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Heat transfer in ultra-high temperature advanced ceramics under high enthalpy arc-jet conditions

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ABSTRACT

Aim of this work is to analyze the response of an ultra-high temperature ceramic at typical heat flux conditions of thermal protection systems of a re-entry spacecraft. In particular, a ZrB_2–SiC based ultra-high temperature advanced ceramic sharp leading edge demonstrator (1 mm nominal radius of curvature) was manufactured and tested in a non-equilibrium high enthalpy supersonic airflow, 20 MJ/kg of peak total enthalpy, by using an arc-jet ground facility. The surface temperature of the leading edge was monitored by infrared thermo-cameras coupled to a two-color pyrometer. The ultra-refractory advanced ceramic leading edge withstood stressful thermo-chemical loads successfully, without obvious failure. Ad-hoc computational fluid dynamics simulations rebuilt the adopted set-up and related experiment conditions: the numerical outputs matched fairly well the experimental in-situ determinations.

1. Introduction

The re-entry from low Earth orbit or from deeper space explorations is, without any doubts, one of the most challenging as well as critical phases of any space missions. When a space vehicle re-enters back to the Earth crossing the atmosphere at a speed of 7–8 km/s, control surfaces such as nose cones and wing leading edges are subject of very stressful heat fluxes up to 10 MW/m^2, or even higher, due to the combination of shock-waves and viscous friction of the surrounding air plasma [1]. The resulting temperature distribution field upon the external surfaces of the flying vehicles poses several challenges since at ultrahigh temperature regimes (ie. above 2300 K) the materials properties change dramatically, severe thermal stresses take place due to restrained local thermal expansion/contractions, and thus overall admissible stress limits should be reduced.

To grasp the order of magnitude of the energies involved, it should be taken into account that a low orbit satellite with a speed of about 8 km/s holds a kinetic energy of about 30 MJ/kg: all the commercial products currently available for thermal protection systems (TPS) and control surfaces of space vehicles are expected to fail, or at least to seriously compromise the potential protection capabilities due to the adverse combination of a thermo-chemical attack followed by extensive loss of mass through erosion, melting, and ablation mechanisms [2].

It follows that TPS play a crucial role in preventing the various substructures of a space vehicle and its payloads to suffer local and global overheating caused by the aerodynamic heat fluxes. Thus, active/passive cooling or other expensive advanced technologies like film transpiration cooling [3] or heat pipes [4] needs to be investigated. However, passive radiation cooling by high temperature thermal protection systems is very efficient. For instance, in Ref. [5] three-dimensional numerical simulations were performed to study the aerodynamic heating behavior on low-density ablative material samples, with different diameters and thicknesses, when exposed to the high enthalpy flow of an electric arc-heated facility. The material was made of a low-density carbon fiber matrix impregnated in phenolic resin. When heated, the resin decomposes and releases pyrolysis gases: under prolonged heating the fibers do also eventually ablate changing the initial geometry of the test sample.

During the last 15 years a novel class of ultra-refractory advanced ceramics, the so-called Ultra-High Temperature Ceramics (UHTCs), has been re-discovered and hence proposed like passive TPS for extreme environments [6]. Within the group of UHTCs, some transition metal diborides (MB_2) and carbides (MC), M = zirconium, hafnium and tantalum, properly engineered with specific additives, have been currently investigated as viable TPS candidates for both re-entry space-crafts and hypersonic cruise

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Nomenclature

C	heat capacity
CFD	computational fluid dynamics
EDS	energy dispersive spectroscopy
H_0	specific total enthalpy
LE	leading edge
M	Mach number
MOR	modulus of rupture
PWT	plasma wind tunnel
k	thermal conductivity
RT	room temperature
SEM	scanning electron microscope
TPS	thermal protection system
UHTC	ultra high temperature ceramic

Greek symbols

ρ	bulk density
ε_λ	spectral emittance
σ	Stephan–Boltzmann constant

Subscripts

LE	leading edge
PT	post test
SL	slug calorimeter

vehicles because of their melting point over 3200 K, mechanical robustness and excellent chemical stability at very high temperatures [6–9]. Actually, although MB$_2$ have melting point temperature ranges between 3000 and 3300 K [10], lower than those of MC between 3500 and 3900 K [10], they possess much better capabilities to manage considerable convective heat fluxes delivered upon the TPS surfaces [11]. This peculiar feature enables to balance the temperature gradients arising inside the devices/components during thermal transients, and therefore to mitigate thermal stresses and surface temperature peaks at their stagnation regions. In other words MB$_2$, a sub-group of refractory and excellent thermal conductors, are particularly suited in applications where non-uniform heat fluxes are involved, allowing internal heat conduction and radiative cooling from regions interested by lower heat fluxes.

TPS materials should be first qualified on-ground and then tested and validated in flight conditions. Plasma wind tunnels (PWTs) may therefore play a key role during qualification procedures. PWTs should be able to reproduce all the conditions occurring during the key phases of a space mission, the re-entry to cite the most critical. Actually, it is really complicated, if not impossible, to concurrently reproduce the main factors characterizing the re-entry environment [12]: total enthalpy, speed, dynamic pressure, density and the chemical composition of the gases impinging TPS surfaces of various dimensions.

Aero-thermodynamic wind tunnels, mainly fed by an electric arc heater and working in a continuous fashion, are most often used to reproduce heat fluxes in order to test the ablation resistance of TPS, as well as to investigate aero-thermochemical issues. In such cases, it is very difficult to determine the thermo-fluid dynamic parameters such as Mach, Reynolds, Knudsen numbers [12]. In fact, as soon as the gas is energized by the arc heater and then forced to pass through a divergent nozzle, its actual composition suddenly changes and only sophisticated diagnostics properly set-up enable to determine it accurately [13]. Numerical modeling very often becomes the only viable and largely recommended tool to predict the thermo-chemical evolution of the gas and to characterize the flow-field surrounding the proof article inside the testing chamber. In addition, because the flow conditions generated in high-enthalpy PWTs are very complex, the verification of the free-stream flow conditions must be a combined effort of experimental diagnostics and CFD simulations through an interactive process, providing a step-by-step improved understanding of the facility performances [13].

In this context, an ultra-high temperature sharp wing leading edge (LE) ceramic demonstrator was manufactured and then tested in a PWT under non-equilibrium supersonic air-flows characterized by stagnation pressures, enthalpies and heat fluxes typical of an atmospheric re-entry. The choice of an UHTC-made sharp LE was motivated by the need of using a proof article capable of maintaining the native dimensions and shape in remarkably aggressive aero-heating conditions. Thanks to in-situ surface temperature measurements together with the rebuilding of the testing conditions via CFD simulations, the mapping of the global equilibrium stagnation temperatures and of the overall heat fluxes were assessed.

2. The sharp leading edge technology concept

Fig. 1 shows the sharp leading edge technology concept: the convective heat flux entering the surfaces of the sharp LE is partly transferred away through the solid and partly re-radiated back to the environment [14]. Since a steady state is achieved, global radiative equilibrium is established, in the sense that the overall surface convective heat flux is balanced by the overall surface radiative heat flux and by the conduction heat transfer: a (relatively) lower equilibrium temperature is achieved if the base material composing the LE and operating at elevated temperature does not degrade significantly its own (high temperature) thermal conductivity. The heat flux distribution over a sharp LE exhibits a typical dependence by the inverse of the square root of the distance from the stagnation point decreasing as the boundary layer becomes thicker [15]. Thus, less intense net heat fluxes take place, recommending as mandatory the need of installing strongly refractory thermal protections only in those parts of the vehicle where the heat fluxes reach the top magnitudes.

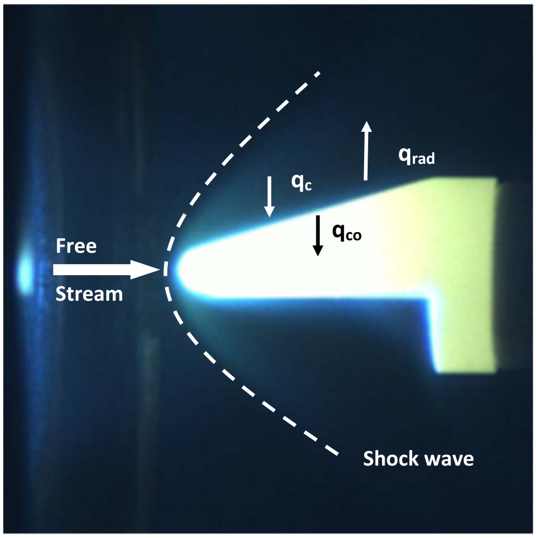

Fig. 1. The sharp leading edge technology concept: the convective heat flux (q_C) is partly transferred by conduction (q_{CO}) and re-radiated to the environment (q_{RAD}).