RE-ENTRY TECHNOLOGY FOR HIGH ENTHALPIC TRAJECTORIES

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Introduction

For the atmospheric re-entry of spacecraft from high energetic trajectories a high-performance thermal protection system (TPS) is needed to withstand the extreme heat fluxes. During sample return missions as well as the entry maneuver into the atmosphere of a gas giant like Jupiter thermal loads may exceed the loads of a re-entry maneuver from earth orbit by two or three orders of magnitude. Such missions are also extremely mass sensitive. In addition, the uncertainty of the modeling of coupled ablation, floating and plasma radiation processes causes a conservative design, which results in an over dimensioning of the TPS.
The objective of our work is the development of an ablative light-weight TPS for high enthalpic trajectories. We also try to exploit knowledge gained during another project, studying the “virtual” characterization of permeable materials used in transpiration cooled structures by means of X-ray computed tomography.

Material development

With the investigation and development of new material and structural concepts in combination with automatable manufacturing concepts we intent to:

- Reduce the system mass to increase the payload
- Build a technology base to realize extreme re-entry missions
- Validate the structural concepts based on plasma wind tunnel (PWT) tests
- Quality assurance by automation of manufacturing steps

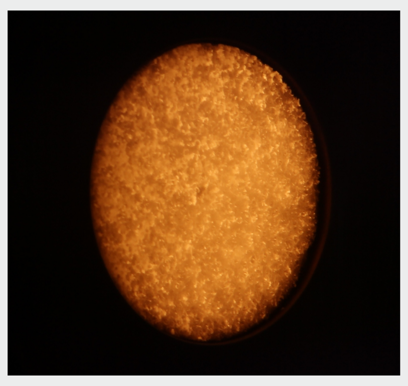

Fig. 01 - Specimen made of C-felt and phenolic resin (plasma wind tunnel PWK1, 2 MW/m² for 60 s)

Reference mission

The NASA sample return mission Stardust was chosen as reference mission for our material development. The return capsule entered earth atmosphere on 15-Jan-2006 with a speed of 12,9 km/s, the highest re-entry velocity of a man-made spacecraft ever. During re-entry a stagnation point heat flux of 12 MW/m² occurred.

Test procedure

PWT samples were produced under variation of the matrix resin and the fiber reinforcement. The test program includes:

- Phenolic, epoxy, silicone and XP-60 based resins
- Carbon and mullite fibers
- Short fibers (10 mm), fabric and felt

The samples will be tested at thermal loads of 2, 6 and 12 MW/m² for 60, 20 and 10 s in the plasma wind tunnel PWK1, operated by the Institute of Space Systems (University of Stuttgart). The intention of these screening tests is to study the influence of the different resin systems as well as the influence of the reinforcement fibers (fiber type, fiber orientation, fiber volume content) regarding the ablative properties of the samples. In Fig. 02 a PWT sample based on C-fabric and phenolic resin is shown (before, during and after PWT test).
To see how an active gas blow out could rise the thermal protection properties and reduce the system mass, the Institute of Aerospace Thermodynamics (ITLR) performs through-flow measurements on highly porous ablation samples (ρ_{exp}= 78 %). Such a sample is shown in Fig. 01 during a PWT test at 2MW/m².

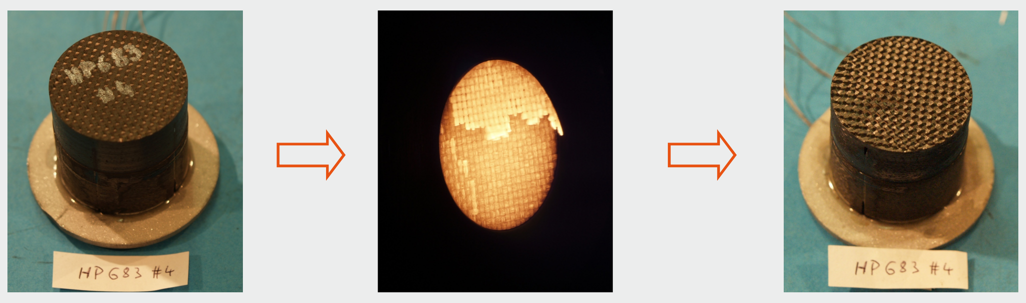

Fig. 02 - PWT specimen (HP683 #4) based on carbon fabric and a phenolic resin. Test conditions: 2 MW/m², 60 s

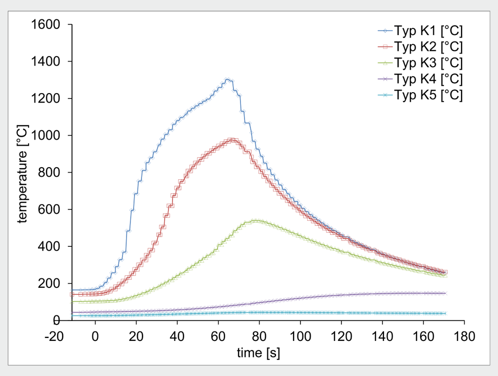

Fig. 03 - Temperature plot of PWT specimen (HP683 #4, 2 MW/m², 60 s)

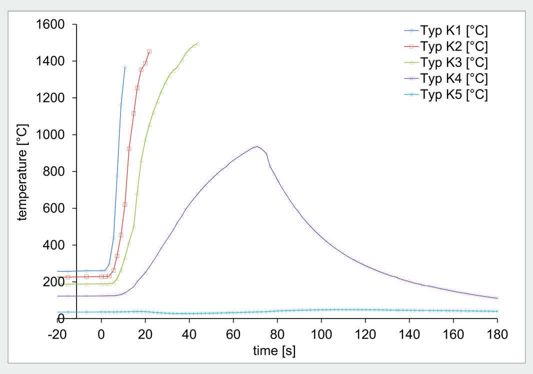

Fig. 04 - Temperature plot of PWT specimen (PC1#1, 2 MW/m², 60 s)

Intermediate result

The 2 MW/m² PWT tests are finished and will be evaluated in the next step. The PWT samples for the 6 und 12 MW/m² screening test campaign are prepared. One lesson learned so far is that fabric reinforced PWT samples show the tendency to delaminate during testing. Depending on the resin used, up to several fabric layers delaminated simultaneously. So it obviously is difficult to gain information regarding the ablative properties of the resin based on the recession rate. Fig. 03 and 04 show the temperature plots of a dense CFRP sample HP683 and the highly porous (open porosity) sample PC1. The heat conduction of sample PC1 is obviously far too high. We assume that the open porosity is causing the huge heat conduction, so we plan to manufacture a modified material with a more foam like resin matrix.

Further steps

After completing the test campaigns, it is planned to produce a low density material based on the knowledge gained from the screening tests. Therefor an infiltration technique was developed which allows the manufacturing of low density materials based on felts and diluted resins.

Material Characterization for use in transpiration cooled structures by means of computed tomography (CT)

The main principle of transpiration cooling is shown in the figure below (Fig. 05). A percolating coolant lifts the hot boundary layer resulting from the mainstream hot-gas forming a coolant layer below. Besides thermal conductivity this mechanism is determined by the permeability of the material and the volumetric heat exchange coefficient between the permeable material and the coolant in non ablative transpiration cooling. Nevertheless we assume, that this statement is also true for ablative materials, where the material itself is acting as the gas generator.

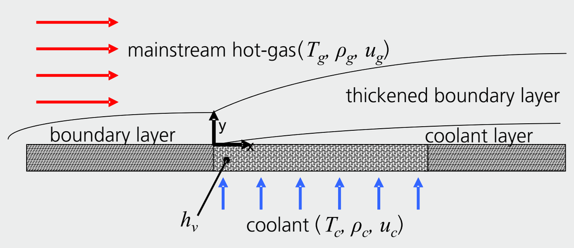

Fig. 05 - Principle of transpiration cooling

The above mentioned material properties of permeability and volumetric heat exchange coefficient have to be determined for the computation of an application. An experimental determination could be time consuming and in the case of the volumetric heat exchange coefficient also quite difficult. Although there exist various approaches in the literature to correlate the microstructure of a material to the permeability for different flow regimes inside the material (e.g. Ergun, Kozeny-Carman), most of these approaches are derived from a certain structure (eg. packed beds of spheres or fibers) and are not easily transferred to other microstructures.

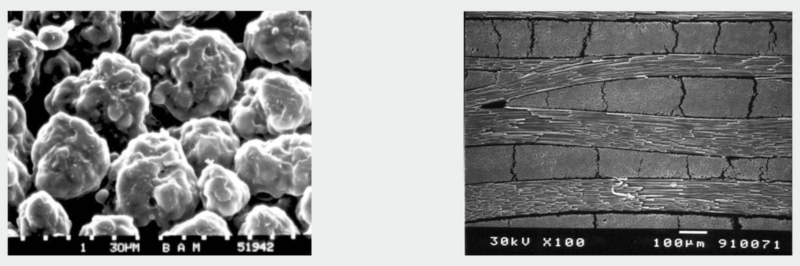

Fig. 06 - Materials of different structure: SEM image of sintered granular PE (left, image from [1]) and C/C-ceramic (right)

From both of the above materials CT-scans were taken, post-processed and a polygonal surface reconstruction was produced (Fig. 07).

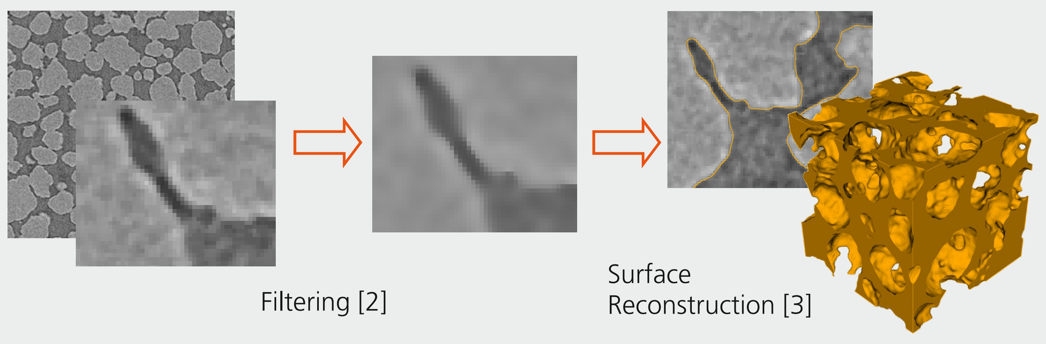

Fig. 07 - Post-processing of reconstructed image and surface reconstruction of the pore space of the granular material

The volumetric image allows measurements of characteristic properties of the porous material, e.g porosity, pore size distribution, inner surface etc, thus allowing a sort of classification of the material. It is as well possible to compute effective transport properties. An example computation of the flow through the porous material is shown in Fig. 08 as well as the non-linear dependency between mass flow and pressure which was also observed in the accompanying tests and could be described by a Darcy-Forchheimer-Brinkmann type of equation.

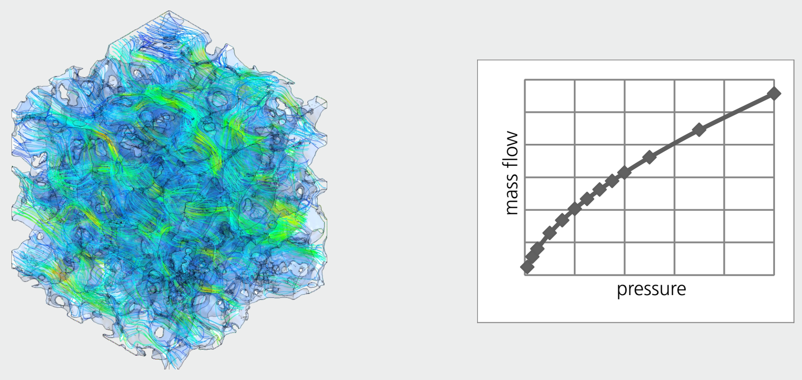

Fig. 08 - Flow through granular material (side length of sample cube: 0.5 mm)

Further steps

It appeared that the results of the flow computations were quite sensitive to deviations of the structure. The effect is the more observable, the smaller the ratio between feature size and voxel size becomes. Therefore the influences of the image post-processing on the reconstructed surface have to be examined again.
In addition to the flow through a material also the outflow into the boundary layer could be considered to be of interest and can also be computed. Linn and Kloker [4] suggest that, depending on the structure of the outflow surface and the mainstream flow regime, in certain cases vortical structures occur in the downstream which might bring the hot boundary layer again in contact with the structure, which would be an undesirable effect.

Piecing the works together

In a next step we intent to manufacture a new batch of presumably felt based PWT samples adapted from the results gained from the screening tests. The idea is to test the new samples in the plasma wind tunnel and to scan the structure of the char and the transition layer afterwards by X-ray computed tomography, thereby allowing an insight into the evolving microstructure. In a first step we aim for the computation of the gas permeation through the char and the transitional layers in steady state to correlate the amount of the pyrolysis gas flow to the temperature measurements from the PWT tests.

Acknowledgments

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