a two-temperature model to cover vibrational non-equilibrium in air. Within the last couple of years a Photon Monte Carlo Method called StaRad (Statistical Radiation) is developed and implemented. [7, 8]. In our early investigations we focused on detailed comparisons with analytical methods. Here, we could demonstrate its general capabilities and its computational precision. Recently an investigation about full 3D radiative transport computations of entry shock layers in earth atmosphere [8] was presented. Here, a detailed description of the method and a discussion about advantages and disadvantages from variations of the method is given.
Since the StaRad radiative transport solver can be coupled to many spectral modeling methods and databases such as PARADE, NEQAIR or HITRAN/HITEMP with this investigation aims at applying our computational setup to the Erath and Martian atmosphere entry shock layers. Furthermore, a discussion of other variations of the method for a further development of the general Photon Monte Carlo Method will be given.
Since a very efficient fluid flow computation method and a radiation method of arbitrary accuracy and computational time (exact for the fictitious number of infinite bundles) is used, several computations along an entry trajectory will be performed to gain an insight of the total heat loads along the trajectory accounting for radiation. The frequency possibilities will be discussed.

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Summary:

Since a very efficient fluid flow computation method and a radiation method of arbitrary accuracy and computational time (exact for the fictitious number of infinite bundles) is used, several computations along an entry trajectory will be performed to gain an insight of the total heat loads along the trajectory accounting for radiation. The frequency possibilities will be discussed.

Volumetric investigation of plasma radiation by means of light field deconvolution

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Investigation of plasma radiation in an arcjet driven facility is demanding due to severely limited optical access and very dynamic processes. This complicates volumetric measurements, which are important for the understanding of many flow phenomena. In this paper, we present our recent advancements in the field of light field deconvolution. Originally developed in the domain of microscopy, this technique allows 3D studies of optically thin, luminous flows. It operates on a single snapshot recording of a plenoptic camera, and as it does not involve any temporal or spatial scanning or multiple viewpoints, this method is especially suited for demanding and dynamic environments like plasma flows.

The key feature of a plenoptic camera is an array of microlenses close to the image sensor, which distributes light rays onto the sensor pixels as a function of their direction. This additional directional data allows to reconstruct 3D information on the recorded scene. In the case of optically thin volumes, reconstruction requires knowledge of the point spread function (PSF), which defines light propagation within the optical system. An experimental approach is proposed to acquire the shift-variant PSF, considering all elements of the photographic setup. Assuming a linear system, the PSF is used as a tool to revert the image formation process in an iterative deconvolution algorithm, which seeks to reconstruct the three-dimensional intensity distribution within object space from a recorded light field image.

This concept was applied to test cases, where transparent, luminous fluid flows were recorded by a commercial plenoptic camera (Raytrix R29). The present paper gives results from these tests, computed by a Matlab code, and demonstrates the successful transfer of light field deconvolution from microscopic to macroscopic scales. As the computationally expensive reconstruction is performed after image acquisition, the temporal resolution of this technique is only limited be the frame rate of the camera, allowing to study fast, transient processes. We show with this paper how plenoptic light field imaging is used to assess the radiating environment in high-enthalpy plasma flows and we present the recent advancements in the experimental setup to improve temporal and/or local resolution.

Summary:

This paper presents light field deconvolution as a volumetric technique to investigate radiation in a high-enthalpy plasma flow. Based on a snapshot recording of a single plenoptic camera, it allows to 3D measurements in demanding environments with limited optical access. We demonstrate the feasibility of the method by means of test cases, present the calibration approach and discuss recent advancements in the experimental setup to improve temporal and/or local resolution.

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Infrared emission measurements of a recombining CO2 plasma

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The study of the convective and radiative heat fluxes to the capsule surface during its atmospheric entry is critical for the design of the thermal protective system. For Mars entry scenarios, where CO2 represents 96% of the atmosphere, the radiative heat flux to the afterbody suffers from large uncertainties - up to 260%. The rapid hydrodynamic expansion of the plasma into the afterbody region results in rapid cooling, chemical recombination, and a departure from equilibrium. This chemical non-equilibrium and the associated radiation are still not accurately modeled, and our goal is to provide experimental data for model validation. Our experiments focus on a fundamental study of the recombination kinetics of CO2 plasmas.

The inductively coupled plasma torch at laboratoire EM2C was used to produce a CO2 plasma at atmospheric pressure. More details of the plasma torch facility can be found in Ref. [4] (see attachment). The CO2 plasma studied here exits the torch through a 1-cm diameter nozzle and is composed of 10% of CO2 and 90% of argon (argon required for stable operating conditions). The plasma is then passed through a water-cooled test-section of various lengths at high speed (~ 500 m/s) to force rapid cooling and chemical recombination. The IR spectra obtained by OES are calibrated in absolute intensity using a tungsten lamp traceable to NIST standards. The calibration procedure considered absorption from cold CO2 and H2O present in the optical path. The complete calibration procedure is described in [5] (see attachment). Figure 1 shows the calibrated and abel-inverted spectrum at the exit of the 35-cm test-section. This corresponds to the local emission at the center of the jet. Emission from both CO and CO2 is present. Several CO/CO2 spectra at different rotational and vibrational temperatures were calculated using the RADIS line-by-line radiative code, in conjunction with the HITEMP-2010 database. The best fit achieved is shown in red. The complete fitting procedure is described in [5] (see attachment).

A 0D chemical kinetic simulation was realized using the Cantera code in conjunction with the Park 1994 kinetics model. The temperature, as measured above using the CO molecular band, was converted into a time-dependent temperature profile, and put into Cantera which then calculates the evolution of the chemical composition. Figure 2 shows the evolution of CO in black and CO2 in red, the dashed lines represent the equilibrium. CO density prediction at 35 cm is in good agreement with our measurement at the exit of the 35-cm test-section. However, the CO2 density is underpredicted by a factor of about 10.

Summary:

An ICP torch was used to produce a CO2/Ar plasma jet at atmospheric pressure. The plasma jet is close to LTE conditions at a temperature of 6650 K. This plasma is then passed at high velocity through a water-cooled test-section that forces rapid cooling and recombination. The thermochemical evolution of the plasma is studied using infrared OES. The measured spectra at the exit of the torch and at the exit of the test-sections are calibrated in absolute intensity and compared with calculations done using the RADIS radiation code. The measurements of temperature and CO/CO2 densities that result provide a test case for comparison with kinetic modeling and CFD predictions. A 0D chemical kinetic simulation was realized using the Cantera code and the Park 1994 kinetics model. CO density prediction is in good agreement with our measurement, however, the CO2 density is slightly underpredicted at the exit of the recombining tube.

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Characterization of an air-xenon operated electric thruster plume through optical emission spectroscopy

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In the future, Air-Breathing Electric Propulsion (RAM-EP) systems may enable low-altitude missions over long lifetimes. The European consortium "AETHER" is currently designing a RAM-EP prototype for ground testing. In the context of this project, an experimental effort has been conducted to characterize the Particle Flow Generator (PFG), which is responsible for providing the RAM-EP system with a high-speed flow representative of actual in-orbit operation. In a first preliminary test campaign, a Sitael 5kW-class Hall-Effect Thruster has been operated with xenon, air, and in a mixed-propellant mode.

Optical emission spectroscopy is a widely used diagnostic method for low-temperature plasmas due to the affordability and simplicity of its experimental setup. The diagnostic relies on an intensity-calibrated spectroscopy system to record the emission spectra from the UV to the near-IR region over a range of wavelengths. The emission spectra are typically interpreted using a model that accounts for transitions between the internal energy levels of the different species of the flow. As the radiation signature of the plasma depends on the species level distribution, spectroscopic measurements allow the extraction of the plasma electron temperature and electron density through the comparison of synthetic and experimental emission spectra.

We compute electron temperatures along the PFG plume axis based on the described approach. The same procedure is applied to obtain radially resolved profiles. We analyze the impact of Xe on the radiative signature of air, and we discuss the possibility of using Xe as trace species to obtain air plasma parameters in a mixed-propellant mode. Finally, we employ a collisional-radiative quasi-1D expansion model to infer plasma conditions at the PFG exit.

Summary:

In the future, Air-Breathing Electric Propulsion (RAM-EP) systems may enable low-altitude missions over long lifetimes. The European consortium "AETHER" is currently designing a RAM-EP prototype for ground testing. In the context of this project, an experimental effort has been conducted to characterize the Particle Flow Generator (PFG), which is responsible for providing the RAM-EP system with a high-speed flow representative of actual in-orbit operation. In a first preliminary test campaign, a Sitael 5kW-class Hall-Effect Thruster has been operated with xenon, air, and in a mixed-propellant mode. We present results obtained from optical emission spectroscopy. In particular, we compute electron temperatures in the PFG plume, and we discuss the possibility of using Xe as trace species to obtain air plasma parameters in a mixed-propellant mode. Finally, we employ a collisional-radiative quasi-1D expansion model to infer plasma conditions at the PFG exit.

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DSMC simulation and spectral analysis of an iron meteorite at 80 km altitude entering Earth's atmosphere

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Observation missions of meteoroids entering the Earth's atmosphere are conducted regularly. Meanwhile a method to replicate the flight in a ground test facilities has been established. Numerical simulations with subsequent comparison of the spectroscopic data, on the other hand, are not yet widely used in this field. This is mainly due to the complex flow environment which not only includes non-equilibrium radiation, but furthermore the outgassing of species from the meteorite.
In this work, simulations of an atmospheric entry of a meteorite with a diameter of 38 mm are performed. A pure iron sphere is assumed and the size and inflow conditions correspond to the ground testing condition. Using the Direct Simulation Monte Carlo method, one trajectory point at an altitude of 80 km is investigated. It is taken into account that iron outgasses on the meteorite's surface and thus influences the flow field. The outgassing process is simulated as an inflow boundary on the meteorite's surface, assuming a constant meteorite shape and composition. Since these iron particles do not enter the shock, but are captured and entrained by the flow, there is a large difference in their electronic excitation temperature, the electronic excitation temperature of the freestream, and the electron temperature. However, iron has many radiative transitions that occur in the expected energy range, so accurate predictions of the excitation temperatures for each species are essential. For this purpose, the open source plasma suite PICLas is coupled with a radiation solver and the

radiative energy is iteratively coupled back into the flow field. A line-of-sight radiation transport is performed and results are compared to the ground-to-flight extrapolated experimental measurements.

Summary:

See content

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Non-equilibrium modeling of inductively coupled plasma discharges

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Background of the study : The windward side of a re-entry vehicle needs to be protected by a heat shield, made of advanced thermal protection materials (TPMs) to overcome the tremendous amount of heat loads during planetary entry. Because in-flight testing of new TPMs is prohibitively expensive, the extreme heat loads imposed on a thermal protection shield during hypersonic re-entry are reproduced by placing a sample of a TPM in a hot jet of plasma. An important class of plasma wind tunnels is the ICP (inductively coupled plasma) facility which offers a large volume of contamination-free plasma for a considerable amount of time as it does not require electrodes to generate the plasma. As a result, ICPs are often preferred for testing of thermal protection systems for re-entry vehicles.

An important aspect in the modeling of ICPs is the possible impact of Non-Local Thermodynamic Equilibrium (NLTE) effects. Most of the ICP studies reported in the literature assume that LTE conditions prevail. This assumption, however, breaks down at low pressures due to lowering of collisional rates among gas particles. As a matter of fact, temperature and chemical composition distributions in low pressure ICPs may show significant departure from equilibrium. Under these circumstances, the availability of accurate NLTE kinetics models is of paramount importance. This task may be achieved, in theory, by adopting a State-to-State (StS) kinetics formulation. In Sts models each internal energy state is treated as a separate pseudo-species, thus allowing for taking into account non-Boltzmann distributions. State-to-State models provide a superior description compared to conventional multi-temperature (MT) models, which are based on Boltzmann distributions. Most StS models assume that the rotational and vibrational energy levels of molecules are populated according to Boltzmann distributions at their own temperatures, T_r and T_v, respectively. These models solve the master equation only for the electronic levels thereby implicitly assuming small departures from Boltzmann ro-vibrational distributions. However, although the assumption of rotational equilibrium may be safely assumed for ICP applications, the same assumption does not hold for the vibrational states of molecules such as N_2 and N_2^+ and may need a vibronic state-to-state treatment. Also, the radiative effects inside the ICP facilities have largely been neglected in most of the ICP studies. There are hardly any literatures presenting a systematic study of radiative effects in ICPs.

The present work demonstrates a high-fidelity multi-physics computational framework to study non-equilibrium and radiative phenomena in inductively coupled plasma discharges. This framework couples the plasma flow solver HEGEL (High fidElity tool for maGnEto-gas-dynamics simuLations) with an electro-magnetic solver FLUX (Finite-element soLver for Unsteady electromagnetix) for the magneto-hydrodynamic modeling of the ICP. The framework is further coupled with a radiative transport solver MURP (MUlti-fidelity Radiation Package) for taking into account the radiative effects while modeling the ICP discharge.

Methodology : The dynamics of NLTE gaseous plasmas treated in this work are governed by the species mass, global momentum and energy, and vibronic energy equations which have been im-

plemented in a finite-volume solver HEGEL which uses the PLATO (PLAsma in Thermodynamic nOn-equilibrium) library for evaluation of plasma-related quantities (e.g. thermodynamic properties,
etc.). The electromagnetic field inside ICPs are governed by the set of Maxwell's equations which are solved in a mixed finite-element solver FLUX. Radiative heat transfer in the ICP facility is investigated using the numerical code MURP which is a finite-volume radiative heat transfer solver encompassing self-consistent non-Boltzmann spectral modules ranging from line-by-line to reduced-order approaches for the accurate and efficient description of plasma's spectral properties desired in the present work. All the above mentioned solvers have been developed at the Center for Hypersonics (CHESS) at University of Illinois.

The governing equations for the plasma are coupled to those for the electromagnetic field via the Lorentz forces and Joule heating source terms. At the same time, the electric and magnetic field within the plasma are affected by the electrical conductivity of the latter. As a result, the two datasets (Lorentz forces and Joule heating for HEGEL, and electrical conductivity for FLUX) are passed at every fluid time-step to accurately capture the magneto-hydrodynamic phenomena occurring within an ICP. Similarily, HEGEL passes the species populations and the temperatures to MURP, while MURP feeds back the computed radiative losses as an energy source term to HEGEL. The required volume coupling between the above mentioned solvers is here realized using preCICE, an open source coupling library for partitioned multi-physics simulations. The electromagnetic equations are solved on a farfield mesh coinciding with the fluid mesh where only the torch section is meshed.

Results : Preliminary simulations have been performed using an electronic CR (collisional-radiative) model for Nitrogen $[e^-,\ N(1-7),\ N_2(1-6),\ {N_2}^+(1-5),\ N^+]$ plasma where we resolve the electronic-states by tightly coupling the electronic master equations with the conservation equations. The calculations have been done for 2D axi-symmetric torch configuration where cold Nitrogen gas is injected through a thin annular injector which gets heated by six parallel inductor coils. The operating conditions for the preliminary calculation are as followed : length of the torch 0.486m, torch radius 0.08m, pressure 1000 Pa, inductor power 50 KW, inductor frequency 0.45 MHz, inlet mass flow 6 g/s. The radial population distributions of the elctronic states of the chemical components at the mid-torch axial location show a significant amount of deviation from the populations obtained using Boltzmann distribution. The electronic state-to-state simulation results show the incapability of the conventional multi-temperature model in predicting the correct plasma physcis and suggest a need to do a more detailed study of ICPs using state-of-the-art CR models.

Conclusion : A high-fidelity multi-physics computational framework to study inductively coupled plasma discharges has been presented. Preliminary calculations using a multi-temperature model show a significant extent of non-equilibrium between the trans-rotational and the electron-electronic-vibrational modes at lower pressures. Furthermore, calculations performed using electronic CR model show a large deviation of the species populations from that obtained using Boltzmann distribution.
Future work will focus on using state-of-the-art vibronic CR models to simulate ICP discharges while taking into account the radiative effects via CFD-radiation coupling.

Summary:

The present work demonstrates a high-fidelity multi-physics computational framework to study non-equilibrium and radiative phenomena in inductively coupled plasma discharges. This framework couples the plasma flow solver HEGEL (High fidElity tool for maGnEto-gas-dynamics simuLations) with an electro-magnetic solver FLUX (Finite-element soLver for Unsteady electromagnetix) for the magneto-hydrodynamic modeling of the ICP. The framework is further coupled with a radiative transport solver MURP (MUlti-fidelity Radiation Package) for taking into account the radiative effects while modeling the ICP discharge. Preliminary calculations using a multi-temperature model show a significant extent of non-equilibrium between the trans-rotational and the electron-electronic-vibrational modes. Furthermore, calculations performed using electronic CR model show a large deviation of the species populations from that obtained using Boltzmann distribution.

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Coupling of Radiation and Spallation of Carbon Ablators in a Plasma Wind Tunnel

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Ablative thermal protection systems (TPS) reduce the heat flux on a spacecraft during atmospheric entry through a number of effects. Modern materials consist of a porous carbon preform which is infiltrated with phenolic resin. During reentry, the resin inside the material pyrolyses which leads to the outflow of cold pyrolysis gases towards the surface and ultimately into the boundary layer and the flow field. This reduces the heat flux into the material. At the surface, the char remaining after the pyrolysis is decomposed through sublimation, oxidation and nitridation. This consumes heat and results in a recession of the ablator surface. In addition, the surface recession is increased through the mechanical erosion of the material, where solid particles are released from the surface. This undesired effect is summarized as spallation. Next to increasing the recession rate, spallation is also believed to alter the flow field and consequentially the radiation environment around the ablator. Yoshinaka et al. detected CN radiation in a supersonic plasma flow upstream of the shock, suggesting that the carbon was transported upstream trough spalled particles. Similar observations were made by Kihara et al. in a supersonic arc-heated flow. On the other hand, in similar ablation experiments by Raiche and Driver there was no significant emission of ablation products. However, in these experiments it is unclear, how much the severity of spallation differs between the tests. In this paper we present results from a test campaign where the number of spalled particles and the CN radiation and pyrolysis gas radiation in the flow field were measured simultaneously.
The test campaign was conducted at the plasma wind tunnel PWK1 at the Institute of Space Systems (IRS) at the University of Stuttgart and was targeted at the study of spallation of carbon preforms and carbon-phenolic ablators. The plasma condition was representative of the aerothermal loads that were experienced by the Hayabusa capsule at an altitude of 78 km during its reentry into Earth atmosphere. Before each test, the sample was placed outside of the flow. As soon as the desired plasma condition was set, the sample was moved to the center of the plasma flow, which defined the start time of the test. Each test had a duration of 30 s and ended with the shut-off of the plasma generator. The tested samples included the two carbon preforms Calcarb CBCF 18-2000 and Fiberform as well as the carbon-phenolic ablators Harlem and ZURAM. ZURAM is developed by the German Aerospace Center (DLR) and is produced using Calcarb as a carbon preform. The Harlem samples were produced at the IRS and both samples based on Calcarb as well as on Fiberform were tested.
The diagnostic setup allowed to study characteristic ablation performance parameters like the surface recession and surface temperature through photogrammetry and thermography respectively. The number of spalled particles were tracked via high-speed imaging. An Aryelle Echelle 150 spectrometer and a spectroscopic setup in Czerny-Turner configuration consisting of an Acton SpectraPro 2750 spectrometer coupled with an Andor Newton DU920N-OE CCD camera were used for measurements normal to the plasma flow.
The Acton SpectraPro spectrometer was located outside of the facility aiming at the sample. The plane-of-sight aligned with the entrance slit of the spectrometer was a horizontal slice in the flow field passing through the stagnation point. The measurement plane covered a width of approximately 66 mm along the stagnation line, comprising of 39 mm upstream of the sample and 27 mm on the sample. This was chosen so that, for the expected recession rate, the ablation layer was covered in the plane-of-sight for the whole duration
of the test. For a 300 lines per millimeter grating, the Andor camera can capture a wavelength range of 120 nm at a spectral resolution of 0.12 nm px−1. The grating was centered at 380 nm aimed at studying the emission of CN in the flow field in the wavelength range of 320 nm to 440 nm.
The Echelle spectrometer was located on the opposite side of the test facility. Optical emission in the range from 250 nm to 880 nm were captured with this instrument. Its field of view was a circular spot with a diameter of 5mm recording the line-of-sight integrated radiance, that is aligned perpendicular to the flow and immediately upstream of the ablator surface. As the surface receded throughout the test, the measurement region moved upstream relative to the surface by up to 2 mm. The data allows to track the emission from pyrolysis products (e.g. H) over time and correlate it to the spallation frequency obtained through the high-speed images.
The final paper will contain an in-depth analysis of spallation rate, the radiation in the flow field and ablation performance characteristics like surface recession and temperature. Comparing the

transient spallation rate with spatial and temporal profiles of CN emission will provide important contributions to the understanding of spallation mechanisms and the effect of spallation on the radiation in the flow field. This data can also serve as a validation for numerical models of spallation and the release of carbonaceous gases through spalled particles into the flow.

Summary:

Results from an extensive ablation test campaign in the plasma wind tunnel PWK1 dedicated to the investigation of spallation are presented. The radiation of carbonaceous species and pyrolysis products in the flow field are analyzed and compared to the surface recession, the number of spalled particles and the surface temperature.