8th International Workshop on Radiation of High Temperature Gases for Space Missions

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Book of Abstracts
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CDSD-vib: A vibrationally specific database refitted from ro-vibrational specific data

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Carbon dioxide radiative prediction is an important aspect in many scientific and industrial applications. Highly accurate databases such as HITRAN\cite{GORDON20173}, HITEMP\cite{ROTHMAN20102139} or CDSD\cite{TASHKUN2003165}\cite{TASHKUN20111403} are designed to reconstruct the spectrum in a given temperature accurately. However, in the context of atmospheric entry these databases have some known drawbacks. The accuracy of these databases depends on the temperature and is gradually degraded as this temperature exceeds the one for which they were designed for. For high temperature (\(T > 3000\) K) conditions, the \ce{CO2} spectrum is rich in features making the size of CDSD4000 computationally prohibitive for use in full spectrum calculations while HITRAN and HITEMP cannot be used at such high temperatures. Furthermore, these databases do not separate the rotational and vibrational degrees of freedom. In the context of atmospheric entry, in the wake flow of a spacecraft, the conditions of the gas are characterized by chemical and thermodynamical non-equilibrium. Full spectrum radiative calculations are carried out to determine the amount of protection necessary in the back shell of capsules. A radiative database that is smaller and allows for non-equilibrium calculations is desirable. In this work, we propose to reduce the size of the database to make it computationally efficient. This is achieved by refitting the ro-vibrational data in databases such as HITRAN or CDSD and reorganize it as vibrationally specific database. The great advantage of the newly generated database is that it can still be applied for ro-vibrational predictions by retaining the global accuracy of the spectrum while being more portable. It can also be used for coupling vibrational state-to-state kinetics calculations, a work that as been started recently\cite{AMAL2016}.

In this work the Carbon Dioxide Spectral Databank 4000 \cite{TASHKUN20111403} (CDSD4000) was used as source data that is to be reorganized and fitted. The obtained database is denoted CDSDvib hereafter. This work is a follow up from previous work from the authors presented previously\cite{VARGAS2018}. While sharing similarities with the previous work the approach for selecting, processing data and the quality of the achieved results are different. The previous worked aimed for a global algorithm for refitting and processing data, this work focuses only on one spectral range and aims at a bottom up approach by a selective method for processing data.

Summary:

A new CO2 IR radiation model based on CDSD + A solution to TC1A-EXOMARS-2016 and TC2A-ShockTube-MSL

Simulation of electronic excitation in transitional atmospheric entry flows.

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1. Introduction

The reentry of space debris is a major safety concern. Since only part of the debris are destroyed in the atmosphere, it is essential to be able to characterize the size, number and impact zone of the remaining fragments. Estimating the survivability of an object and its trajectory requires an accurate knowledge of the aerothermodynamics of the shock layer surrounding it.

At high altitudes and low freestream densities, the flow is in the transitional regime and shows rarefaction effects while maintaining a strong chemical activity. This highly non-equilibrium configuration may be simulated using the Direct Simulation Monte Carlo method. To achieve a reliable description of the interplay between chemical processes and the non-Boltzmann population of excited levels, one must resort to using detailed chemical models. In state-to-state models, each level is considered a distinct species (or rather "pseudo-species") and followed individually. The resulting distribution provides valuable information to assess non-equilibrium radiative effects.

The application of such models proves to be difficult. The range of concentration of the various excited states spans over orders of magnitude. Most of them act as trace species, which are problematic for particle methods. Indeed, in a typical DSMC study, each simulated particle represents billions of real gas particles, so that the computation is affordable. If trace species are present, this ratio must be decreased to keep enough simulated particles of each species and have meaningful samples. The higher the number of species (i.e. levels) and their energy, the higher the computational penalty, making the computational cost of a state-to-state simulation prohibitive. One must then consider indirect strategies, such as the one presented in this work.

1. Computational method

Boccelli et al. [1] have developed a Lagrangian reactor approach to refine the thermochemical description of pre-existing aerodynamic calculations using improved chemical models. It allows introducing an arbitrary number of new species and chemical processes. These are described by a rate equation using temperature-dependent reaction rates. It can therefore cope with any number of trace species, being free of statistical noise issues associated with DSMC.

The basic assumption underlying the method is that the trace species have a weak influence on the bulk flow. One may therefore decouple the computation of these species kinetics, and a simplified chemical scheme in the aerodynamic simulation suffices to obtain the main features of the flow. The method seems especially appropriate for the computation of electronically excited states kinetics: given typical shock layers temperatures, these are produced in small amounts merely influencing the global density and velocity fields.

The decoupled high-fidelity chemical simulation is overlaid on the flow field. Assuming steady-state and neglecting diffusion, the advection terms in the different governing equations are written as derivatives with respect to the streamline curvilinear abscissa. The resulting equations are ordinary differential equations solved with a forward marching method along each streamline. This allows for a substantial speedup with respect to a coupled approach.

The procedure involves three successive steps:
(1) Perform a baseline simulation with only major species and chemical processes;
(2) Extract aerodynamic quantities $u(s), T_m(s), x_i(s)$ along one or more streamlines ($s$ is the curvilinear abscissa, $i$ the species index and $m$ denotes the internal energy mode);
(3) Solve the species mass conservation and the energy modes conservation equations along the streamlines with refined chemistry.

In the Lagrangian solver, the flow is modelled with a two-temperature $T^*-T_v$ model. The rotational mode is assumed to be in equilibrium with translation at temperature $T$, while the vibrational mode in equilibrium at $T_v$, free electrons are coupled to vibration. Since a state-to-state description of the electronic levels is adopted, no equation is needed for the electronic energy mode; it only requires to solve a mass conservation equation for each level.

1. Kinetic models
The baseline simulation employs a mixture comprised of the neutral species N\textsubscript{2}, O\textsubscript{2}, N, O and NO. The chemical model includes dissociation and exchange (Zel’dovich) reactions, implemented through the TCE model. Relaxation of the molecules rotational and vibrational energy is handled with the usual empirical models.

The detailed Lagrangian-reactor based computation makes use of the CoRaM state-to-state model developed at CORIA [2]. It takes into account numerous electronic levels of N\textsubscript{2}, O\textsubscript{2}, N, O, NO and their ions. The kinetic scheme covers the related excitation/deexcitation processes by heavy particle and electron impact as well as chemical reactions (dissociation/recombination, ionisation/recombination, exchange, dissociative recombination/associative attachment, etc.).

1. Application

The test case is a 2D air flow around a 20 cm diameter cylinder. Freestream temperature and pressure are $T_{\infty} = T_{v,\infty} = 200$ K and $p_{\infty} = 1.38$ Pa. The Mach number is 26 ($V_{\infty} = 7.5$ km/s) and the Knudsen number based on the diameter is 0.01. These conditions are typical of those experienced by debris at an altitude of 80 km.

Acknowledgements:

J. Am. wishes to acknowledge the support of L. Walpot, European Space Agency and C.N.E.S. (Centre National d’Etudes Spatiales).

References:


Summary:

Non-equilibrium chemistry and radiation in the shock layer of hypersonic entry flows are greatly influenced by electronically excited species. The computation of these species in the transitional regime using the DSMC method is a challenging task owing to their low concentration. A strategy to deal with such flows is presented. A Lagrangian reactor approach is adopted to compute the population of excited species, starting from a baseline solution provided by a prior DSMC simulation. The method allows for an arbitrary refinement of the chemical model to take into account trace species and is particularly suitable for state-to-state computations.
dynamics and behaviors that a mere vibrational specific methodology would tend to hide or to misinterpret. This work presents the authors’ new findings concerning the importance of the rotational component in the diatoms’ excitation and dissociation processes, which resulted from the examination of an extensive database of ro-vibrational rate coefficients and 0-D simulations for the four systems mentioned above. Gephi [5], a software for social and biological network visualization, has been used for understanding the connectivities and analyzing the links between the molecules’ quantum states: in agreement with the results of Sahai’s algorithm for grouping N2 levels [6], the states characterized by low rotational energy (J < 80) appeared to be strongly connected to the ones sharing the same vibrational state; for levels with higher J, however, the larger the rotational contribution to the molecule’s energy, the more isotropic in the quantum numbers space such connections tended to be. Moreover, the preferential channels for exciting the high-lying energy states presented the same structures in all the diatoms analyzed by the authors so far; this fact motivates the very similar excitation dynamics that has been noticed when heat bath simulations have been performed in different chemical systems (Fig. 1). Rotation has also shown to have a crucial role in the molecule’s dissociation: a strong positive correlation has been found between the energy-distance of a ro-vibrational state from the centrifugal barrier and its specific dissociation rate (Fig. 2).

REFERENCES

Summary:
This work presents the authors’ new findings concerning the importance of the rotational component in the diatoms’ excitation and dissociation processes, which resulted from the examination of an extensive database of ro-vibrational rate coefficients and 0-D simulations for 4 chemical systems of high interest in Hypersonics community.

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LAGRANGIAN DIFFUSIVE REACTOR FOR DETAILED THERMO-CHEMICAL COMPUTATIONS OF PLASMA FLOWS

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INTRODUCTION

A broad range of high-enthalpy and plasma technology applications exhibit thermochemical nonequilibrium effects, ranging from solar physics and thermal plasmas [1], combustion and plasma-assisted ignition [2], diagnostics [3], and materials technology in general. In aerospace applications, the radiative heat flux to the heat shield of planetary entry probes [4] depends on the populations of atomic and molecular internal energy levels, often out of equilibrium. In particular, many chemically reacting species are present in atmospheric entry flows for space vehicles reaching entry velocities higher than 10 km/s [5]. Aiming at deep space exploration, detailed chemical mechanisms become of primary importance to optimize the efficiency of electric propulsion devices [6].

The simulation of plasmas with atomic and molecular energy level populations out of thermochemical equilibrium requires a comprehensive modeling of all the elementary collisional and radiative processes involved. Detailed simulations are based on a large set of chemical species and their related chemical mechanism [7]. Coupling such mechanisms to flow solvers is computationally expensive and often limits their application to 1D simulations.

The simulation of non-trivial geometries becomes feasible by adopting strategies to lower the computational cost associated with chemistry modeling, while retaining a good level of physical realism; principal component analysis (PCA), energy levels binning and rate-controlled constrained-equilibrium (RCCE) being some possible approaches (see for example [8]). Yet, the problem remains complicated enough to run out of the current supercomputing capabilities when real-world applications or design loops are targeted.

A pragmatic way to address the problem still relies in strong simplifying assumptions.

The idea of decoupling flow and chemistry is sometimes used in the chemistry community to include detailed mechanisms into lower-fidelity baseline solutions [9].

In atmospheric entry plasmas, a Lagrangian method using a collisional-radiative reactor has been coupled to a flow solver [10] based on the 1D method proposed by Thivet to study the chemical relaxation past a shockwave [11]. Lagrangian tools, allowing for the refinement of an existing solution with very small computational effort, are based on fluid models.

The aim of this work is to develop a method for including detailed thermochemical effects into lower-fidelity baseline solutions through an efficient Lagrangian diffusive reactor. Our approach starts from a baseline solution for a plasma flow, by extracting the velocity and total density fields along its streamlines, and thus decoupling thermochemical effects from the flowfield. The main assumption is that fine details of the species energy level populations, as well as trace species in the mixture, do not severely impact the hydrodynamic features of the flow. This is the case for many applications, such as the aerodynamics of a jet, the location of a detached shock wave, or the trail behind a body flying at hypersonic speed. As long as the total energy transfer can be modeled by means of some effective chemical mechanism, a more detailed description of the thermo-chemical state of the plasma can be obtained by re-processing the baseline calculation using more species and chemical reactions.

The originality of this contribution consists in exploiting the Lagrangian nature of the proposed method, developing a general solution procedure based on an upwinded marching approach, adding rarefied, multi-dimensional, and dissipative effects. The consequence is a drastic boost in the computational efficiency, allowing to deal with a large number of chemical species.

We propose to develop a tool to obtain reasonably accurate predictions of the thermochemical state of a flow using an enlarged set of species and describing thermal nonequilibrium via multi-temperature, state-to-state, or collisional-radiative models. As a proof of concept, we account for radiation-flow coupling via escape factors. Reaching higher accuracies using detailed chemistry output of the Lagrangian reactor to solve the radiative transfer equation can be studied in a future work.

The presented strategy can be employed as a design tool to obtain information too expensive for a fully coupled approach. Alternatively, it can also be used for diagnostic purposes to promptly estimate the effect of different physico-chemical models into realistic simulations: this allows us to understand whether a simplified modeling can be suitable for the considered problem. Finally, with respect to particle-based flow simulations, such as those obtained with the Direct Simulation Monte Carlo Method (DSMC), the proposed method smooths out the noise and irregularities associated to the inherent stochastic approach, improving the prediction of minor species. Electronic energy levels, which would require a particularly detailed and computationally intensive approach otherwise, can also be easily computed.
The capabilities of the method are assessed against five problems, namely: (i) Chemical refinement, (ii) Thermal refinement, (iii) State-to-state refinement, (iv) 2D rarefied flow, and (v) Mass and energy diffusion.

In all the performed testcases, we investigate the accuracy of the thermochemical description and its computational cost.

References


Summary:

The simulation of thermochemical nonequilibrium for atomic and molecular energy level populations in plasma flows requires comprehensive modeling of the elementary collisional and radiative processes involved. Coupling detailed chemical mechanisms to flow solvers, is computationally expensive and often limits their application to 1D cases. We describe the development of an efficient Lagrangian reactor moving along streamlines of a multi-dimensional baseline flow simulation to introduce detailed thermochemical effects. The method is efficient and allows to the model both continuum and rarefied flows while including mass and energy diffusion. The solver is tested on normal shockwaves and 2D and axisymmetric blunt-body rarefied hypersonic flows, where the Lagrangian reactor shows able to drastically improve the baseline simulations at a very low computational cost. The solver is also immune from statistical noise, which strongly affects the accuracy of calculations obtained through the Direct Simulation Monte Carlo method, especially considering minor species in the mixture. Results demonstrate that the method enables applying detailed mechanisms to multidimensional solvers to study thermochemical nonequilibrium flows.

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NOVEL APPROACH FOR MODELING NON-EQUILIBRIUM KINETICS AND RADIATION FOR CO2 WAKE FLOWS

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The current study is aimed at developing a simulation framework that is rooted in ab-initio theory and deals with thermal, chemical, and radiative non-equilibrium during hypersonic planetary entry in a unified manner. Computing the population of individual energy states or the radiative intensity corresponding to a given frequency is unfeasible, even for the simplest flow problem, owing to the large number of internal levels and possible collisional/radiative excitation pathways in a gas. The prohibitive cost of state-to-state kinetics is remedied in the present work by adopting a reduced-order model based on coarse graining and the maximum entropy principle [1]. Additionally, an adaptive grouping methodology [2] to identify and lump together groups of states that are likely to equilibrate faster with respect to each other is employed which results in more accurate reduced-order models.

The problem of model-reduction for radiation transfer problems is motivated by a desire to accurately characterize the rapid variation in spectral properties such as opacity and emission using averaged or “homogenized” frequency-independent values. The use of multi-group Planck-averaging in conjunction with a novel binning strategy allows this complex behavior to be modeled in a cost-effective manner. The present work also employs a finite-volume (FV) approach to compute the angular-integrated three-dimensional radiative intensity for the entire domain which opens the door to flow-radiation coupled calculations [3].

The new physics-based modeling framework is used to analyze the flowfield and radiative heat transfer in the backshell of the Mars Science Laboratory (MSL) entry vehicle during hypersonic planetary entry. The coarse-grain model allows a high-fidelity (non-Boltzmann) description of the \( \text{CO}_2 \) vibrational state population. The reduced-order radiative transfer equations solved using the FV approach enable accurate computationally-efficient coupled calculations of the radiative heat flux emanating from the major \( \text{CO}_2 \) infrared bands.

REFERENCES

Summary:
This work presents a unified, computationally tractable, physics-based modeling framework for analyzing the flowfield and radiative heat transfer in the backshell of the Mars Science Laboratory (MSL) entry vehicle during hypersonic planetary entry.

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Modeling of Laser Induced Breakdown in gases

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The first observations of Laser Induced Breakdown (LIB) in gases were made upon the days of the invention of lasers and were initially reported by Maker. In those experiments it was observed that, gases which are normally transparent to optical radiation (e.g., Air), could be transformed in high-temperature plasmas by focusing a laser beam onto a small volume. When the operating conditions (e.g., ambient pressure) are such that the process is collision-dominated, the plasma formation occurs in two-steps: (i) creation of priming electrons via Multi-Photon Ionization (MPI) and (ii) cascade
ionization initiated and sustained by energy absorption in free-free electron-heavy interactions (i.e., inverse Bremsstrahlung).

The purpose of this work is to develop a self-consistent physico-chemical description of LIB in gases. The interaction between the laser and the plasma is described via a fluid model based on the Navier-Stokes equations. Non-Local Thermodynamic Equilibrium (NLTE) effects are taken into account using a two-temperature model. The radiation field is modeled based on the Radiative Transfer Equation (i.e., Kinetic Theory of Photons). Extending beyond many works in the literature, the proposed model accounts for the creation of priming electrons via MPI. This avoids to start the simulation with an initial artificial cold plasma. The inclusion of MPI, which is often thought to be important only in initiating the plasma, affects the shape and evolution of the plasma kernel as discussed in detail in a companion work. To obtain numerical solutions, the governing equations are discretized in space using a second-order finite-volume method. The system of equations is time-integrated by an implicit dual-time-stepping method. Applications consider the breakdown stage and the early post-breakdown evolution in air and oxygen plasmas.

Summary:
This work proposes a computational model to describe laser-plasma interactions under non-equilibrium conditions. Its innovative aspect consists in the self-consistent kinetic model for plasma formation which accounts for production of priming electrons via multi-photon ionization, energy absorption in free-free transitions and cascade ionization.

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STELLAR CO2: A database for vibrationally-specific excitation and dissociation rates for Carbon Dioxide

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This work presents the STELLAR (State-To-State ELementARy Rates) database update for CO2, providing a dataset suited for the modeling of vibrationally-specific excitation (V–T) and dissociation (V–D) processes in Carbon Dioxide.

The implemented datasets provide a better and more physically consistent description of the physical-chemical processes in emerging applications (such as state-to-state modeling of Venus and Mars atmospheric entries, plasma reforming of SynGas, or oxygen production on Mars), as compared to legacy approaches such as the ones based on first-order perturbation theories (FOPT), such as the SSH model.

The dataset proposed here is based on the Forced Harmonic Oscillator (FHO) theory, which is known to be capable of providing more physically-consistent rates in the high translational temperatures regime of shocked flows, as compared to FOPT theories. The FHO theory has been extended to the modeling of collisions between linear triatomic molecules such as CO2, and phenomenological intermolecular potentials have been selected through comparisons with experimentally obtained state-to-state rates.

Although the proposed theoretical description is a considerable improvement from legacy FOPT descriptions, it still makes use of a considerable deal of underlying assumptions and is expected to be superseded in the future by more sophisticated approaches such as Potential Energy surfaces (PES) based trajectory models. However it is expected that this dataset will help improve the accuracy of the state-to-state models developed in atmospheric entry applications and most critically Mars and
Venus entry applications, since CO2 radiation is a considerable design driver, who strongly depends on an accurate description of the V–T and V–D rates of excitation and dissociation of CO2.

An application of the model to two theoretical test-cases such as the relaxation from initial conditions \((T_{tr}, T_{v}) = [10,000K, 300K]\) (heating of the gas to 10,000K), and relaxation from initial conditions \((T_{tr}, T_{v}) = [300K, 10,000K]\) (cooling of the gas to 300K) is also presented in this work.

Summary:
A new state-to-state model for CO2 dissociation

ExoMars / 33

Simulation of SCHIAPARELLI entry aerothermal flight data

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ESA recently flew an entry, descent, and landing demonstrator module called Schiaparelli that entered the atmosphere of Mars on the 19th of October, 2016. The instrumentation suite included heatshield and backshell pressure transducers and thermocouples (known as AMELIA) and backshell radiation and direct heatflux-sensing sensors (known as COMARS and ICOTOM). Due to the failed landing of Schiaparelli, only a subset of the flight data was transmitted before and after plasma black-out. The goal of this paper is to present comparisons of the flight data with calculations from NASA simulation tools, DPLR/NEQAIR and LAURA/HARA. DPLR and LAURA are used to calculate the flowfield around the vehicle and surface properties, such as pressure and convective heating. The flowfield data are passed to NEQAIR and HARA to calculate the radiative heat flux. Comparisons will be made to the COMARS total heat flux, radiative heat flux and pressure measurements. Results will also be shown against the reconstructed heat flux which was calculated from an inverse analysis of the AMELIA thermocouple data performed by Astrium. Preliminary calculations are presented in this abstract.

Summary:
SIMULATION OF SCHIAPARELLI ENTRY AEROTHERMAL FLIGHT DATA WITH TOOLS FROM NASA AMES AND NASA LANGLEY

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Aerothermal Characterization Data of COMARS+ in L2K Martian Flow Environment (TC1B)

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The aerothermal characterization of the instrumentation package COMARS+ of the Schiaparelli lander of the Exomars 2016 mission has been carried out in Martian flow environment of the arc heated facility L2K. The combined sensors COMARS and the broadband radiometer for radiative heat flux measurements were able to successfully measure the radiative heat flux on the back cover close to the vehicle shoulder for the first time on a Mars entry vehicle. To allow further validation of the
numerical codes applied to simulate flow field and radiation properties of the EXOMARS COMARS+ flight data from Schiaparelli capsule descent phase (Test cases test cases TC1A), further Martian atmosphere experiments in DLR’s arc heated facility L2K with dedicated diagnostics are being performed. Two test case flow conditions with different enthalpies have been identified for a mixture of 97% carbon dioxide and 3% nitrogen representing the chemical composition of Martian atmosphere to measure thermochemical and radiation properties in the free stream and behind a shock layer of a scaled model of the Schiaparelli capsule.

The COMARS+ broadband radiometer is used to measure the radiation properties of both the free stream and the shock region. For characterization of the thermochemical properties of free stream and shock region non-intrusive spectroscopic measurement techniques as Fourier Transformed InfraRed spectroscopy (FTIR), UV-VIS Emission Spectroscopy (ES), Laser Induced Fluorescence spectroscopy (LIF), and Diode Laser Absorption Spectroscopy (DLAS) are used. Additionally profiles of Pitot pressure and heat flux have been measured to verify homogeneity of the free stream at the model location.

**Summary:**

The aerothermodynamic characterization of the instrumentation package COMARS+ of the Schiaparelli lander of the ExoMars 2016 mission has been carried out in Martian flow environment of the arc heated facility L2K. The combined sensors COMARS and the broadband radiometer for radiative heat flux measurements were able to successfully measure the radiative heat flux on the back cover close to the vehicle shoulder for the first time on a Mars entry vehicle. To allow further validation of the numerical codes applied to simulate flow field and radiation properties of the EXOMARS COMARS+ flight data from Schiaparelli capsule descent phase (Test cases test cases TC1A), further Martian atmosphere experiments in DLR’s arc heated facility L2K with dedicated diagnostics are being performed. Two test case flow conditions with different enthalpies have been identified for a mixture of 97% carbon dioxide and 3% nitrogen representing the chemical composition of Martian atmosphere to measure thermochemical and radiation properties in the free stream and behind a shock layer of a scaled model of the Schiaparelli capsule.

The COMARS+ broadband radiometer is used to measure the radiation properties of both the free stream and the shock region. For characterization of the thermochemical properties of free stream and shock region non-intrusive spectroscopic measurement techniques as Fourier Transformed InfraRed spectroscopy (FTIR), UV-VIS Emission Spectroscopy (ES), Laser Induced Fluorescence spectroscopy (LIF), and Diode Laser Absorption Spectroscopy (DLAS) are used. Additionally profiles of Pitot pressure and heat flux have been measured to verify homogeneity of the free stream at the model location.

**ExoMars / 43**

**Flight Data of the COMARS+ Instrumentation Package of the ExoMars Schiaparelli Lander**

**Authors:** Ali Gülhan, Thomas Thiele, Frank Siebe, Rolf Kronen, Thorn Schleutker, Lars Steffens

The instrumentation package COMARS+ was part of the back cover instrumentation of the ExoMars Schiaparelli lander and consisted of three COMARS sensors and one broadband radiometer. The aerothermal sensors called COMARS combine four discrete sensors measuring static pressure, total heat flux, temperature and radiative heat flux. The Schiaparelli capsule was launched on top of a Proton launcher on 14th March 2016. The entry into the Martian atmosphere took place on 25th October 2016. All COMARS+ sensors operated nominally during the complete entry phase. But the complete flight data package is not available due to an anomaly that led to the failure of Schiaparelli shortly before landing. Nevertheless, a subset of the COMARS+ flight data was transmitted real-time during the entry phase and was received by the ExoMars 2016 orbiter, with the exception of the plasma blackout phase (see Figure 1). The radiative heat flux on the back cover close to the vehicle shoulder was measured successfully for the first time on a Mars entry vehicle. The measured maximum radiative contribution was more than 60 % of the total heat flux at the first measurement point after the blackout phase. These measurements confirm recent findings that radiative heating can be a significant portion of the total heating on the back cover during Mars entry. In addition measured total heat flux rate on the back cover has been compared with the stagnation point heat flux rate.
Summary:

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ExoMars / 55

Rebuilding of icotom radiometer data during SCHIAPERELLI MARTIAN ENTRY

Authors: Julien Annaloro¹; Pascal Boubert²; Arnaud Bultel³; Marie-Claude Druguet¹; Emmanuel Duffour⁵; Mickaël Jacquot⁷; Viviana Lago⁶; Sébastien Menecier³; Frédéric Perisse³; Nicolas Rembaut³; Philippe Rivière⁷; Anouar Soufiani³; Martin Spel³; Damien Vacher³

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In spite of the crash of Schiaparelli, the Exomars Descent Module in October 2016, following a nevertheless successful aerothermodynamic entry, data from the infrared radiometers ICOTOM embedded of the COMARS modules was sent to the orbiter before and after the blackout phase. Three pairs of radiometers were located in line on the back shield of the probe in order to monitor the infrared radiation received by the thermal protection system from CO and CO2 molecules. Within a pair, one ICOTOM (B1) was dedicated to the range 4.17-5 µm (2000-2400 cm⁻¹) and the other one (B2) was dedicated to the range 2.6-3.36 µm (2950-3850 cm⁻¹) in order to collect cold and CO2 bands as well as CO rovibrational radiation. Flight data provided radiative heat flux densities in both ranges for three locations in the shield, especially at the end of the hot phase. Lower housing temperatures than expected led to recalibration of the ICOTOM depending on the incoming flux and on the sensor own temperatures.

In order to derive of maximum of information about the thermodynamic status of the gas behind the spacecraft, CNES gathered laboratories and companies to rebuild the aerodynamic field, the chemical composition, the non-equilibrium status and the radiative transfer within the back body plasma from numerical simulation and on-ground experiments.

The main purpose is to obtain a comprehensive numerical tool able to recover the flight measurements and to deal with similar entry situations in the future. Only few hypotheses were made
especially about the equilibrium status of the plasma and about the angle of attack of the probe. Then the implicit-in-time code has been developed for 3D geometry and includes partial state-to-state chemistry. Kinetic chemical models developed for 0D and 1D geometry were reduced in order to make them compatible with reasonable computation times. However, a full (vibrational and electronic) model is used along lines in the flow with a Lagrangian approach. A specific scheme has been established to describe the vibrational structure of CO2. That model has been made compatible with chemical and radiative calculations. Solving the radiative transfer equation within the back body plasma implies to take into account possible non-equilibrium effect in CO2 vibrational populations. Following a line-by-line model working out of equilibrium, a statistical narrow-band model was developed in order to reduce the time cost of calculations involving aerodynamics, chemistry and radiation. However, radiation transfer calculations were not coupled to the aerothermochemistry calculations and are carried out as a post-treatment on the fields of densities and temperatures (when applicable).

Another important part of the project consists of ground tests of ICOTOM radiometers on plasmas close to those encountered by Schiaparelli. That experimental approach is to confront the signals given by the ICOTOM radiometers and the heat flux densities derived from them with laboratory measurements obtained by optical and laser spectroscopy and interferometry. Ground plasma flows are then used as test cases both for ICOTOM measurements and for numerical simulation. Various facilities such as ICP and arc-jet plasmas were used within that study.

Summary:
The flowfield around Schiaparelli was rebuilt including partial state-to-state approach. After having adapted the radiative model of CO2 to non-equilibrium situations, the radiative transfer equation was solved within the back body plasma in order to be compared with flight data from infrared ICOTOM radiometers. Complementary experiments on ground plasma facilities were carried out in order to improve the understanding of CO2 vibrational population and CO2 dissociation.

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VUV emission measurements in an ICP torch facility

Authors: Sean McGuire\textsuperscript{1}; Brett Cruden\textsuperscript{1}; Christophe Laux\textsuperscript{2}; Augustin TIBERE-INGLESSE\textsuperscript{2}

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For manned missions beyond earth orbit, the radiative heat flux is expected to represent a significant portion of the total heat flux to the capsule surface. This is due to the high entry speeds and large capsule sizes expected.\textsuperscript{[1, 2]} Examples of where the radiative heat flux becomes substantial include missions to Venus\textsuperscript{[1]} and Mars return to earth missions\textsuperscript{[3]}. A substantial portion of this radiative heat flux occurs in the VUV portion of the spectrum.\textsuperscript{[4, 5]} For Venus and Mars atmospheres, composed primarily of CO2, the CO(4+) band in the VUV represents either a significant or dominant portion of the radiative heat flux. It is therefore important to validate the radiation models used for this system and to reduce the corresponding uncertainty as much as possible. The work of Brandis et al.\textsuperscript{[6]} and Cruden et al.\textsuperscript{[5]} compared experimental measurements of CO(4+) radiation in the NASA EAST shock tube facility with theoretical predictions using established radiation codes. Their goal was to validate the predictive capabilities of these radiation codes. However, the models underestimated the measured radiation by a factor of 2. One potential reason for this discrepancy, among others, is that the bands responsible for CO (4+) emission have not relaxed to the equilibrium post-shock temperature.

Our goal is to address this issue. The plasma facility at laboratoire EM2C operates at atmospheric pressure and provides a plasma in chemical and thermodynamic equilibrium at approximately 7000 K. We therefore have the capability to study emission from an equilibrium plasma, with the entire chemical composition and thermodynamic state accurately described by a single temperature. We
can compare the measured emission to that predicted from radiation codes to validate these codes. For the radiation calculations, we use the code SPECAIR.[7] For the experimental measurements, we use a McPherson VUV vacuum spectrometer capable of making measurements down to 120 nm. We have a preliminary comparison between experimental measurements and theoretical predictions down to 165 nm. The preliminary measurements show good agreement between the model predictions. Our goal is to extend these measurements down to 150 nm and to perform a comparison between several different models available in the literature. We also plan to study VUV emission from air plasmas in order to study the VUV NO bands in the UV/VUV regions of the spectrum.


Summary:
For the moment I submitted a blank placeholder file.

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Generating High Speed Earth Re-entry Test Conditions in an Expansion Tube

Authors: Christopher James¹; Steven Lewis¹; David Gildfind¹; Richard Morgan¹; Timothy McIntyre¹

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Future space missions, such as planned asteroid sample return missions or interplanetary missions such as return from Mars, will involve entrance speeds from 13 to 15km/s. While current hyperbolic Earth re-entry conditions such as Apollo, Hayabusa, and Stardust all featured some degree of radiative heating, a 15 km/s Earth entry will cross the threshold into the region where radiative heat flux is of a similar order of magnitude to the convective heat flux and conditions will be ‘radiatively coupled’. Radiative coupling means that the amount of radiative energy transfer in the shock layer results in significant departure from the assumption that the shock layer is adiabatic. For these flows to be modelled correctly, a radiative energy exchange term must then be added to the CFD source terms when the flow is simulated. This increases computational time and is a situation which has rarely been experimentally simulated.
The degree of radiative coupling is generally characterised using a non-dimensional number called the ‘Goulard number’ [1] which is the ratio of radiative energy flux to the total energy flux in the shock layer. A Goulard number above 0.12 is generally considered ‘strongly coupled’, with a Goulard number below that value being classed as ‘loosely coupled’. Loosely coupled conditions can be simulated with a normal CFD flow solver, with radiation calculations able to be performed after the CFD calculations have finished. Generally, due to scaling increasing convective heat flux in ground testing facilities, it is very hard to generate proper strongly coupled conditions in expansion tubes. A flow velocity of around 14 km/s would be required to generate strongly coupled conditions in X2.

Recently, equilibrium radiative heating up to 15.5 km/s was investigated experimentally in the Electric Arc Shock Tube (EAST) facility at the NASA Ames Research Center by Brandis et al. [3] by studying shock relaxation and integrated radiative power from a passing shock wave. This was compared to recent simulation data by Johnston et al. [4] and used to lower parametric uncertainties for high speed Earth re-entry from [32%, −21%] to [9.0%, −6.3%].

While NRST facilities used for the study of planetary entry are generally limited to the study of shock relaxation due to their very short test times, expansion tubes are very useful in these situations as they are capable of generating a real aerothermodynamic test flow for a short period of time. This allows them to not only be used for the study of shock relaxation over a test model, but also other flow phenomena which occurs over test models. This includes the study of shock standoff, wall heat flux, or even the study of hot or cold wall ablation using either resistively heated test models [5,6] or plastic or epoxy test models [7].

This paper investigates the possibility and feasibility of generating these high speed Earth re-entry conditions in the X2 expansion tube [8] at the University of Queensland (UQ).

REFERENCES


Summary:
Please find the abstract attached.

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EXPANSION TUBE EXPERIMENTS OF GRAPHITE ABLATION AND RADIATION IN HYPERVELOCITY EARTH-ENTRY FLOWS

Authors: Ranjith Ravichandran¹; Steven Lewis¹; Christopher James¹; Richard Morgan¹; Timothy McIntyre²

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The atmospheric entry of spacecraft is characterized by very high entry speeds and the formation of a bow shock in front of the blunt body. The sudden deceleration of the vehicle converts the kinetic energy of the vehicle into thermal energy of the gas which gets dissipated in the form of convective and radiative heat transfer. The gas species trapped inside the shock layer undergo a very high temperature rise in the order of thousands of kelvin that brings about dissociation, ionization and recombination reactions. To safeguard the vehicle and the scientific returns it may contain from the extreme heating conditions during entry, a thermal protection system (TPS) is employed. The basic constituent of the TPS in most cases is carbon and carbon based ablative materials. In this work, the ablation of carbon is experimentally studied under hypervelocity Earth-entry conditions generated in the X2 expansion tube facility at The University of Queensland, Australia.

A two-dimensional wedge model has been designed with an ablation source [1] mounted onto the compression face of the wedge, connected by copper electrodes. Graphite samples in the shape of rectangular strips have been used as the ablation sources which were resistively pre-heated using a DC power supply to simulate representative re-entry wall temperatures. The temperature of the pre-heated graphite strips was measured by a non-intrusive diagnostic technique called dual-wavelength signal ratio thermography [2]. The signal ratio between the two optically filtered images was used to obtain the two-dimensional temperature map of the heated strips.

The pre-heated graphite strip, upon exposure to the high enthalpy test gas flow, starts ablating and the ablated products mix with the flow which then pass through the expansion fan and further into the afterbody region. The evolution of the entrained ablation products and their interaction with the flowfield is experimentally investigated in this work. Optical diagnostics such as high speed video imaging and ultraviolet (UV) emission spectroscopy were used. The ablated carbon interacts with the nitrogen species available in the test gas flow and results in the formation of the cyanogen radical (CN) – a well-known radiator. The CN violet band emission is investigated for different wall temperature cases and the spatial and spectral distribution of radiance will be discussed. From the shapes of the vibrational transitions of the CN violet band, we have also attempted to extract the vibrational and rotational temperatures of the species by fitting the experimentally recorded spectra with the synthetic spectra.

REFERENCES


Summary:

Interaction of ablating carbon, from preheated graphite strip, with re-entry flows was experimentally studied in expansion tube X2. The flowfield was investigated using UV emission spectroscopy and CN violet band was studied for different cases from which we have attempted to estimate temperatures.
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Overview of ESA activities in the areas of Flight Vehicle Engineering

Authors: Guillermo Ortega¹; Louis Walpot²

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This keynote deliver the status of the ESA activities in the newly created area of flight vehicle engineering and aerothermodynamics. The keynote show mission, programs, technologies, and techniques on the above mentioned areas and provides an overview of the Agency current and upcoming activities.

This keynote will also include a small round table about ESA upcoming research activities on the field of radiation.

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Generic / 30

REFLECTIONS ABOUT THE CONCEPT “POPULATION DISTRIBUTION” AND THE THEME “SEPARATION OF MOLECULAR DEGREES OF FREEDOM”

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Thermodynamics has always been a fundamental and necessary discipline in support of fluid dynamics. In subsonic and (moderately) supersonic flows, the thermodynamic description of the fluid is relatively simple and can be accomplished at macroscopic, phenomenological level. Things complicate when energy densities in the flow field increase, as in aerothermodynamics. Nonequilibrium processes appear and the physical modeling requires a more incisive thermodynamic description whose understanding’s quest goes deeper into the microscopic layer of the physics at hand. In order to gain that understanding, we must be prepared to zoom in at molecular-structure level and to acquire sufficient knowledge of the necessary elements of quantum mechanics. In general, our thermodynamics-description strategy is based on perfect-gas mixtures whose molecules are thought to be in quantum-mechanical stationary states before and after collisions and/or interactions with fields. Accordingly, we introduce the concept of “quantum-state population distribution” and then we either follow a multi-temperature approach (Boltzmann population distributions) or a state-to-state approach (non-Boltzmann population distributions) to characterize the nonequilibrium dynamics of the physicochemical processes taking place in the fluid. The idea behind this practice seems so natural and, above all, so quantum-mechanically consistent that we take it for granted and we proceed to apply it without hesitation. But, does quantum mechanics really teach that this is the right thing to do? How does the concept “population distribution” arise within a quantum-mechanical context? This presentation attempts to find answers to these questions. The pursuit of the answers
necessarily drags on stage also the controversy regarding the separation of molecular degrees of freedom, a still frequently debated theme regarding which the author pointed out some misunderstood aspects a few years ago [1].


Measurement Techniques / 57

How atomic nitrogen overpopulation enhances molecular radiation in a recombining nitrogen flow?

Authors: Augustin TIBERE-INGLESSE; Sean McGuire; Christophe Laux

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We use optical emission spectroscopy to measure spectrally resolved radiation from a recombining nitrogen plasma for temperatures ranging from 3200 to 7000 K. An inductively coupled plasma torch is used to create an equilibrium plasma, which is then forced to rapidly recombine by flowing through a water-cooled tube. The density of atomic nitrogen is measured and found to be overpopulated. This overpopulation has an influence on the measured molecular radiation, enhancing it by a factor up to 100000.

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Absolute number density calibration of two-photon induced polarization spectroscopy with atomic oxygen

Authors: Arne Meindl; Stefan Löhle; Irina Kistner; Andreas Schulz; Stefanos Fasoulas

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3 Institute of Interfacial Process Engineering and Plasma Technology IGVP, University of Stuttgart, Germany
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Two-photon induced polarization spectroscopy (TIPS) is a laser diagnostic technique that relies on the simultaneous absorption of two photons, one being contributed by a strong, circularly polarized pump beam and the other by a weaker, linearly polarized probe beam. The two beams are crossed at a slight angle thus defining the measurement volume. Through consideration of the two-photon selection rules while choosing a suitable two-photon absorption transition to probe, it can be assured
that the absorption of one photon from each beam induces a polarization rotation within the probe beam. The induced polarization rotation can be detected behind an analyzing polarizer which is a linear polarizer in crossed alignment with the linear polarization of the probe beam.

TIPS has been used for detection of various molecules as well as of atomic hydrogen and xenon in the past. The study presented in this paper will feature some of the very first measurements of atomic oxygen ever performed using TIPS. The laser diagnostic setup has been developed in the High Enthalpy Flow Diagnostics Group (HEFDiG) at the Institute of Space Systems (IRS). The microwave-powered plasma source has been developed by the Institute of Interfacial Process Engineering and Plasma Technology (IGVP).

The TIPS signal is created in the moment of absorption thus rendering the technique immune to quenching effects and allowing for measurements at high pressures where fluorescence-based techniques would struggle or not work at all. This paper will feature measurements of atomic oxygen performed in an O₂ plasma created at atmospheric pressure in a microwave-powered burner.

The absolute number density calibration for measurements of atomic oxygen in the O₂ plasma is realized using xenon as a transfer species. This calibration approach originates with TIPS with atomic hydrogen and has since become a popular tool for calibration of laser-induced fluorescence measurements of atomic oxygen. A xenon cold gas cell is positioned at the measurement location and allows for TIPS measurements with controllable number densities of xenon. Since the ratio of the two-photon absorption cross-sections for the oxygen and the xenon transition is known, absolute number densities can be determined.

In the final paper, TIPS measurements of atomic oxygen in ambient pressure O₂ plasma will be presented along with TIPS measurements of xenon for absolute number density calibration. A detailed discussion of the absolute number density calibration method for TIPS with atomic oxygen will be presented along with different approaches through accurate lineshape modelling.

Summary:

This paper will present the current advancements in measurements of absolute atomic oxygen number densities. So far, two-photon induced polarization spectroscopy has been applied to atmospheric pressure plasma conditions. This is the first time that this technique has been used successfully for quantitative measurements of atomic oxygen. The paper will contain a detailed discussion on the calibration approach through lineshape modelling while using xenon as a reference species.

Measurement Techniques / 49

SPECTRAL EMISSIVITY OF UHTC COATINGS FOR SUPER LIGHT-WEIGHT THERMAL PROTECTION SYSTEMS OF SPACE RE-ENTRY VEHICLES

Authors: Carlo Purpura¹; Eduardo Trifoni²

Co-authors: Marius Kutemeyer²; Gennadiy Frolov³; Irina Neshpor⁴; Laura Silvestroni⁵; Maria Parco⁶

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A test campaign was performed in the GHIBLI arc jet facility in the framework of the European funded LIGHT-TPS project, devoted to research and development of Ultra-High Temperature Ceramics (UHTC) coatings on Ceramic Matrix Composites (CMC) for super light-weight Thermal Protection Systems (TPS) of space re-entry vehicles.

Two UHTC coatings made of different zirconium diboride (ZrB2) compositions, ZrB2-3SiC-5WC and ZrB2-20SiC-10AlN, were tested with the aim of increasing the oxidation resistance of the Carbon/Carbon (C/C) CMC substrates. In particular four UHTC coated flat disks of 20 mm of diameter were exposed to an hypersonic jet of plasma composed of air and argon for a total duration of 5÷6 minutes, achieving a maximum surface temperature of 1800÷2000℃ at stagnation pressures of 23÷25 mbar. The UHTC coating made by ZrB2-20SiC-10AlN survived the tests forming an oxidized surface layer.

Three different pyrometers have been used to measure the surface temperature in the disk stagnation area. During the tests, one pyrometer was repeatedly switched from two-color to single-color mode in order to evaluate the experimental emissivity of the surface at different temperatures. At the end, in the range of temperature from 1700 to 2000℃ the measured spectral emissivity values at the wavelength of 0.9 μm varied between 0.5 and 0.8 for ZrB2-3SiC-5WC samples and between 0.6 and 0.4 for ZrB2-20SiC-10AlN ones.

Summary:
Spectral emissivity evaluation in plasma wind tunnel of UHTC coatings

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A compact FMCW reflectometer/interferometer design for the monitoring of atmospheric entry flows

Authors: Ricardo Ferreira¹; Jose Dias²; Antonio Silva³; Mario Lino da Silva¹; Luis Lemos Alves¹; Bruno Goncalves¹

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A compact reflectometer has been developed at Instituto de Plasmas e Fusão Nuclear for Fusion plasma monitoring applications. This work describes the application of this diagnostic to the conditions and requirements of atmospheric entry flows, where the knowledge of the properties for the plasma surrounding the vehicle is key.

Indeed, on the next experimental fusion reactors, the number of suitable diagnostics to measure relevant plasma quantities is very limited. Millimeter wave diagnostics are one of the obvious choice due to the limited in-vessel access requirements and front-end robustness. Frequency-Modulated Continuous-Wave (FMCW) reflectometry is a well established technique to measure electron density profiles and to provide feedback for plasma position and shape control in such applications.

As the telecommunication industry is focused on the next network generation such as 5G, manufacturers are releasing high performance Monolithic Microwave Integrated Circuits (MMIC) in a large scale and at affordable prices. For such reasons a prototype of a coherent fast frequency sweeping RF back-end was developed at IPFN-IST using commercial MMICs. One of the design goals for the back-end prototype focuses on the flexibility of the system, so that it can be easily matched to the required frequency ranges. The back-end alone covers the NATO J-Band (10 GHz to 20 GHz) and it is designed to drive external full band frequency multipliers resulting in an ultra-wideband coverage up to 140 GHz.

This means that such a diagnostic may be deployed for other plasma monitoring applications. One such application is the atmospheric entry of a Spacecraft, where the knowledge of the properties for
the plasma surrounding the vehicle, and namely the electron densities, is key for a) the validation of Computational Fluid Dynamic models with a comparison against predicted electronic densities; and b) the validation of radiative transfer models, since the radiative properties of a plasma are highly dependent on the populations of the excited electronic states of the plasma species, and since these excited states are preferentially populated through electron-impact reactions.

The potential for this improved reflectometer architecture, as pertaining these applications which are also key to IPFN activities, have motivated the current investigation, wherein the reflectometer is expected to be firstly field-tested on the ESTHER shock-tube in interferometer mode, and then further validated in reflectometer mode on ground test facilities plasma plumes, and ultimately on entry demonstrators, which may be as small as cubesats (3U architectures).

This work presents the reflectometer architecture, discussing the main key design features and the prototype performance. A numerical simulation of the reflectometer waves propagation is also presented for a representative high-speed Earth entry configuration (Phobos Sample Return capsule).

Summary:

Description of a novel reflectometer design for electron densities measurements in shock-tubes and entry vehicles.

Meteorites / 61

Spectral Analysis of Meteor Ablation by the Canary Island Long-Baseline Observatory (CILBO)

Authors: J.J. Zender\(^1\); Regina Rudawska\(^1\); Detlef Koschny\(^1\); Stefan Loehle\(^2\); Louis Walpot\(^1\); Maraffa Lionel\(^1\)

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The elemental composition in our early solar system is still one of the key questions to understand its evolution as well as our solar system objects (planets, asteroids, comet, ...) as we know them today \([4,5]\). Since many decades, scientists try to unravel this composition by a wide variety of experiments, i.e. by laboratory analysis of Interplanetary Dust Particles (IDPs) available from the Cosmic Dust catalog obtained by NASA ER-2 aircraft \([11]\), laboratory analysis of the Lunar soil samples brought back from the Apollo missions between 1969 and 1972, laboratory analysis of the Stardust particles collected at comet 81P/Wild \([2,3]\), as well as laboratory analysis of meteorites. Besides the measurement on ground, first results from space based instrumentation are now available, i.e. the COSIMA instrument on-board Rosetta analyzed dust grains from comet 67P/Churyumov-Gerasimenko \([1,9]\). Another indirect method of the analysis of elemental composition, is the analysis of the spectra obtained from the CILBO (Canary Island Long-Baseline Observatory) \([10]\) funded by the SCI Faculty. We will compare the chemical abundances obtained from several ground-based laboratories, space based experiments, and the CILBO spectral observations. The results obtained by the different sources are quite wide spread. Ground-based samples have the disadvantage that they might have been contaminated before their analysis. Space based experiments typically observe only one target, and it might be difficult obtain general conclusions. Meteor spectra analysis can provide the elemental abundances of many different dust particles from different cometary parent bodies (although we admit that our currently obtained observational (i.e. spectral) accuracy could be vastly improved). To obtain quantitative results from the CILBO spectral calibration requires not only a thorough calibration of the data, but also the modeling of the meteor ablation in the atmosphere. The modeling is rather complex and we use the PARADE tool in collaboration with our colleagues from ESA/TEC-M as well as with the University of Stuttgart (Faculty funded). We report on the required modeling work and its current progress \([6,7]\), as well as the activities executed at the University of Stuttgart.
to proof the correctness of the modelling work with corresponding laboratory experiments. The provided work would not be possible without Faculty funding!


Summary:
The talk will provide an overview of the elemental composition analysis using a diversity of methods, and then detail on the spectroscopy of meteors.

Meteorites / 68

Numerical simulation of a H5 chondrite radiative field: comparison with the experiments performed at the VKI plasmatron facility

Author: Bruno Dias

Co-authors: James B. Scoggins ²; Laurent Soucasse ³; Philippe Rivière ⁴; Anouar Soufiani ⁴; Thierry Magin ¹

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1. Introduction Meteoroids largely disintegrate during their entry in the atmosphere, contributing significantly to the input of cosmic material to Earth. Yet, their atmospheric entry is not well understood. Among the daily material delivered into our planet, the Chelyabinsk event in 2013 [1] renewed awareness of potential hazards motivating the planning of deflection and mitigation strategies of incoming asteroids. These strategies rely on the knowledge of the physical properties of the material and structure of the incoming object. At the range of velocities typical of meteor phenomena, radiation becomes highly significant, the intense light observed during a meteor entry is mainly due to the radiation of the air and metallic species, where the latter are
coming from ablation products. The current models to study meteor entries are focus in the ablation of small particles in the upper atmosphere. They usually rely on a zero-dimensional approach providing lack of an accurate treatment of the particle interaction with the atmosphere, from the fluid dynamic point of view. Moreover, experimental studies on meteoroid material degradation in high-enthalpy facilities are scarce and when the material is recovered after testing, it rarely provides sufficient quantitative data for the validation of simulation tools. In the work of [2], the author investigated the thermo-chemical degradation mechanism of a meteorite in a high-enthalpy ground facility able to reproduce atmospheric entry conditions. Time resolved optical emission spectroscopy data of ablated species allowed to identify the main radiating atoms and ions of potassium, sodium, magnesium, and iron. Three HR4000 spectrometers were used covering a wide spectral range (200 nm to 1000 nm) with a 2 mm distance from each other being the closest 1 mm from the surface. A H5 chondrite sample was cut into a cylindrical shape and it was embedded in a hemispherical holder of 50 mm diameter and 45 mm length made out of cork-composite ablative material and exposed to 1 MW/m² heat flux. The objective of this work is to simulate the plasmatron experiment by means of computational tools and to compare the spectral and total intensity with the measurements performed during the experiment. Solving the RTE by integrating the spectrum computed with the Line-by-Line (LBL) method becomes computationally very expensive for complex molecular spectra. In this work we use a hybrid statistical narrow band model (HSNB) [3,4] which has the feature of presenting an accurate description of the radiative flux with low CPU by dividing the spectra into narrow bands and compute the intensity in terms of averages. We extended the database to alkali and metallic atoms such as Fe, Mg, Si, Na, Al and many others. Due to the weak spectral density of the atomic lines, the LBL method is used to compute their contribution to the total intensity.

2. Methodology
The plasmatron flow field is reproduced by using a 1D Stagnation-Line solver where the physico-chemical properties are provided by the Mutation++ library built at the VKI [2]. The evaporation/condensation of a molten layer is estimated by solving a surface mass balance where the production terms are computed with the Hertz-Knudsen law. Also, oxidation and nitridation reactions were included to simulate the presence of carbonaceous species such as CN and CO due to the presence of the cork holder. Once the flow field solution is obtained one can build spherical caps around the sample assuming constant properties, leading to a 2D representation of the boundary layer. Moreover, the shape of the torch jet and the full plasmatron chamber is also included. This representation of the flow field is essential for the generation of the line of sight on which the Radiative Transport Equation (RTE) can be integrated and directly compared (as a post-processing) with the spectrometer measurements. Several optically thick and thin systems are considered including the CO and CN mechanism due to the presence of cork. Due to the saturation of the Na line (586 nm) during the experiment, this line has been removed from the experimental spectra.

3. Results & Conclusions
Several experimental time steps were chosen for the comparison with the numerical results. The measured surface temperature is imposed as a boundary condition for the numerical simulations. From the recorded spectra it is observed the appearance of a Planck continuum which might be due to the swelling of the cork and/or the boiling of the meteorite material. Based on that a swelling function in time is considered and the spectrometers which point directly to a surface are disregarded.

It is observed a strong effect of CN (violet) due to the presence of cork. This mechanism also coincides with the region where the second most important ablated species, Fe, shows the most important lines. It is also observed a significant emission of the N2(1+) and N2(2+) systems. Moreover, the small presence of potassium, K, around 10⁻⁶ mole fraction shows a strong impact on the spectral intensity.

A good agreement was observed in the spectral intensity of Fe by choosing and evaporation coefficient equal to the unity and a condensation coefficient around 0.3. Even though there cannot be a direct comparison of the strongest ablated species, Na, due to its experimental saturation, when included, the simulated spectral intensity becomes 10 times higher than the experimental, suggesting the importance of such element.

The mass loss of the sample predicted by the Hertz-Knudsen law is around 5mg which agrees reasonably well with the measurement after the experiment, 3 ± 1mg.

The use of cork as a sample holder complicates the comparison between the experimental and numerical results. Mostly due to swelling effects and presence of the carbonaceous species produced during ablation.
4. References


Summary:

Meteor entry is characterized by complex shock layer physics such as radiation, evaporation of the meteoroid surface and the resulting chemistry process with the air constituents. Moreover, several meteor observations include spectral measurements from which their composition can be inferred. Recently a ground facility experiment of an H5 chondrite was performed at the VKI plasmatron facility which includes the measurement of time resolved optical emission spectroscopy data of ablated species. In this work we present a model able to reproduce the ablation of meteors and the comparison of the numerical radiative field with the one observed in the experiments. It is observed that the numerical results agree generally well with the experimental data when nitridation and oxidation gas-surface reactions are included due to the presence of a cork sample holder.

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Artificial Shooting Stars on demand: Aerothermodynamics and Flight Data

Authors: Adrien Lemal\textsuperscript{1}; Koh Kamachi\textsuperscript{1}; Lena Okajima\textsuperscript{1}

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The paper and presentation will introduce the mission and the R&D activities with respect to material, plasma sciences undertaken by the Japanese space start-up ‘Astro Live Experiences’ (ALE) to develop safe, unparalleled and on-demand shooting stars. Various topics will be covered including, but not limited to:

- the ALE mission and benefit for society
- modeling of plasma and material brightness, fragmentation processes
- characterization of material brightness in arc-wind tunnels and,
- flight data.

Summary:

Results:
- Brightness computations
- Arc-jet characterization
- Upcoming flight data sample
Radiative Heating of the Saint Valentin Meteor Entry

Authors: Mario Lino da Silva¹; Luis Fernandes¹; Ricardo Ferreira¹; Joao Vargas¹; Philippe Reynier²

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We present a Computational Fluid Radiative Dynamics simulation of the Saint Valentin entry. CFD simulations have been carried out using the ESA code TINA, whereas radiative transfer simulations have been carried out using the SPARK Line-by-Line code, with an updated database capable of reproducing molecular VUV radiation of high temperature air plasmas.

A sensitivity analysis of the radiative fluxes to the different atomic and molecular systems taken into account in the database will be presented and discussed.

The solution for TC2B-ShockTube-Lunar will also be presented, using the SPARK code in 1D configuration and the spectral database utilized in this work.

Summary:

A CFD + Tangent Slab radiation simulation of a Meteorite Entry + A contribution to TC2B ShockTube-Lunar

AIRBORNE OBSERVATIONS OF RE-ENTERING SPACE DEBRIS

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The results of the airborne observation of ATV-1 resulted in excellent data about re-entry break-up [1]. The triangulation of the video data showed experimentally the distribution of debris on ground and the spectral data allowed some insight into the destructive entry process [1].
ATV-1 during re-entry flight (photo: C. Carpenter/B. Moede, NASA Ames)

The High Enthalpy Flow Diagnostics Group participated since then in all airborne re-entry observation campaigns of entering object and I was the science lead of the planned observation campaign of the last ATV-5, a mission which was cancelled at the last possible moment due to malfunctions aboard ATV-5 [2]. The paper gives an overview on airborne observation missions. It highlights challenges, preparation procedures and give an outlook into what data sets can be achieved. Recent results from missions I participated, WT1190F und CYGNUS OA6, will be presented as well. The paper gives an outlook of what is required to be experimentally simulate these effects on ground and how future events can be implemented in order to develop a database for re-entry break-up. The outlook will go into what can be drawn with respect to meteorite analysis.

References:

Summary:
The paper provides spectroscopic data from flight observation and ground testing of space debris and meteorites.

**Numerical Simulations / 63**

**Modeling And Experimental Investigation On CO2 Dissociation For Oxygen Production Under Martian Conditions**

**Authors:** Tiago Silva; Polina Oglobina; Vasco Guerra; Lohan Terraz; Ana-Sofia Morillo-Candas; Olivier Guaitella
Sending a manned mission to Mars is often viewed as one of next steps in space exploration. Naturally, all the challenges associated with this endeavour must be well-understood in order to sustain a permanent human presence. One of these challenges is the creation of a breathable environment. In this work, it is argued that a sustainable oxygen supply in Mars can be achieved by converting carbon dioxide directly from the Martian atmosphere. Under this scenario, it is then necessary to find breakthrough technology that efficiently converts CO₂. Here we propose the use of non-thermal plasma technology. This weakly-ionized gas medium allows the coexistence of energetic electrons with relatively cold gas molecules. Under such conditions, far from thermodynamic equilibrium, it is possible to intensify traditional chemical processes and to achieve molecular dissociation with high energy efficiencies. With this in mind, we address the possibility to use plasma as a viable and very interesting approach for oxygen production in Mars. This contribution presents a joint combination of experimental and modeling studies in which we have simulated the Martian conditions with the purpose of understanding the main mechanisms responsible for an efficient production of O₂ via CO₂ decomposition.

**Summary:**
State-to-State model for CO₂ dissociation in Mars conditions

**Numerical Simulations / 22**

**Radiation Modeling in the PIC-DSMC code PICLAS**

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**Abstract**

Radiation processes are important for the description and understanding of plasma phenomena, since the radiative heat flux on the capsule can be substantial [¹]. Experimental measurements are often complicated for several reasons. An alternative is the numerical simulation. Here, the common approach is the coupling of a CFD method with a radiation solver and a radiation transport solver. Especially the efficiency of these methods in dense flow regions, where radiation transfer becomes most important is an advantage. Nevertheless, the treatment of non-equilibrium effects in the flow field, which can strongly influence the radiative heat transfer, becomes problematic with CFD methods. To overcome this problem, a gas kinetic description of the plasma is necessary. This is often done by using the Direct Simulation Monte Carlo Method (DSMC) [2]. Previous approaches of coupling a particle code with a radiation solver [3, 4] revealed indeed promising results. Using DSMC, it is possible to produce detailed information about flow species, which can vary widely from the average. Detailed information about rotational, vibrational, and electronic excitation temperatures as well as the density of each species can be directly used as input variables for each cell of the radiation calculation, which would cause significant difficulties using CFD flow field data. A critical point of the radiation modeling is the solution of the Radiation Transport Equation (RTE). Here, different algorithms exist with different levels of accuracy and computational effort. In the Monte Carlo Method [5], the energy is divided into an integer number of particles. Their properties
like wavelength, direction, and position are randomly assigned. The way of each beam through the cells is traced and the optical path is calculated. Subsequently, the RTE is solved in the direction of the beam. In this work, first results of solving the RTE for radiation data, which are calculated within the PIC-DSMC code PICLas, are presented.

Acknowledgement

The authors gratefully acknowledge funding provided by Airbus Defence and Space, by Ariane-Group and by the Deutsche Forschungsgemeinschaft (DFG) within the project "Partikelverfahren mit Strahlungslöser zur Simulation hochenthalper Nichtgleichgewichts-Plasmen" (project number 393159129).

References


Summary:

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3D MONTE CARLO RADIATIVE TRANSPORT COMPUTATION FOR MARTIAN ATMOSPHERIC ENTRY

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Entry computations for Martian atmosphere yield to significant radiative heat loads. CO2 is the main constituent of this 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 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 and accurately predict the heat load on the entry vehicle.

In 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 [2] 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 [3,4] for entry flow computations is used. It features equilibrium and non-equilibrium computations for earth atmosphere and equilibrium computations for a Martian atmosphere. Within the last couple of years a Photon Monte Carlo Method called StaRad (Statistical Radiation) is developed and implemented. In our early investigations [5,6] we focused on detailed comparisons with analytical methods. Here, we could demonstrate its general capabilities and its computational precision. Recently we published an investigation about full 3D radiative transport computations of entry shock layers in earth atmosphere [7]. Here, a detailed description of the method and a discussion about advantages and disadvantages from variations of the method is given.

Since our Photon Monte Carlo radiative transport solver can be coupled to many spectral modeling methods and databases such as PARADE [8], NEQAIR [9] or HITRAN/HITEMP [10] we move forward with this investigation and apply our computational setup to the Martian atmosphere entry shock layer. 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.

REFERENCES


Summary:
What to write here?

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Simulations of Carbon Dioxide Infrared Radiation in Shocked and Expanded Flows

Authors: Ulysse Dubuet1; Adrien Lemaî2; Satoshi Nomura3; Hiroki Takayanagi3; Shingo Matsuyama3; Kazuhisa Fujita3

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Background

Upcoming missions to Mars considered by JAXA generate strong motivation in designing advanced thermal protection systems (TPSs) with low design margins, in an effort to reduce the launching costs and increase the scientific value of the mission by embedding larger payloads and to enhance the reliability and safety of the reentry systems. The sizing of the TPSs relies on the knowledge of the physico-chemical processes heating the spacecraft on its front and back covers using a combined approach based on ground experiments and numerical simulations. For entries into CO2-based atmospheres, measurements contributed to mitigate the uncertainties in front shell TPS. The back shell received little attention since the heating loads, especially the radiative heating, were deemed negligible. However, recent numerical studies demonstrated that the radiative heating encountered by a spacecraft on its back shell was dominated CO2 infrared (IR) radiation (at 2.3, 2.7, 4.3 and 15\(\mu\)m) and was of the order of magnitude of the convective heating. These findings triggered measurement campaigns of CO2 IR radiation under nonequilibrium and during expansion.

This paper aims at assessing the various radiation models with respect to the works of, to strengthen the predictive capabilities of the current simulation tools, and to compute the radiative heating withstand by a Martian reentry spacecraft.

Methodology

In this work, we want to reproduce absorption and emission spectra obtained through various experiments (nozzles, shock-tubes, expansion-tubes). The radiation emitted from a CO2-based mixture is computed with the in-house Structured Package for Radiation Analysis (SPRADIAN) code and the Carbon Dioxyde Spectroscopic Databank (CDS). This database was selected after the works of Lemal et al. (2018). In this work, we use a multi-temperature model for the calculation of the populations of the different rovibrational levels.

The present work considers the complete expression of the effective Hamiltonian to compute the rovibrational energy levels. The Hamiltonian is built using the same parameters as Tashkun, and the rovibrational levels’ energy are obtained through its diagonalization. It is possible to extract the contributions of the different couplings and interactions by decomposing the Hamiltonian before diagonalization, and applying the change of basis to the different parts of the Hamiltonian. This allows to use the rovibrational levels’ energies in within the multi-temperature model for nonequilibrium conditions.

Once the Hamiltonian built, it is possible to calculate the levels’ populations. Using a 5-temperature model, we need to consider a pseudo-temperature applied to the coupling and interaction part of the levels’ energy. In order to investigate multiple cases, we chose to use \(T_{\text{coupling}} = T_{\text{a}}^a T_{\text{b}}^b T_{\text{c}}^c T_{\text{rot}}^d\) with \(a + b + c + d = 1\); by choosing appropriate exponents, we will be able to investigate the impact on the populations of considering the coupling and interactions’ part of the levels’ energy with some particular vibrational mode.

Results

A database of approximately 7.3M states has been computed using Python’s numpy, pandas and multi-threading libraries (with a maximum polyad number of 40, a maximum rotational number of 300 and an energy cutoff of 55000cm\(^{-1}\)).

The correctness of the calculated energies was checked thanks to equilibrium simulations in the 2.7 and 4.3\(\mu\)m regions. We compared SPRADIAN’s results to Depraz’s EM2C database, Depraz’s use
of CDSD [Depraz et al. (2014)] and Vargas’s results [Vargas et al. (2018)]. Better agreements with CDSD were obtained than the former EM2C database and Vargas’s results.

Other tests were performed by trying to reproduce EAST experimental emission spectra for a $3.12\text{km.s}^{-1}$ shock wave. We observed the same behaviour than Cruden et al. (2014) and RADIS [Pannier et al. (2018)], i.e. that the frozen chemistry describes the emission spectra better than the equilibrium chemistry. Nonetheless, some discrepancies were observed with RADIS simulations, for the same input temperatures and pressures.

Other simulations investigated the influence of the pseudo-temperature on the absorption and emission spectra, under nonequilibrium conditions. The first results show a small impact of the choice of the pseudo-temperature, especially on the absorption coefficients.

The absorption and emission spectral shapes are very sensitive to nonequilibrium conditions. Future shock-tube experiments at Chofu Aerospace Center will be investigated through the spectral fitting method, using these new simulation tools.

**Conclusion**

The first simulations made thanks to the improved radiative solver give good agreement at equilibrium, and an useful spectral shape sensitivity for nonequilibrium conditions. The coupling and interactions part of the levels’ energies thus seems to have a non-negligible impact on absorption and emission spectra.

It will also be possible to perform spectral fitting on the future experimental spectra obtained with JAXA experimental facilities. Investigations of previous expansion-tube experiments are also planned, using CFD (with JAXA in-house code JONATHAN) and radiative simulations.

**Summary:**

This paper presents the efforts in simulating the infrared radiation emitted by CO2 under nonequilibrium conditions, such as encountered in shock waves and wakes, when CO2 undergoes dissociation and recombination, respectively. This paper addresses the modelling and computation of CO2 spectral properties with the Carbon Dioxide Spectral Databank (CDSD-4000) under thermal nonequilibrium, under the multi-temperature formalism. Schemes to split the level energy into its pure vibrational, rotational and vibration-rotation coupling and interactions contributions are proposed and implemented into JAXA in-house solver to compute nonequilibrium spectral properties. Available experimental data under equilibrium and nonequilibrium conditions were used to evaluate the correctness of the implementation and the performances of the spectral code. The influence of the energy splitting model on CO2 infrared radiation is discussed.

**Numerical Simulations / 37**

**A pseudo-elastic mesh r-adaptation algorithm for hypersonic flows in COOLFluiD**

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**1. Introduction**

Computational Fluid Dynamics (CFD) represent the most cost-effective tool to characterize re-entry flows aiming at providing an accurate prediction of engineering inputs (e.g. surface heat fluxes) for
the design of TPS and the overall success of space missions. The vast majority of state-of-the-art CFD codes tackling hypersonic applications rely on second-order Finite Volume (FV) that are robust and easy to implement. Unfortunately, achieving an accurate heat flux prediction is still a challenge even on simple geometries, leading to an unoptimized design of the TPS. CFD analysts acknowledge the importance of using well-designed grids to obtain accurate flow results, since mesh/shock misalignment lead to shock instability, noisy post-shock regions and poor heat flux predictions. To overcome those deficiencies, state-of-the-art ATD simulations require demanding mesh generation processes and grid convergence studies resulting in a high run-time and considerable computational effort. All this makes numerical analysis more challenging and time-consuming especially for those kind of applications where high aspect ratio meshes are needed, close to the space vehicle walls, in order to resolve boundary layer features and obtain accurate numerical heat fluxes. Adaptive Mesh Refinement (AMR) represent a robust procedure for improving the quality of the physical results, especially heat flux prediction, due to a local increase of the grid resolution and mesh/shock alignment, at the price of an increased algorithmic complexity.

2. Adaptive Mesh Refinement

In our previous work, a robust and efficient r-refinement algorithm (i.e. repositioning of mesh points based on the solution of a pseudo-elastic system of equations) has been developed and already applied to multiple test cases. The existing AMR algorithm works on triangles, isotropic quadrilateral and tetrahedral cells, is fully parallel, implemented as a standalone module and totally physics-independent, letting the user decide which monitor physical quantity to use for driving the adaptation according to the application. In this work, we develop novel concepts and integrate them into the existing AMR algorithms, in order to automatically improve 2D Cartesian high aspect ratio meshes and being able to overcome the unphysical stagnation heat flux peak resulting from state-of-the-art FV simulations on an initially unfitted mesh.

- Semi-torsional (ST) spring for 2D Cartesian meshes
In this work, we propose a new variant of the ST spring analogy that can be applied to 2D quadrilateral meshes. The novel ST combines local physical and geometrical properties.

- Hybrid Spring Analogy (HSA)
The idea for the HSA is to define a certain distance, denoted acceptable distance, from a user-defined boundary in which the mesh will incorporate two different spring concepts. In this work, HSA leads to specify two different dynamic mesh motions: (1) nodes close to the wall boundary are frozen and (2) the others are free to move based on the solution of the associated pseudo-elastic system.

- Smoothing the nodal displacement
The mesh distribution is not uniform and this affects the nodal wall distance computations which is needed within the HSA. We observed that the limit of each wall distance contour crosses some cells and hence, within the same cell, different nodal wall distance values exist. Hence, starting from the limit cells located at the acceptable distance, i.e. interface, a linear interpolation applied to the dynamic mesh motion from blocked nodes to a full movement is proposed.

- Smoothing the spring network
The use of the HSA can be extended to split the mesh into three different spring concepts. The original idea was to use the following three different spring analogies: Blocked nodes close to the wall, ST analogy for the transient and linear spring analogy for the rest of the grid. The latter is used in order to refine the shock only by physics-based gradients. A jump in the stiffness coefficient from the ST spring concept to the linear one is observed and introduces brutal changes in the displacement of the nodes leading the code to crash due to the bad mesh quality. An exponential interpolation is applied to smooth the spring constant from the ST to the linear one.

- Solution interpolation
The AMR is a post-processing step. In this manner, the cell-center value is conserved and moves due to the nodal displacements. Since the r-refinement suffers when dealing with high aspect ratio meshes, the flow field is affected negatively by the adaptation and for some test cases, the shock gets too close to the boundaries, leading to a blow-up of the solution. Hence, an interpolation step after the mesh refinement is implemented to ideally dissociates the computations of the nodal movement and the solution in each cell center value in order to preserve the shock position and the subsonic flow distribution.
3. Hypersonic Flow simulations

The reference test case presented is the hypersonic flow around the Qarman CubeSat. QARMAN is the CubeSat for Aerothermodynamic Research and Measurements on AblatioN of VKI, developed in the framework of the QB50 project. For the present results, dissociated air with five species is considered: $O, N, NO, O_2, N_2$. For the TCNEQ simulation a two-temperatures model is used considering the following free-stream conditions:

- $M = 8.46$
- $p = 39.53[Pa]$
- $\rho = 1.970 \cdot 10^{-4}[kg/m^3]$
- $T = 530.3[K]$
- $T_v = 2343.3[K]$

In addition the wall is considered isothermal with $T_w = 1000K$.

Using our new AMR based on the flow density as a monitored flow field variable, the grid is adapted and mesh points migrate toward the bow shock, increasing the grid node density around the shock. This result indicates how promising is the proposed approach for tackling high-aspect ratio Cartesian meshes.

To highlight the improvement of the physical results, COOLFluiD heat flux estimation is computed on the same fitted and unfitted computational grid. When applying our new AMR algorithm, the unphysical heat flux stagnation peak resulting from state-of-the-art FV simulations on an initially unfitted mesh disappears leading to more accurate predictions when applying the newly developed physics-based AMR.

References


Summary:

When predicting heat fluxes acting on Thermal Protection Systems (TPS) of space vehicles during the hypersonic re-entry phase, state-of-the-art numerical flow solvers do not automatically achieve the required accuracy, even on simple geometries, unless great care is taken when generating the corresponding computational mesh. Within this context, our work proposes an improved mesh adaptation algorithm based on r-refinement (i.e. repositioning of mesh points based on the solution of a pseudo-elastic system of equations) especially designed to handle high-aspect ratio cells, as required by viscous hypersonic flow calculations. The target application for this work is the flow simulation and, in particular, the heat flux prediction around a blunted QARMAN CubeSat geometry. The COOLFluiD aerothermodynamic (ATD) code, i.e. a state-of-the-art second-order implicit Finite Volume solver for thermochemical nonequilibrium flows, is used for all computations, together with linear meshes. Our mesh adaptation algorithm, based upon the concept of hybrid spring analogy in combination with both physics- and geometry-based stiffness definitions, manage to better capture the shock layer properties and shows its potential for automatically tackling the heat flux issue on our representative 2D testcase.
1. Introduction

Hypersonic aerothermodynamics (ATD) involves a plethora of complex physical phenomena. The harsh environment within the post-shock region produces a significant effect on the flow where fluid properties such as specific heat, viscosity and thermal conductivity can no longer be considered constant as in traditional aerodynamics. Instead they vary with temperature, pressure and chemical composition. Under these conditions, the space vehicle’s TPS experiences high thermal loads due to among others an exothermic chemically reacting boundary layer around the re-entry vehicle.

The developed open-source high-order solver focuses on thermo-chemical nonequilibrium (TCNEQ) hypersonic viscous flows. The Flux Reconstruction (FR), or Correction Procedure via Reconstruction (CPR), formulation is used, coupled with a novel positivity preserving shock capturing scheme adapted to TCNEQ flows. The solver is part of the world-class open-source framework for multiphysics modeling and simulations COOLFluiD. More information on the development of this platform can be found in [1,2].

2. Flux Reconstruction Code

The FR formulation is a compact high-order method with a large computational efficiency as compared to traditional low-order methods. It was originally developed by Huynh in [3]. The FR approach is readily adaptable to high-performance parallel architectures and is capable to deal with complex unstructured geometries. Our high-order FR code, which is parallel and fully implicit, is able to solve the Euler and Navier-Stokes equations in 2D and 3D. In addition, its structure is extremely modular and can be easily coupled to arbitrary sets of advection-diffusion-reaction PDEs. In particular, the FR solver is extended to solve TCNEQ flows by adapting the convective and diffusive flux schemes in order to deal with the extended set of governing equations, by interfacing the Mutation library for providing the physico-chemical properties, by adding the source term discretization to the FR method, by implementing boundary conditions and a novel shock capturing scheme. Robust shock capturing is the main pacing item for high-order finite element-type CFD methods. In the vicinity of discontinuities within the flow field, spurious oscillations appear due to the Gibbs phenomenon. This effect is more severe for higher orders, stronger shocks and more complex physical models. Several schemes to overcome this problem have been investigated in among others [4,5]. However these schemes have not been successfully applied in conjunction with FR to viscous hypersonic flows, let alone TCNEQ. The present solver incorporates a modified positivity-preserving Localized Laplacian Artificial Viscosity scheme adapted to TCNEQ flows.

3. Hypersonic Flow Simulations

The reference test case presented is the hypersonic flow around the QARMAN CubeSat. QARMAN is the QubeSat for Aerothermodynamic Research and Measurements on AblatioN of the von Karman Institute, developed in the framework of the QB50 project.

For the present results, dissociated air with five species is considered: $O, N, NO, O_2, N_2$. For the TCNEQ simulation a two-temperatures model is used. The wall has a constant temperature of 500K. The considered free stream conditions are:

- Mach = 8.46
- $p = 39.53$ Pa
- $\rho = 1.970 \cdot 10^{-4}$ kg/m$^3$
Using the FR solver, promising flow fields for second- and third-order of accuracy were found on a 2D mesh consisting of curved quadrilateral elements. The results were compared with the Finite Volume solver of COOLFluiD and a good agreement was found in terms of flow field and heat flux prediction.

References


Summary:

Numerical simulations of hypersonic flows around re-entry vehicles and space debris have traditionally been carried out with low-order Computational Fluid Dynamics (CFD) codes using a multi-temperature finite rate chemistry model. The vast majority of state-of-the-art codes rely on standard second-order schemes that are robust and relatively easy to implement. However, achieving accurate heat flux predictions and accurately capturing viscous effects such as shock wave-boundary layer interaction remains problematic even on simple geometries. This may potentially lead to an unoptimized design of the Thermal Protection System (TPS) of hypersonic vehicles. High-order finite element-type methods show great promise and are well-consolidated for certain classes of CFD applications such as turbulence, aero-acoustics, etc. These methods attain a much higher accuracy per degree of freedom as compared to traditional low-order methods. Additionally, they are very efficient in a massively parallel environment. However, these methods are still in their infancy for hypersonic applications due to the difficulty of robustly capturing shocks.

The present paper presents a novel high-order Flux Reconstruction solver that is capable of simulating hypersonic thermo-chemical nonequilibrium flows. The Flux Reconstruction method is coupled with a novel positivity-preserving shock capturing scheme in order to handle strong shocks. This solver is developed in the open-source COOLFluiD platform for multi-physics simulations. The applicability of the present solver to simulate the flow around the QARMAN CubeSat during re-entry is demonstrated.

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SELF-CONSISTENT STATE-TO-STATE MODEL FOR HYDROGEN IONIZATION IN HYPERSONIC SHOCK TUBE

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The paper is focused on the state-to-state kinetics modeling the dissociation and ionization of hydrogen in high-enthalpy shock tubes. The model determines the rate coefficients of electron impact processes from the non-equilibrium electron energy distribution function (eedf) obtained solving the Boltzmann equation.

**Summary:**

The paper is focused on the state-to-state kinetics modeling the dissociation and ionization of hydrogen in high-enthalpy shock tubes. The model determines the rate coefficients of electron impact processes from the non-equilibrium electron energy distribution function (eedf) obtained solving the Boltzmann equation.

**Numerical Simulations**

**Computational Fluid Readative Dynamics of the Galileo 1995 Jupiter Entry: An Assessment of Radiative Models and Databases Impact on Wall Heat Fluxes Uncertainties**

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We present a reinvestigation of the Galileo 1995 Jupiter entry, where we attempt to reinvestigate the question of the excessive heating at the shoulder, which is postulated to occur due to radiative heating.

We consider two improvements to the radiative model: H2 molecular systems contributions to the plasma emission and absorption coefficients are accounted for, and a ray-tracing model for wall radiative heating is also considered, as opposed to the more traditional tangent slab approach.

Calculations have been carried out using the Software Package for Aerodynamics, Radiation, and Kinetics (SPARK). a 1D Axysymmetric model has been considered, and a high-temperature, multi-component transport description has been developed, using the Gupta–Yos mixing rule adapted by Bruno for the case of H2/He mixtures. The kinetic model is adapted from Reynier. The grid has been carefully tailored at the shoulder, so as to allow for ray-tracing simulations in this region.

Besides the reference calculation which will be compared against other data from the literature, as well as the actual fluxes derived from the Galileo probe TPS recession data, this work will present a few parametric sensitivity studies, including but not limited to: ray-tracing vs. tangent slab; atomic vs. molecular radiation; discrete vs. continuum radiation, etc...

Finally a solution for **TC2C-ShockTube-Saturn** will be presented, using the SPARK code and the spectral database from this work.

**Summary:**

A CFD + Ray-Tracing radiative transfer solution for the 1995 Jupiter entry of Galileo + a solution for TC2C-ShockTube-Saturn
Radiation supported plasma waves in non-equilibrium laser discharges

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Laser breakdown is observed when a high-intensity laser beam is focused into a small region of gas. The discharge is composed of two stages: (a) creation of the priming electrons, and (b) formation of a highly conductive and absorbing plasma. This initial phase is then followed by a post-discharge, characterized by the formation and propagation of a shock wave from the focal region. The breakdown threshold intensity for laser-generated plasmas depends on specific gas, the background pressure, the laser wavelength, and any presence of impurities. In this work, we present validation against experiments of a non-equilibrium model for laser induced-breakdown and the investigation of plasma kernel dynamics. The application considers laser generated air plasma at atmospheric background conditions. The hydrodynamics are described with the chemically reactive Navier-Stokes equations and the non-equilibrium effects are accounted for with a three temperatures model. Laser-plasma interaction over nanosecond time scales has been modeled with the Radiative Transfer Equation (RTE), including both multiphoton ionization (MPI) and inverse Bremsstrahlung (IB). For model validation, the absorbed energy has been compared against experiments. Preliminary results show that the laser generated plasma exhibits a two-lobe structure, developing both in the forward and backward directions. The extent of the rear lobe is both axially and radially larger than the forward lobe. As the laser is turned on, the first electrons are created via MPI. After those electrons are formed, the incident laser radiation is absorbed through IB. The electrons become in turn very energetic and an avalanche process dominated by electron impact ionization (IE) is initiated. While the reactants for MPI are depleted in the plasma core, MPI is still responsible of the formation of the new electrons at the kernel’s boundary. Because of these newly generated electrons the mixture becomes opaque at the plasma boundary and the location of laser energy deposition moves from the inner to the outer plasma layer. This, in turn, guides the dynamics of the radiation sustained plasma waves.

**Summary:**
Laser breakdown is observed when a high-intensity laser beam is focused into a small region of gas. The discharge is composed of two stages: (a) creation of the priming electrons, and (b) formation of a highly conductive and absorbing plasma. The application considers laser generated air plasma at atmospheric background conditions. The hydrodynamics are described with the chemically reactive Navier-Stokes equations and the non-equilibrium effects are accounted for with a three temperatures model. For model validation, the absorbed energy has been compared against experiments. Results show that Multiphoton ionization and inverse Bremsstrahlung guide the dynamics of the radiation sustained plasma waves.

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**Sensitivities to Plasma Radiation Database Generation for a Prospective High Speed Earth Entry Demonstrator Mission**

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Previous investigations have demonstrated how flowfield modelling can effect predicted level of radiation on a prospect future demonstrator-vehicle concept entering at hyperbolic velocity (Merrifield 2014). Thus far, sensitivities within the radiation database have only be briefly examined (Joiner 2015) by comparing PARADE and NEQAIR radiation databases. A significant difference uncovered in this brief analysis was that PARADE produced considerably higher intensities of N2 radiation than NEQAIR.

PARADE is the European Plasma Radiation Database and is freely available to ESA entities. There has been a considerable gap in the active development of this database (~5 years) but development is scheduled to restart soon to support the operation of ESTHER, a European high enthalpy shock tube designed to investigate radiation physics and shock layer kinetics associated with planetary entry. Given this gap in development, it is prudent to gauge the status of PARADE against other available databases, particularly with respect to high speed Earth return. In the first instance, this will proceed by a detailed comparison with results obtained from SPARTAN. The practical significance of the uncovered differences and uncertainties will be discussed in relation to effects on entry vehicle design justification and necessitated future studies to progress the state of knowledge and the capability of European Plasma radiation databases.

Summary:
Comparison of Plasma Radiation Databases for High Speed Earth Return

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**Shock Tubes / 56**

**European Shock-Tube for High Enthalpy Research: Test Trials and Instrumentation Setup Definition**

**Authors:** Mario Lino da Silva¹; Rui Gomes¹; Ricardo Ferreira¹; Rafael Rodrigues¹; Luis Lemos Alves¹; Bruno Goncalves¹; Arthur Smith²; Jim Merrifield²; Victor Fernandez Villac³

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Status of ESTHER and the associated VUV and CO2 IR instrumentation TRP’s

Summary:
Status of ESTHER and the associated VUV and CO2 IR instrumentation TRP’s

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**SHOCK TUBE MEASUREMENTS OF RADIATIVE HEATING FOR TITAN AND NITROGEN**

**Authors:** Aaron Brandis¹; Brett Cruden²; Christopher Johnston³

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Detailed spectrally and spatially resolved radiance has been measured in the Electric Arc Shock Tube at NASA Ames Research Center for conditions relevant to Titan entry, with varying atmospheric composition, free-stream density (equivalently, altitude) and shock velocity. The test campaign measured radiation at velocities from 4.7 km/s to 8 km/s and free-stream pressures of 0.1, 0.28 and 0.47 Torr with a variety of compositions. Radiances measured in this work are substantially larger compared to that reported both in past EAST test campaigns and in other shock tube facilities. Depending on the metric used for comparison, the discrepancy can be as high as an order of magnitude. Due to the difference with previously reported data, a substantial effort was undertaken to provide confidence in the new results. The present work provides a new benchmark set of data to replace those published in previous studies. The effect of gas impurities identified in previous shock tube studies was also examined by testing in pure N2 and deliberate addition of air to the CH4/N2 mixtures. Furthermore, a test campaign in pure N2 was also conducted with the aim of providing data for improving fundamental understanding of high enthalpy flows containing N2, such as high-speed entries into Earth or Titan. These experiments cover conditions from approximately 6 km/s to 11 km/s at an initial pressure of 0.2 Torr. It is the intention of this paper to motivate code comparisons benchmarked against this data set.

Summary:

SHOCK TUBE MEASUREMENTS OF RADIATIVE HEATING FOR TITAN AND NITROGEN FROM THE ELECTRIC ARC SHOCK TUBE AT NASA AMES

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SHOCK LAYER KINETICS OF CO AND CO2-BASED ATMOSPHERES

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ABSTRACT

The present paper reports the analysis of shocks in pure CO at velocities from 3-9 km/s in NASA Ames' Electric Arc Shock Tube (EAST) facility, with the intent of simplifying the analysis of CO2 shockwaves produced during Martian and Venus entries. Tunable diode laser absorption spectroscopy measurements were performed concurrently with emission spectroscopy over a wide spectral range (VUV through Mid-infrared). The temperature trends extracted from the data show CO dissociation rates much faster than suggested by previous models. The trend of C2 radiation suggests rates for C2 exchange and dissociation that are 1-2 orders of magnitude higher than those employed in the Park or Johnston models. Radiation in the mid-infrared from molecular CO is at odds with absorption measurements.

1. INTRODUCTION

In previous years, spectrally and spatially resolved measurements of shock layer radiation in shocks composed of CO2 and mixtures (with N2/Ar) relevant to Martian and Venus entries have been reported \(^3\). Among other things, these measurements have been used to revise shock layer radiation models that are used for aeroheating predictions [2]. These updated models are now being employed by NASA flight projects. While these models were found to better predict the EAST data than the
legacy models of Park [3], and are not inconsistent with available flight and ground test data in CO2, some question remains as to their correctness.

A more recent set of experiments was conducted to separate the impact of CO2 dissociation by starting the shock from CO molecules and using tunable diode laser absorption spectroscopy (TDLAS) to probe the molecular ground state and obtain translational temperature information [4]. This work focuses on the analysis of this shock tube data.

2. EXPERIMENTAL

Experiments were conducted in the NASA Ames Electric Arc Shock Tube (EAST) and have been reported elsewhere [4]. The EAST facility is a 10 cm inner diameter shock tube which is driven by an electric arc source. The shock waves travel 7.9 m downstream to the test section where measurements are performed. The TDLAS measurement performs a scan of CO absorption as a function of time at a fixed position in the tube. The properties of the laser allow for the measurement of a 0.07 nm spectral range in 0.5 s. The line measured corresponds to the fundamental vibrational transition of CO at a rotational quantum of J=51. A Gaussian or Voigt fit to the lineshape allows the extraction of an average translational temperature over the 0.5 s scan period. The intensity of the absorption may also be used to obtain the number density of CO.

Fig. 1. Spectrally and spatially resolved radiance data obtained from an incident shockwave in CO

Concurrently, four spectrometers obtain an image of the shock at one moment of time (accumulated over 0.1-1.0 s) at a fixed position, covering an axial length in the tube of 12.5 cm. The data is spectrally resolved and calibrated to units of absolute radiance. An example of such data is given in Fig. 1.

3. ANALYSIS

Temperature analysis of the shock is obtained from three different methods. The translational temperature is obtained from the Doppler width in the TDLAS data [4]. Rotational and vibrational temperatures are obtained by fitting the shape of C2 spectra. Electronic temperature is obtained by taking the Planck-limited data in the vacuum ultraviolet [1]. All four of these temperatures are co-plotted in Fig. 2 for a representative test. These are compared to predicted temperatures using three different CO dissociation rates. For this condition, the rate of Hanson [5] best represents the data. This rate is at odds with that of Schwenke, which is based on ab initio calculations from the electronic ground state of CO [6]. It is suggested that the difference may be attributed to the dissociation through metastable states of CO which would cut the activation energy for dissociation nearly in half.

Fig. 2. Measured temperature profiles and predicted temperatures using different CO dissociation rates

Fig. 3. Comparison of radiance attributed to C2 Swan bands on the basis of different reaction kinetic choices for CO dissociation and C2 dissociation/exchange

There are two reactions that influence the C2 density behind the shock. The rates proposed by Park [3] are 1-2 orders of magnitude larger than other measurements in the literature. An example of altering these rates is shown in Fig. 3 where the rates of Fairbarn [7, 8], along with the dissociation rate from Hanson, changes the shape of the C2 radiance curve versus that obtained from the Johnston model, which is based on Park’s rates, bringing it into better agreement with the measured data. The overprediction at the peak radiance is attributed to the lack of a non-Boltzmann model for C2. Measurements at much higher velocity, however, are better matched with the Johnston model. Thus, it is suggested that a new rate be constructed that matches the Johnston rate at high temperature and the Hanson rate at low temperature.

4. CONCLUSIONS

The full paper will discuss the above analysis in further detail along with aspects of CO radiation in the vacuum ultraviolet and near infrared.

5. REFERENCES


Summary:
Shock tests in pure CO have been examined to update modeling parameters in CO/CO2 atmospheres.

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**Revised shock layer radiation modeling for air**

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**REVISED SHOCK LAYER RADIATION MODELING FOR AIR**

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**ABSTRACT**

At the previous RHTG workshop, we reported a series of shock layer radiation measurements collected between 7-9 km/s and the corresponding disagreement to predicted radiance through the NEQAIR and DPLR codes. This presentation summarizes revisions to modeling practices in DPLR and NEQAIR as a result of this data and a revised comparison to both the shock tube data and radiometer data collected from the Orion Exploration Flight Test 1 (EFT-1). Significant improvements are demonstrated, with some remaining open questions.

1. **INTRODUCTION**

At RHTG-7, a presentation was given by the authors on a series of shock layer radiation measurements performed in air at velocities between 7-9 km/s, with focus on the non-equilibrium region of the shock. Comparisons against CFD and radiation predictions were performed using three different chemical kinetic model sets, two electron impact excitation databases and two different approximations of the 2-temperature model (i.e. Te=TT or Te=Tv). The findings included the following: 1) N2 and NO radiation was underpredicted by all models; 2) the quality of N2+ radiation predictions were dependent upon the pressure of the test and the model employed; and 3) predictions of atomic radiation were mixed, with some lines predicted well under certain modeling assumptions and conditions, while other lines were predicted better at different conditions/assumptions \(^1\).
This paper reviews these specific disagreements and the adjustments made to radiation models to improve the agreement. The adjustments include a re-examination of the quasi-steady state (QSS) models in NEQAIR and the reaction kinetics employed for air chemistry. The impact of these revisions upon the comparisons to shock-tube data will be discussed, and the new model will then be used to analyze radiometer data from the Orion Exploration Flight Test 1 (EFT1).

2. MODELING

The quasi-steady state calculations within NEQAIR were re-examined in the light of the new data. For the most part, NEQAIR’s QSS model has not been altered since the original work of Park [2].

The heavy-particle impact rates in NEQAIR have been revised to be consistent with literature values for the quenching of molecular states. The state-specific heavy-particle dissociation rates were also updated to be consistent with dissociation rates used in the CFD models. This involved scaling the state-specific dissociation rates such that the total dissociation rate is matched for a Boltzmann population of electronic states. Changes were also made to electron impact processes in the molecular QSS formulation. Besides updating excitation and dissociation rates, corrections were made to the integrations performed over both the electron energy distribution and the distribution of rotational states. Similar corrections were incorporated into the electron impact dissociation rates. These electron impact dissociation rates were then used to revise or introduce electron impact dissociation rates into the CFD models. Other processes that were added into the molecular QSS calculation include predissociation, and interactions of the excited states with other molecules and atoms through exchange and associative ionization reactions. In all cases, the inverse of every process is included in order to satisfy microscopic reversibility.

The atomic radiation models were also updated. Chiefly the update consisted of an examination of electron impact processes from different sources. Ultimately, a merged database containing the excitation rates of Huo [3] for allowed transitions, and Park [2] for spin forbidden transitions, was employed. Heavy-particle excitation is also introduced based on the work of Lemal, et al. [4] A final consideration is the interaction of excited atomic species with molecular ions, such as the dissociative recombination of N2+ into N. For much of the non-equilibrium regime, this is the dominant reaction determining the N atom concentration, thus should be included in the QSS balance. Assumptions regarding which states are involved in this process have significant impact on atomic radiation.

The reaction kinetics for the flowfield model is also re-examined. The major issue regards the rates of dissociation and exchange involving NO and their impact upon NO radiation. The NO exchange and dissociation processes are updated to be consistent with rates reviewed in the Journal of Physical and Chemical Reference Data [5, 6]. A single adjustable parameter was employed to match the measured data: the ratio of atomic to molecular dissociation rate for NO. A ratio of 5 was found to reproduce the data well over a range of pressures spanning almost two orders of magnitude. This is in contrast to the factor of 22 employed in Park [2] and Johnston [7] models.

3. DATA COMPARISONS

As alluded to in the previous section, the ability to predict molecular non-equilibrium radiation is now greatly improved. Figure 1 shows a comparison of radiance at 7.3 km/s and 0.7 Torr freestream pressure as a function of wavelength and position behind the shock. The non-equilibrium radiative overshoot is captured more accurately, as is the spectral profile. Further comparisons will be given in the final paper.

Fig. 2. Error in predictions of EFT1 flight data using the original and revised radiation models

This model has also been applied to the conditions of the EFT1 flight which returned to Earth from highly elliptical orbit at about 8.5 km/s. The data in its raw form is restricted, therefore the relative disagreement in prediction is presented in Fig. 2. The initial baseline model underpredicted the radiometer signal by about 80-90% (meaning the measurement was 1.8-1.9x the prediction). The revised radiation and kinetics model now are within 30-40% of the data at two time points that are within the radiative heating pulse. If CO2 and Ar are included in the flowfield model, this serves to increase the radiance further, so that the prediction is now within 10% of the measurement, which is considered an excellent agreement. The first data point shown is early in the flight where the absolute magnitude of radiation is not large. All models overpredict at this time point. This overprediction is primarily attributed to radiation from N2+.

4. REFERENCES

Summary:
Shock Tube data collected in air at the last workshop has been analyzed and used to revise the radiation model for air. The new model has been tested against EFT1 flight data.

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Preliminary Results from Emission Spectroscopy Measurements of Radiating Air Shock Layers in the T6 Free-Piston Driven Shock Tube

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During atmospheric entry high velocity free-stream gas decelerates rapidly through a shock near the vehicle surface. This sudden compression results in very high post-shock temperatures which are sufficient to cause thermochemical changes in the gas, including dissociation and ionisation. The internal energy modes of the flow also become excited, causing electromagnetic radiation to be emitted. For high entry velocities, large craft or high altitude aerobraking the heat-load from this radiation can exceed that due to convective effects. Predictions of this radiative heating are essential to thermal protection system design, but their numerical simulation is challenging. The post-shock flow during peak heating for many planned missions exhibits thermochemical non-equilibrium, optically thick radiative effects and radiation/flow-field coupling. Experimental datasets are therefore essential to provide validation cases for numerical codes, building confidence in the accuracy of their predictions.

A common method for the experimental investigation of radiative heating is to test using a scaled model, as has been presented by several authors (e.g. [3, 4]). However, sub-scale models cannot match both radiation scaling and binary scaling simultaneously [5, 6]. An alternate method employed in shock-layer radiation experiments involves the passing of a planar shock through a quiescent gas with density and composition matched to a trajectory point of interest (see for example [7, 8]). This produces conditions analogous to those along the stagnation line of an entry vehicle and allows reproduction of the exact conditions experienced in flight. This approach is taken when performing radiation experiments in the T6 tunnel’s shock tube modes, allowing the non-equilibrium processes which occur behind the shock to be analysed.

The T6 Stalker Tunnel has recently undergone initial commissioning at the University of Oxford.
T6 is a multi-mode facility, wherein a free-piston driver can be coupled to a range of downstream architectures to permit operation as a reflected shock tunnel, expansion tube or two types of shock tube. The first shock tube has been designed specifically for shock-layer radiation studies and possesses a large 225mm internal diameter for greater integration path length/test time, aluminium construction to prevent carbon contamination, diaphragms at either end to ensure chemical purity and CaF2 windows integrated into the tube wall. The aluminium shock tube will be commissioned later this year. The present work instead uses the smaller diameter steel shock tube, with an internal diameter of 96.3mm and predicted maximum shock speed capability of 18 km s⁻¹ in air.

In these experiments the shock front is imaged as it exits the shock tube. An intensified sCMOS camera is coupled to a Princeton Instruments IsoPlane-320 spectrometer and a single image of the shock captured as it enters the test section. The shock image is focused onto the spectrometer slit using a combination of powered and flat UV-enhanced aluminium mirrors. The entire optical path can be calibrated in-situ for absolute spectral radiance using an integrating sphere. This arrangement results in a two-dimensional map of the variation in spectrally-resolved radiance with distance behind the shock. This data can subsequently provide insight into the sources of radiative emission, as well as the non-equilibrium thermochemical processes which occur in the shock front.

The full paper will present experimental UV/Visible spectra acquired using emission spectroscopy for a range of shock speeds in atmospheric air. A comparison will also be made to computational codes and data from existing facilities.

References


Summary:

This work presents first measurements of radiation from air shock layers in a new high enthalpy pulse facility.

Close-out and follow-up RHTG-9 discussion (Louis Walpot)
Louis Walpot