Ground to Flight Investigations of Hayabusa with Ablation Effects

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1. INTRODUCTION

Thermal protection systems (TPS) are imperative to the survival of space vehicles especially during superorbital re-entry to Earth. The design of thermal protection systems requires in-depth knowledge of the thermal loading experienced during re-entry. The thermal loading data is mostly determined using ground testing and can be backed up by numerical modelling including computational fluid dynamics (CFD). The verification of this data with flight data is invaluable and a recent, rare example of an opportunity for comparison was the Hayabusa asteroid sample return mission, which landed in Australia in 2010. During this re-entry a team of international scientists collected spectral data which can now be used for comparison and verification of ground test and modelling data.

Ground testing of subscale models at flight equivalent hypervelocity flow conditions (8 - 12 km/s) can be performed in hypersonic impulse facilities such as the X2 expansion tunnel at The University of Queensland. A recently developed method at The University of Queensland (UQ) enables heated reinforced carbon-carbon (RCC) models to be tested at temperatures representative of those experienced in flight (2000 - 3000 K), in addition to testing with cold-wall metallic models. Hot wall testing allows more realistic simulation of re-entry flow characteristics including important thermal surface effects (surface chemistry, catalycity) which has previously not been possible due to the short testing time scales compared to Plasma Wind Tunnel facilities (PWT).

The *eilmer3* compressible flow CFD code is used extensively for simulating atmospheric re-entry vehicles at flight and laboratory conditions. Simulations of the Hayabusa aeroshell incorporate heated walls, as well as surface catalycity, to accurately model the conditions experienced by the TPS. These simulations can be coupled with SACRAM, a 1D thermal response ablation modelling code, to include the effects of ablation and pyrolysis at critical points on the model surface. The modelling of these effects in *eilmer3* and the coupling with SACRAM is in early stages and the development is progressing with a current European Space Agency (ESA) TRP project on Ablation-Radiation Coupling (ARC), led by EPFL.

Current work is investigating the effects and validity of heat flux scaling correlations applied to a range of scaled models with the Hayabusa geometry and flight equivalent flow conditions. This will be achieved through results of CFD simulations, coupled to radiation and ablation modelling, and expansion tunnel testing with hot and cold wall models. Increased understanding of scaling methods will allow higher fidelity heat loading data to be acquired allowing more efficient and effective design of TPS.

This paper will discuss preliminary results from *eilmer3* CFD simulations with ablation modelling and the development towards modelled surface chemistry and solver coupling. An outline of planned experiments in the X2 expansion tunnel, including background on the RCC heating method and test conditions, will also be presented.

2. EXPERIMENTS AND TEST CONDITIONS

X2 Expansion Tunnel Experiments

Expansion tunnels are very good at reproducing hypervelocity flow conditions experienced by flight vehicles during re-entry, but the use of cold wall metallic models coupled with the extremely short test times in the X2 facility (on the order of 100 µs) results in negligible temperature increase of the model surface, and therefore a different thermal response to flight. A new technique developed by Zander [1] allows the use of hot wall models in X2 by resistively heating reinforced carbon-carbon (RCC) to temperatures on the order of 2000 - 3000 K, which are representative of temps experienced in flight [2]. The presence of CN was the metric selected to show surface reactions were taking place during the very short test times. Preheating of the RCC is necessary for X2 testing so that the model reaches a sufficient temperature prior to the test, and through this process any remaining resin is burnt off, leaving just the carbon to ablate during the test. Small pieces of material can be seen ablating off the cylindrical model surface in the high speed camera image shown in Fig. 1, recorded 50 microseconds into a test. Experiments for the ARC project are currently underway and results will be compared to the modelling, as described in the following sections. Goals for future testing include developing methods to identify surface chemistry in spectra and determine an experimental mass flow rate due to ablation, and extend to testing with carbon phenolic-type materials in order to achieve pyrolysis effects, as well as ablation.

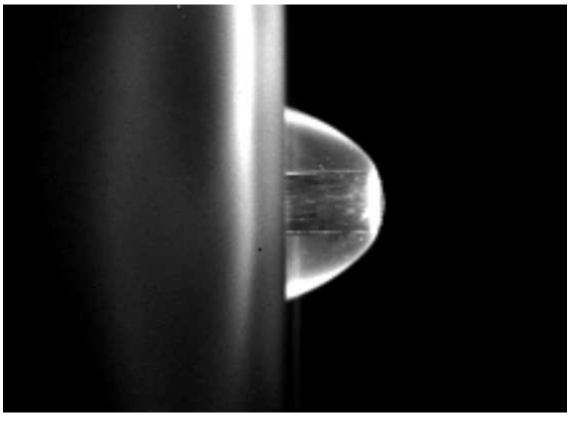

Fig. 1: A high speed camera image of a heated RCC model 50 µs into a test (Image courtesy F. Zander).

Test Conditions for Expansion Tunnel Experiments and CFD Simulations

Test conditions corresponding to crucial points on the Hayabusa trajectory have been identified for the ESA-ARC project [3]. These include full-scale conditions taken from Hayabusa flight data and tunnel scale conditions that have been adapted from the full scale conditions to closely approximate flight stagnation enthalpy and flight equivalent speeds. The fast90A and medium90A conditions from Table 1 are the expansion tunnel test conditions for the ESA-ARC project, and medium90B has been selected for use in simulations as an extra point of comparison, even though not a condition for current X2 tests.

Table 1: Test conditions for experiments and simulations derived for the ESA-ARC project.

Condition	*H1 (peak total heating)*	*H2 (peak radiative heating)*	*fast90A (X2 condition)*	*medium90A (X2 condition)*	*medium90B (X2 condition)*
Flight equivalent speed [m/s]	10520	10770	10990	10060	10425
Total enthalpy [MJ/kg]	59.3	60.4	60.4	50.6	54.4

3. FLOWFIELD SIMULATIONS

Numerical simulation of the flowfield around an aeroshell provides detailed analyses of the flowfield chemistry and physics, as well as a good comparison to flight and experimental data. The *eilmer3*code has been used for the full-scale and sub-scale Hayabusa simulations in this work, with a number of assumptions and simplifications made in the modelling at this stage in the ARC project. A brief overview of the structure of *eilmer3* is presented along with selected preliminary results.

Computational Fluid Dynamics with *eilmer3*

eilmer3 is a compressible flow computational fluid dynamics (CFD) code developed by The University of Queensland, in partnership with the Interdisciplinary Aerodynamics Group (IAG) at EPFL and several other partners. The main code collection consists of a pre-processor, the main simulation program and a post-processor, and libraries for thermochemistry, radiation, geometry and numerical methods [4]. *eilmer3* can simulate a specialised range of compressible flow problems, including aeroshells at re-entry and ground test conditions. Compressible flow solutions (in two dimensions for this work) are obtained by applying a cell-centred, finite-volume approach to the integral form of the compressible Navier-Stokes equations, given in (1).

$$\frac{\partial}{\partial t}\int_V U dV = -\oint_S \left(\overline{F_i} - \overline{F_v}\right)\cdot \hat{n} dA + \int_V Q dV \tag{1}$$

S represents the bounding surface and $\hat{n}$ the outward-facing normal of the control surface, and in 2D axisymmetric flow, V represents the volume and A the area of the cell boundary per unit radian in the circumferential direction [4]. The conserved quantities for the thermal non-equilibrium model are density (ρ), x- and y-momentum per volume, total energy per volume, vibrational energy for mode m, electron-electronic energy and mass density of species s, provided in vector form in (2).

$$U = \begin{bmatrix} \rho & \rho u_x & \rho u_y & \rho E & \rho e_{v_m} & \rho e_e & \rho f_s \end{bmatrix} \tag{2}$$

The flux is separated into inviscid, $\overline{F_i}$, and viscous, $\overline{F_v}$, components. In 2D, the viscous components are calculated from the axisymmetric viscous stresses and viscous heat fluxes and the source term, Q, is a combination of geometry, chemistry, thermal energy exchange and radiation terms. A full discussion of the flux vector and source term formulations, as well as solution methods, is provided in the *eilmer3* user guide [4].

3.2 Models Chosen, Assumptions and Simplifications

Models need to be chosen for the thermal non-equilibrium of the air plasma as well as for the ablation species interaction within the boundary layer. Assumptions and simplifications have been made in work to date in order to obtain preliminary results and perform verification tests. Present simulations use the Park [5] chemistry model for air and ablative species, and the 20 species included are:

$$C, O, N, H, CO, C_2, N_2, CN, NO, O_2, H_2, C_3, C_2H, C^+, O^+, N^+, H^+, NO^+, N_2^+, e^-.$$

There are 24 reactions in Park's model: 12 exchange reactions, 5 dissociation reactions 4 electron impact ionisation reactions, and 2 associative ionisation reactions. The low number of reactions, although making the model numerically faster, ignores some potentially important mechanisms. The Abe model, comprising 26 species and 50 reactions, is being created for eilmer3 by means of chemical species data, reaction files and collision integrals [6].

Simulations have been designed to replicate both flight and expansion tunnel conditions and therefore have to take into account different surfaces that could be used. At present, the available material data comes from the NASA test case material TACOT (Theoretical Ablative Composite for Open Testing) [7], however, acquisition of carbon phenolic data will enable more realistic heat shield simulations. Full-scale simulations can currently utilise a user-defined boundary condition for pyrolysis gas injection only, and without ablation, mass flow rates of injected species are low and the gases will remain close to the wall. Modelling surface reactions and char mass flow module is under development as part of the ESA-ARC project. At the boundary, an energy balance takes place whereby the energy coming into the surface from the flowfield, in the form of convective and radiative heat flux, is balanced by the energy re-radiated into the flowfield and carried by mass entering the flowfield. This surface energy balance is controlled in the boundary condition by total mass, momentum, energy and species mass fluxes.

Wall catalycity can be included in modelling to compare to ground test results to simulations with mass injection. At present there are two options available in *eilmer3*: non-catalytic, where the wall has no influence on reactions, or super-catalytic, where the wall forces recombination to freestream concentrations. The latter effect is sometimes prevalent in expansion tunnel tests with cold-wall metallic models.

Preliminary Results

The results presented are preliminary results from simulations at full-scale and subscale, to show what is currently achievable with the code. Important parameters to consider from simulation results are the stagnation line temperature profiles, species concentrations, especially when including pyrolysis and ablation, and convective, radiative and total heat flux, especially with different wall effects.

An example stagnation line temperature profile plot has been provided in Fig. 2 for a full-scale Hayabusa model at the H2 condition. A two-temperature model splits the modes into two sets: translational-rotational, and vibrational-electron-electronic. Across the shock there is a large region of non-equilibrium as the translational-rotational modes rise sharply in temperature and relax through the shock layer to meet the vibrational-electron-electronic modes in equilibrium closer to the wall.The shape of the temperature profile is expected to change near the wall when a finite-rate catalytic wall or mass injection boundary condition is used. The reasons for the curves lacking smoothness in areas around the peaks is entirely within the code, and since the production of these plots, the code has undergone improvements in energy exchange modelling to improve these features.

The stagnation line temperature profiles compare well in magnitude to Winter et al [8], however, *eilmer3* pairs the temperature modes differently to Winter et al and so a larger region of non-equilibrium can be seen in Fig. 2. The shape of the temperature profiles meets the work of Potter [9], as expected through similar use of the *eilmer3* code.

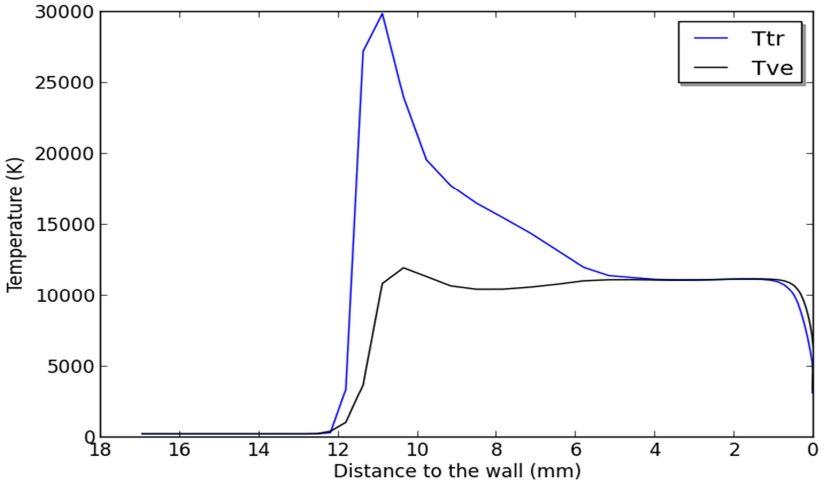

Fig. 2: Stagnation line temperature profile for the H2 full-scale condition, non-catalytic case.

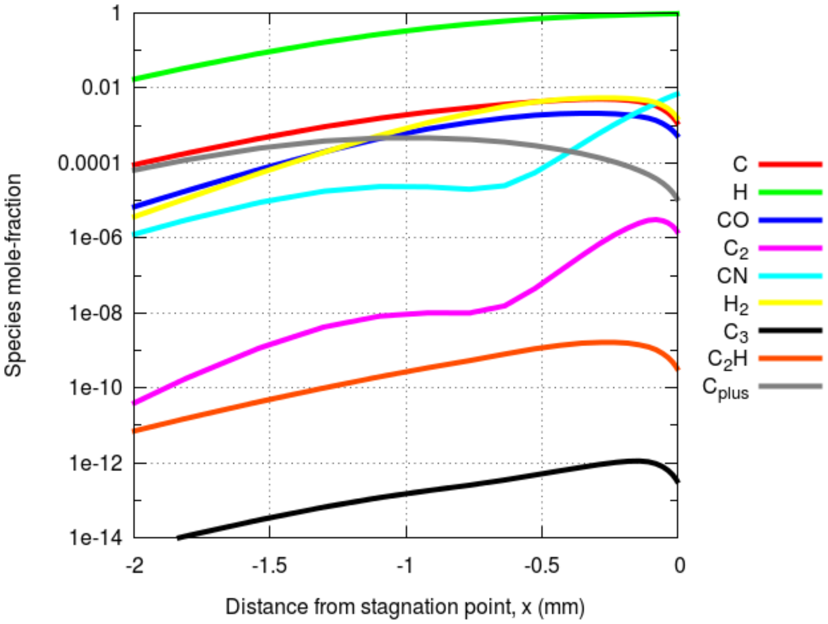

Fig. 3: Concentrations of pyrolysis gas species near to the wall, H2 condition.

The species concentrations are important to observe in simulations to gain an understanding of the chemical processes that are occurring in the shock and boundary layers, and at the surface. Spectra can then be created through *eilmer3*'s inbuilt radiation solver or codes such as Fluid Gravity's PARADE to compare to flight or experimental data. Fig. 3 illustrates the pyrolysis gas species concentrations in the region close to the wall for a full-scale simulation at the H2 condition. Since this simulation has pyrolysis gas injection only, without ablation from the surface, species such as C_3 have very low concentrations. The species that result from reactions in the pyrolysis gas at equilibrium wall temperature and pressure conditions (as in [5]) have the highest concentrations. There is a sharp drop-off of all pyrolysis species concentrations beyond this region, as the mass flow rate is very low and the species do not traverse further into the flowfield. The mass flow rate has been computed in SACRAM, a 1D material response solver discussed in the next section, and will increase approximately ten-fold with the inclusion of ablation, assuming the trends in Park [5] are followed. The results in this plot have are in the process of validation as the coupling is still in development to include surface reaction effects: this is a goal for future work within the ARC project.

Heat flux is a parameter of interest for the influence of radiation, diffusion and ablation, as well as scaling analysis using empirical correlations, and results at full-scale are presented in Fig. 4 as an example of heat flux analysis for the ESA-ARC project. The points Qconv_h1_ARC and Qconv_h2_ARC are the Hayabusa flight convective heat flux values, and Qcond_h1 and Qcond_h2 are the corresponding conductive heat flux values. It is assumed that convective

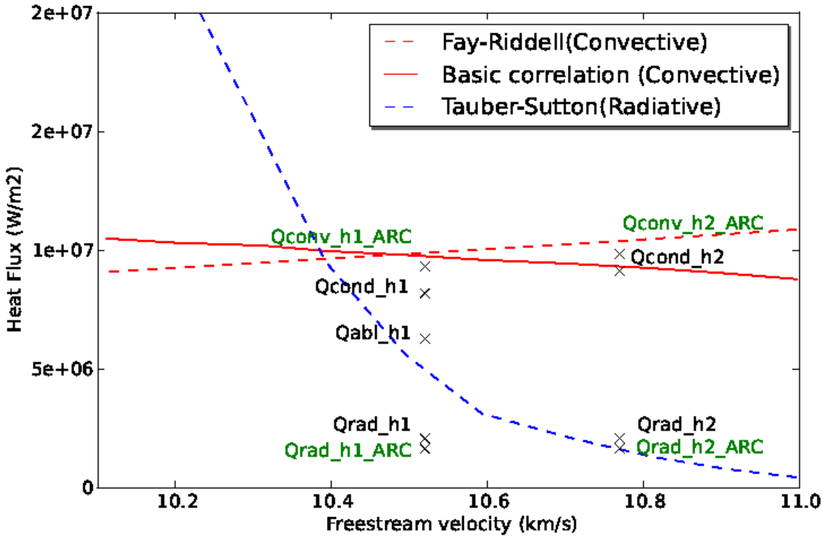

Fig 4: Various heat fluxes compared with empirical correlations.

heat flux is the sum of a conductive heat flux term and a diffusive heat flux term, and upon improvements to the diffusion modelling, it is hoped that the diffusive heat flux will provide the difference between the numerical and flight data points. The inclusion of ablation lowers the conductive heat flux (Qabl_H1) for the H1 condition, and it is predicted that the extra difference to the flight point could be made up by a larger diffusive heat flux, due to mass injection. These convective/conductive heat fluxes match reasonably well with the relevant scaling correlations, as do the H2 radiative heat fluxes, but a larger difference can be seen between the H1 data points and the Tauber-Sutton correlation.

4. ABLATION CODE AND COUPLING DEVELOPMENT

Modelling Material Response

Heat loading will influence the thermal response of the TPS and the mechanisms of pyrolysis (gas formed from resin) and ablation (surface reactions with fibres) need to be modelled accordingly. Pyrolysis gases are treated using SACRAM, a one-dimensional thermal response code developed by Joshi et al [10] and based on the work of Amar [11]. SACRAM solves the mixture energy, gas phase continuity and solid phase continuity equations using Fourier's law to model conduction, Darcy's law to model porous flow and the ideal gas law to model states of the pyrolysis gases. The governing equations are solved through a control volume finite element spatial discretisation method (CVFEM), an Euler implicit time integrator and a contracting grid scheme. A Newton iterative method is applied to solve the series of non-linear equations. Fig. 5 illustrates the operation of SACRAM, taking heat flux and temperature values from the flowfield to calculate the pyrolysis gas mass flow rate, and new species concentrations through the user-defined boundary condition back to the flowfield.

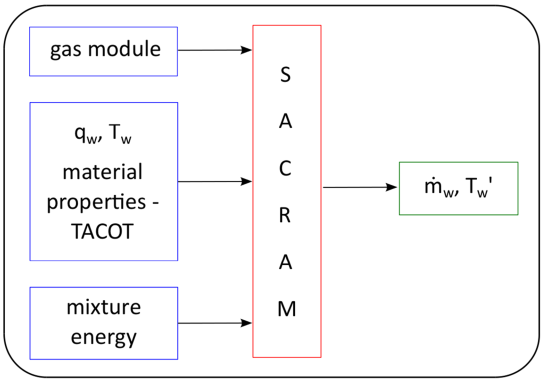

Fig. 5: Operation of 1D material response code SACRAM.

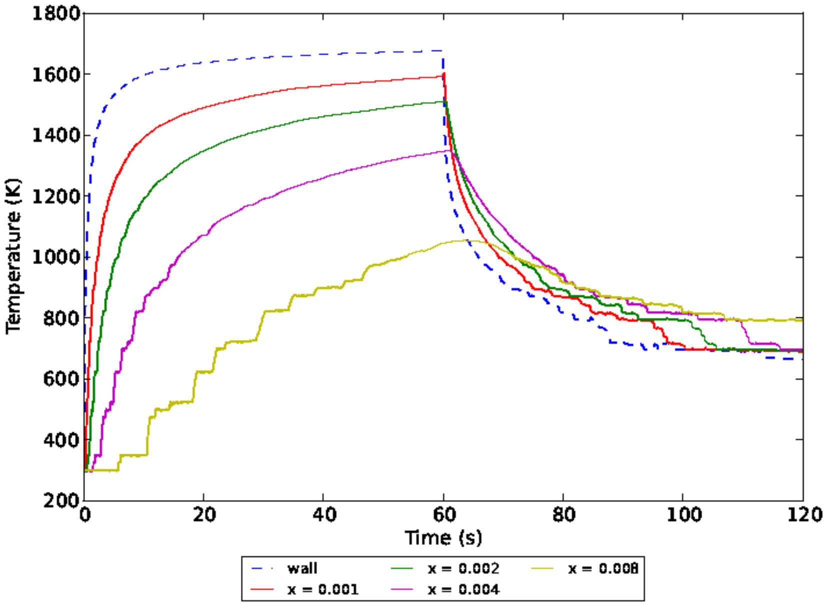

Fig. 6: Temperature profiles for SACRAM test case.

The SACRAM solver has been verified using the TACOT data [7] and the following response test case:

- Ramp up the flux from 0 - 0.45MW/m^2 in 0.1s;
- Hold constant at 0.45MW/m^2 from 0.1s - 60s;
- Ramp back down from 0.45-0MW/m^2 from 60s - 60.1s;
- Hold constant at 0MW/m^2 until 120s.

The results presented in Fig. 6 and Fig. 7 are similar to those presented by Joshi et al [10] but have been updated by the authors after development of the SACRAM code. The behaviour of the temperature profiles at different points through the surface (where x is the distance from the surface in metres) meets the test case specifications in Fig. 6.The pyrolysis gas mass flow rate, or blowing rate, $\dot{m}_g$ calculated by SACRAM is shown in Fig. 7.

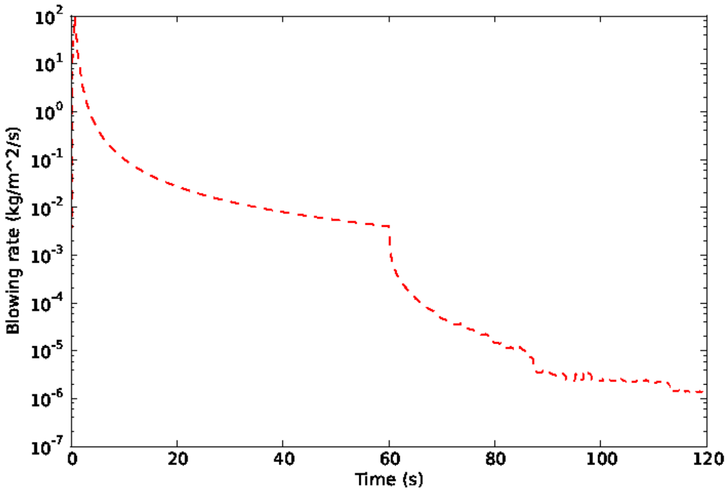

Fig 7: Blowing rate of pyrolysis gases over test time.

Flowfield and Material Response Coupling

The partnering of SACRAM with *eilmer3* is illustrated in Fig. 8. The material response solver and CEA (NASA's Chemical Equilibrium with Applications solver) provide pyrolysis gas parameters to the user defined ablation boundary condition. This boundary condition interacts with the flowfield throughout the simulation until convergence is reached, usually after a prescribed number of body lengths of flow.

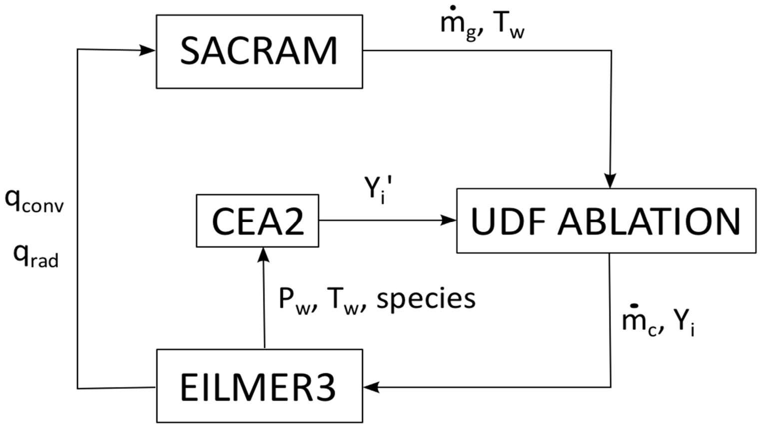

Fig. 8: Coupling of SACRAM and *eilmer3*.

The coupling between material response and flowfield through this iteration loop can be loosely or strongly coupled. A loosely coupled approach runs the flowfield simulation to convergence, executes the material response solver with required flowfield values, returns a new set of values to re-run the flowfield simulation, continues this process until convergence of a shared metric between material and flowfield solvers. A strongly coupled approach achieves a converged flowfield result in one run of the flowfield simulation, executing the material response solver at certain time intervals during the flowfield simulation. The interface for loose coupling of the flowfield and material response solvers is a shell script that executes each solver, passing values as required, and using a python script to evaluate the convergence of a metric. For stronger coupling, the material response solver is executed within the boundary condition script at specified time steps, automatically updating the required parameters. This interface is still in early stages of development, as work focuses on how to optimise the running of both the flowfield and material response solvers and minimise computational expense.

5. CONCLUSIONS AND FUTURE WORK

The comparison of flight data to experimental and computational results is of great importance in the development of ground testing methods, enabling greater understanding of thermal loading experienced during atmospheric re-entry and improving future design of thermal protection systems. The Hayabusa mission has provided a rare set of flight data that is a focus for the ARC project and its continuing expansion tunnel testing and computational simulations. The potential for simulating subscale and full-scale models at expansion tunnel and flight conditions, respectively, has been shown through use of the *eilmer3* code. Linking with SACRAM, the ability to model ablation effects is under development, as demonstrated by preliminary results; however, these are yet to be validated.

Future work for the ARC project that follows the work presented in this paper includes:

- X2 testing with heated RCC aeroshell models, for direct comparison with CFD;
- Development of eilmer3, including improved diffusion and catalycity models, and improvements to radiation modelling, including polyatomic species;
- Development of ablation boundary conditions, including combined pyrolysis and ablation modelling;
- Improvements to SACRAM, including coupling to eilmer3 and expansion to more material data sets;
- Inclusion of other chemistry models.

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