Development of Testing Conditions for Gas/Surface Interaction Studies in Atmospheric Reentry Simulations

José Pedro Soares Pinto Leite

Dissertação para obtenção do Grau de Mestre em Engenharia Aeroespacial

Júri

Presidente: Fernando José Parracho Lau
Orientador: Luís Rego da Cunha de Eça
Vogal: Filipe Szolnoky Ramos Pinto Cunha

Novembro de 2012
Acknowledgments

* To my parents that always supported me.

* To Prof. Olivier Chazot for all the help, hints, coaching and the basic idea for this work.

* To Francesco Panerai for his unmeasurable help for this work. My research without is PhD Thesis and his expertise as background would have been much more darker. Sorry for all the things I did in the wrong way and infinite amount of stupid questions.

* To Pascal Collin, the super-technician, because He Is The Man.

* To Bernd Helber for all the help and patience in the processing of the spectrometry results.

* To Prof. Luis Eça for all the help and coaching before, during and after my stay in VKI.

* To Prof. João Teixeira Borges, Prof. Luis Eça, Prof. Fernando Lau, Prof. Pedro Serrão, Prof. Ferry Schrijer and Prof. Fluvio Scarano from IST and TUDelft for those great first courses in Mechanics, Fluid Mechanics and Aerodynamics.

* To all my friends and colleagues at the von Kármán Institute because the great environment was a big help for the development of this work.
Abstract [English]

Since the beginning of the space exploration that the design of the thermal protection system ("heat shield") of a planetary reentry vehicle (a vehicle that enters the atmosphere of a planet coming from the outer space) had been a challenge for the design engineers. Problems arise because of the lack of a fully comprehension of the physico-chemical processes involved, specifically Aerothermodynamics and Gas/Surface Interactions. In this thesis, the Local Heat Transfer Simulation methodology is used to fully reproduce the aerothermchemical conditions in the nose stagnation point of a reentry vehicle in a ICP Plasma Windtunnel, the Plasmatron, installed at the von Kármán Institute and capable of produce high enthalpy flows.

Using the the LHTS methodology, the oxidation of Silicon Carbide based thermal protective materials is investigated and both the passive-to-active transition and the operational limits of these materials are accessed. The materials tested are going to be used in the IXV mission under project by the European Space Agency.

A pioneer testing methodology was developed to be used in high enthalpy facilities in order to understand the effect of surface temperature in surface recombination coefficient (catalycity) and heat flux from the plasma to the wall. Preliminary data was obtained and a sensitivity analysis were done to access the reliability of the method. Plus, is proposed a method to construct an computationlys efficient AeroThermodynamic DataBase for emissivity, catalycity and heat flux to be used in design and CFD codes and applicable both for passive and active concepts of thermal protective systems.

Keywords: Thermal Protective Systems, Ground Testing, Gas/Surface Interactions, Aerothermodynamics, Oxidation, Catalycity

Resumo [Português]

Desde o início da exploração do espaço que o design do sistema de protecção térmica ("escudo térmico") de um veículo espacial de reentrada planetária, ou seja, que entra na atmosfera de um planeta vindo do espaço exterior, tem sido um desafio para os projectistas. Os problemas surgem por causa da falta de uma boa compreensão dos processos físico-químicos envolvidos, especificamente fenômenos aerotermodinâmicos e interacções gás/superfície. Nesta tese, a metodologia de Simulação Local de
Transmissão de Calor (LHTS) é utilizada para reproduzir totalmente as condições aerotermoquímicas no ponto de estagnação do nariz de um veículo espacial de reentrada dentro de um túnel de plasma, o Plasmatron, instalado no Instituto von Kármán e capaz de produzir jactos de muito elevada entalpia.

Utilizando a metodologia de LHTS, a oxidação e limites operacionais de materiais de protecção térmica baseados em Carboneto de Silício são investigados. Estes materiais vão ser utilizados na missão IXV, da responsabilidade da Agência Espacial Europeia.

Uma metodologia de teste foi desenvolvida para ser utilizada em instalações de entalpia elevada, a fim de compreender o efeito da temperatura da superfície no coeficiente de recombinação (catalicidade) e no fluxo de calor do plasma para a parede. Dados preliminares foram obtidos e uma análise de sensibilidade foi feita para testar a fiabilidade do método. Para além disso, é proposta uma metodologia para construir uma Base de Dados Aerotermodinâmica computacionalmente eficiente para utilização em codigos de design e CFD e empregável em conceitos passivos e activos de sistemas de protecção térmica.

**Palavras-Chave:** Sistemas de Protecção Térmica, Ensaios em Solo, Interacções Gás/Superfície, Aerotermodinâmica, Oxidação, Coeficiente de Recombinação
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<tr>
<td>AP</td>
<td>Active-to-Passive</td>
</tr>
<tr>
<td>ARD</td>
<td>Atmospheric Reentry Demonstrator</td>
</tr>
<tr>
<td>ATDB</td>
<td>AeroThermodynamic DataBase</td>
</tr>
<tr>
<td>BL</td>
<td>Boundary Layer</td>
</tr>
<tr>
<td>CERBERE</td>
<td>Catalycity and Enthalpy ReBuilding for a REference probe</td>
</tr>
<tr>
<td>CERBOULA</td>
<td>CERBERE + NEBOULA</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CMC</td>
<td>Ceramic Matrix Composite</td>
</tr>
<tr>
<td>CS</td>
<td>Cooled Sample setup</td>
</tr>
<tr>
<td>C/SiC</td>
<td>CMC with SiC matrix and Carbon fibre reinforcement</td>
</tr>
<tr>
<td>DAC</td>
<td>Data Acquisition Card</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
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<tr>
<td>GSI</td>
<td>Gas-Surface Interaction</td>
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<tr>
<td>HF</td>
<td>Heat Flux</td>
</tr>
<tr>
<td>HFreq</td>
<td>High Frequency</td>
</tr>
<tr>
<td>HER</td>
<td>Herakles - A Safran Group Company (Previously SPS)</td>
</tr>
<tr>
<td>ICBM</td>
<td>Inter-Continental Ballistic Missile</td>
</tr>
<tr>
<td>ICIASF</td>
<td>International Congress on Instrumentation in Aerospace Simulation Facilities</td>
</tr>
<tr>
<td>ICP</td>
<td>Inductively-Coupled Plasma</td>
</tr>
<tr>
<td>IPM-RAS</td>
<td>Institute for Problems in Mechanics of the Russian Academy of Sciences</td>
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<tr>
<td></td>
<td>(in russian: ИПМех РАН - Институт проблем механики РАН)</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>IST</td>
<td>Instituto Superior Técnico - Faculty of UTL</td>
</tr>
<tr>
<td>IXV</td>
<td>Intermediate eXperimental Vehicle</td>
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<tr>
<td>LHTS</td>
<td>Local Heat Transfer Simulation</td>
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<td>LTE</td>
<td>Local Thermo-chemical Equilibrium</td>
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<thead>
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<tr>
<td>MESOX</td>
<td>Moyen d’Essai et de Diagnostic en Ambiance Spatiale</td>
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<tr>
<td>MLR</td>
<td>Mass Loss Rate</td>
</tr>
<tr>
<td>MTA</td>
<td>MT Aerospace</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NDP</td>
<td>Non-Dimensional Parameter</td>
</tr>
<tr>
<td>NEBOULA</td>
<td>NonEquilibrium BOUndary LAyer</td>
</tr>
<tr>
<td>PA</td>
<td>Passive-to-Active</td>
</tr>
<tr>
<td>PEGASE</td>
<td>PErfect GAS Equation Solver</td>
</tr>
<tr>
<td>PLC</td>
<td>Power Line Communication</td>
</tr>
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<td>PROMES</td>
<td>Le Laboratoire PROcédés, Matériaux et Energie Solaire</td>
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<tr>
<td>RS</td>
<td>Radiative equilibrium Sample setup</td>
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<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>SPS</td>
<td>Snecma Propulsion Solide - Previous name of HER</td>
</tr>
<tr>
<td>SSO</td>
<td>Space Shuttle Orbiter</td>
</tr>
<tr>
<td>TPM</td>
<td>Thermal Protection Material</td>
</tr>
<tr>
<td>TPS</td>
<td>Thermal Protection System</td>
</tr>
<tr>
<td>TRP</td>
<td>Technology Research Programme</td>
</tr>
<tr>
<td>UQ</td>
<td>Uncertainty Quantification</td>
</tr>
<tr>
<td>UTL</td>
<td>Technical University of Lisbon</td>
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<tr>
<td>VKI</td>
<td>von Kármán Institute for Fluid Dynamics</td>
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### Roman symbols

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<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific Heat</td>
</tr>
<tr>
<td>$\bar{c}_p$</td>
<td>Frozen Specific Heat = $\sum y_i c_{p,i}$</td>
</tr>
<tr>
<td>$D$</td>
<td>Dissociation Energy of the Recombining Molecule</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter</td>
</tr>
<tr>
<td>$\mathcal{D}$</td>
<td>Diffusion Coefficient</td>
</tr>
<tr>
<td>$\text{Da}$</td>
<td>Damköhler number = $\tau_{fl}/\tau_{ch}$</td>
</tr>
<tr>
<td>$E$</td>
<td>Energy</td>
</tr>
<tr>
<td>$H$</td>
<td>Specific Total Enthalpy</td>
</tr>
<tr>
<td>$h$</td>
<td>Specific Enthalpy</td>
</tr>
<tr>
<td>$\overline{h}$</td>
<td>Convection Coefficient</td>
</tr>
<tr>
<td>$I$</td>
<td>Intensity</td>
</tr>
<tr>
<td>$J$</td>
<td>Mass Flux</td>
</tr>
<tr>
<td>$k$</td>
<td>Catalytic Reaction Rate</td>
</tr>
<tr>
<td>$\text{Le}$</td>
<td>Lewis Number = $\rho D \bar{c}_p / \lambda$</td>
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List of Symbols

\( \mathcal{M} \)  
Mass Flux (atoms)  
kg m\(^{-2}\) s\(^{-1}\)

\( m \)  
Mass or Particle Mass  
kg

\( \dot{m} \)  
Mass Flow Rate  
kg s\(^{-1}\)

\( \text{NS} \)  
Number of Species \( i \)  
-

\( \text{Nu} \)  
Nusselt Number = \( \tilde{h}D/\lambda \)  
-

\( n \)  
Number Density  
m\(^{-3}\)

\( \tilde{n} \)  
Normal to the Wall (oriented: gas to wall)  
-

\( p \)  
Pressure  
Pa = kg m\(^{-1}\) s\(^{-2}\)

\( Q \)  
Heat  
J

\( \dot{Q} \)  
Heat Rate  
W = J s\(^{-1}\)

\( q \)  
Heat Flux  
W m\(^{-2}\)

\( R \)  
Radius  
m

\( \text{Re} \)  
Reynolds Number = \( \rho V D/\mu \)  
-

\( \text{Sc} \)  
Schmidt Number = \( \mu/(\rho D) \)  
-

\( T \)  
Temperature  
K

\( V \)  
Velocity  
m s\(^{-1}\)

\( v \)  
Freestream Plasma Velocity  
m s\(^{-1}\)

\( W \)  
Spectral Radiance  
W m\(^{-2}\) sr\(^{-1}\) \( \mu \) m\(^{-1}\)

\( W_{\lambda_1 \rightarrow \lambda_2} \)  
Integrated Spectral Radiance between \( \lambda_1 \) and \( \lambda_2 \)  
W m\(^{-2}\) sr\(^{-1}\)

\( \dot{w} \)  
Reaction Rate  
kg m\(^{-3}\) s\(^{-1}\)

\( y_i \)  
Mass Fraction  
-

\( \bar{y} \)  
Atom Mass Fraction  
-

Greek symbols

\( \beta \)  
Energy Accommodation Coefficient  
-

\( \beta \)  
Velocity Gradient  
s\(^{-1}\)

\( \gamma \)  
Catalycity  
-

\( \Delta \)  
Boundary Layer Thickness  
m

\( \delta \)  
Uncertainty  
-

\( \varepsilon \)  
Emissivity  
-

\( \lambda \)  
Wavelength  
m

\( \lambda \)  
Thermal Conductivity  
W kg\(^{-1}\) K\(^{-1}\)

\( \mu \)  
Viscosity  
kg m\(^{-1}\) s\(^{-1}\)

\( \rho \)  
Density  
kkg m\(^{-3}\)

\( \tau \)  
Characteristic Time  
s
Subscripts

amb ambient
app apparent
cond conductive
cal calorimeter
cat due to catalycity
ch chemical reaction
cw cold wall
D dissociation
d dynamic
diff diffusive
e boundary layer outer edge
eff effective
ei electric - imposed on the HFreq generator
exp experimental
F formation
fl flow
geo geometric
i relative to specie i
int intrinsic
m model
pj post-jump
post after test
pre before test
rec recombination
s static
sol solid
t total
w wall
wet wetted
∞ freestream
List of Symbols

Superscripts

0 blackbody
F relative to flight
GT relative to the ground test
(n) iteration n
↓ impinging on the surface
↑ transferred to the surface
‡ leaving the surface

Constants

c Speed of Light 299792458 m s$^{-1}$
e Base of the Natural Logarithm 2.718281 -
\( \hbar \) Planck’s Constant 6.6260693 \times 10^{34} J s
\( k_B \) Boltzmann’s constant 1.380658 \times 10^{-23} J K^{-1}
\pi Pi 3.14159265 -
\sigma Stefan-Boltzmann constant 5.670373 \times 10^{-8} W m^{-2} K^{-4}
Chapter 1

Introduction

1.1 Hypersonic Flows and Atmospheric Reentry

With the birth of “faster than sound” aircrafts with the flight of Charles “Chuck” Yeager in October 14th, 1947, new and challenging problems arise and countless generations of scientists and engineers had been fighting to break the frontiers of the human knowledge and provide safer, faster and cheaper ways to travel around the world and beyond. But the “brand new world” of supersonic and specially hypersonic flow showed that Socrates was more than right: “I know one thing, that I know nothing”.

Along the years, specially during the firsts flights of hypersonic vehicles, the X-15 flight tests [1], scientists discovered several new phenomena that were not predicted by the theories at the time and the same still keep happening today. But, before further development it is important to give the description of what is hypersonic flow.

1.1.1 The Hypersonic Flow Regime

In fact, there isn’t an universally accepted concept that could tell us what is an hypersonic flow but is usually accepted that it is a flow with a free stream Mach number grater than 5. Although, this is not totally accepted by the scientific community as we can read in the citation presented in the next page.

For the proposes of this work and simplicity, hypersonic flow will be considered a flow with a free stream Mach number grater than 5 and in which the high temperature gas properties play a non negligible roll. One of the fields were the hypersonic flow regime play an important roll is the so called Atmospheric Reentry.
1.1.2 The Atmospheric Reentry

The history of Atmospheric Reentry (also called Planetary Reentry) begins in the Cold War between USA and USSR with scientists from both sides trying to understand the new phenomena arising from the hypersonic flight conditions. These concerns have arisen from the design of new weapons, the ICBMs and their reentry warheads, and consequently the investigations on these matters were also propagated to the Space Race during the second half of the twentieth-century.

Nowadays reentry still represents one of the most fascinating challenges for scientific research in the space technology context and both for atmospheric reentry and hypersonic cruise vehicles the aerothermochemical environment is still the least known constrain for the design of such machines. This is result of the extremely complicated coupled physical phenomena involved.

Reentry is defined as the trajectory of a celestial body (asteroid, spacecraft, etc.) between the moment in which it first “fells” the planet atmosphere and the moment in which it touches the ground. These two limits are not absolutely fixed and usually vary according to the problem. For the “upper” limit on Earth, for example, the altitude of 120km is usually accepted, despite the fact that the official limit for space is the Kármán line at 100km altitude. The lower limit is more variable, and can be defined as the moment in which the vehicle touches the ground, opens a parachute or changes in flight condition “mode” (for example, for the Space Shuttle the hypersonic reentry is defined until the moment in which a condition of Mach \( \frac{5}{2} \) is reached) [2].

During reentry, the spacecraft travels in a speed much higher than the speed of sound. Because of it, a bow shock wave is formed in the front of the vehicle. In the nose stagnation point region, the shock wave is almost a normal shock wave and through it the flow is decelerated to subsonic speeds and both pressure and temperature increase by several orders of magnitude. In a reentry from earth orbit the temperature is usually high enough to promote dissociation in the gas and for a spacecraft returning from the moon or Mars it is usually enough to promote ionization [3].

Reentry can be divided in two groups, low-speed reentry and high-speed reentry. Low-speed reentry corresponds to a reentry in which the initial speed is bellow the corresponding orbital speed and a high-speed reentry to one in which the initial speed is in the order of magnitude of the escape velocity. It can be also divided into ballistic or gliding reentry according to the lift-over-drag ratio of the vehicle. Examples of such vehicles are presented in figure 1.2. IXV, the base vehicle for this work, can be classified as gliding reentry vehicle.

1.2 Families of Thermal Protection Systems

Thermal protection systems can be divided in 3 main groups: Active, Passive and Semi-Passive. Figure 1.1 represents most of the current concepts for TPS and detailed information about each one can be found in [1, 4, 5].

\(^1\)Extracted from [3]
Almost everyone has their own definition of the term hypersonic. If we were to conduct something like a public opinion poll among those present, and asked everyone to name a Mach number above which the flow of a gas should properly be described as hypersonic there would be a majority of answers around five or six, but it would be quite possible for someone to advocate, and defend, numbers as small as three, or as high as 12.

P. L. Roe, comment made in a lecture at the Von Kármán Institute, Belgium, January 1970

It is important to notice that until now the samples tested in the VKI Plasmatron were always tested according to the concept of Hot Structure or highly Insulated Structures because the samples were in radiative equilibrium with the environment without allowing conductive heat loss [6, 7]. The new method developed in this work (see section 3.7.1) allow the determination of the aerochemical environment, surface catalycity and heat transfer for several different TPS concepts like Convective Cooling, Heat Pipe, Heat Sink Structure and Insulated Structure (for insulation types in which the conductive HF is not negligible).

1.3 Aim of This Project

The aim of this work is to further continue the work developed all over the years in VKI about aerothermodynamics of reentry vehicles.

In this framework, as collaborator of Francesco Panerai, Post-Doc Fellow in VKI, I actively partic-
ipate in the experimental TRP Oxidation campaign and in a substantial part of the post-processing of the results. The results of this campaign is presented in chapter 5.

The development of a new experimental method to increase the Plasmatron operations capabilities, including new methods for GSI research are presented in chapter 4 and 6 and are almost exclusive responsibility of the author (except some already referenced acknowledgements).
Introduction

(a) Apollo Command Module - A Typical Ballistic Reentry Vehicle

(b) Space Shuttle Orbiter - A Typical Gliding Reentry Vehicle

Figure 1.2: Artist’s Impression of Different Vehicles During Reentry
Chapter 2

Catalycity and Oxidation Research - A Bibliographical Review

2.1 Gas Surface Interaction and Catalycity

2.1.1 Principles of Catalycity

As we saw in section 1.1.2 the aero thermochemical environment around a reentry body in a low speed reentry is dominated by phenomena such as chemical reactions in the flow and wall and heat transfer by conduction, convection, recombination and radiation. All this mechanisms play a role in the heat flux balance at the wall. This has important implications on the final surface temperature and conduction heat flux into the wall which will be the main parameters that drive the selection of the TPS for the mission. This selection is very complicated because the TPS itself will play a role in the final picture because of the chemical characteristics of the surface. This coupling between the surface and the flow itself is usually called Gas/Surface Interaction or GSI. When dealing with the effect of the surface in the flow several problems arise basically because of lack of knowledgeable in this kind of phenomena at high temperature and low pressure, despite all the efforts conducted in solving that problems since the 50s [1].

One of the factors that contribute more for the heat transfer to the wall is the exothermic reactions occurring there. The reactants for this reactions are the dissociated and ionized atoms generated by the bow shock wave in the front of the vehicle. These atoms eventually reach the surface which acts as a catalyst and promotes the exothermic recombination reactions. This process is called heterogeneous catalycity.

But not all the atoms that reach the wall undergo the recombination process into molecules. The probability that this reaction occur is defined as the recombination coefficient or catalycity. Catalicity can than be defined as the ratio between the flux of recombined atoms over the flux of
Figure 2.1: Limit Cases for Surface Catalycity

impinging atoms on the surface for a certain specie \( i \).

\[
\gamma = \frac{M_{i,\text{rec}}}{M_i^\downarrow} \quad (2.1)
\]

In this work, only 2 recombination reactions were considered: \( O + O \rightarrow O_2 \) and \( N + N \rightarrow N_2 \) and the same recombination coefficient is used for both. Some recent investigations [8, 9] shown that the production of NO (\( N + O \rightarrow NO \)) can be so important as the reactions above, but the mechanism for its formation is not yet completely understood. In chapter [5] is also referred that the reaction \( Si + O \rightarrow SiO \) should also be taken into account due to its highly exothermic nature.

The 2 limit cases for catalycity are the fully-catalytic wall (\( \gamma = 1 \)) and the non-catalytic wall (\( \gamma = 0 \)) that are represented in figure 2.1.

Following the same approach of Panerai [7], we can define the experimental values of \( \gamma \) as effective, apparent catalycity, which relates with the true catalycity by the formula

\[
\gamma = \gamma_{\text{app,eff}} = \tilde{\beta} \cdot \gamma_{\text{app}} = \frac{E^4}{D} \cdot \gamma_{\text{app}} = \frac{E^4}{D} \frac{S_{\text{wet}}}{S_{\text{geo}}} \gamma_{\text{int}} \quad (2.2)
\]

in which \( \gamma_{\text{int}} \) is the true microscopic catalycity in a multi-temperature model (temperature of the flow different from the temperature of the wall). For more information the reader is advised to consult Thoemel [10], Barbante [11] and Panerai [7].

2.1.2 Catalycity, Heat Shield Design and Simulation

One of the biggest unknowns when designing a new hypersonic vehicle is the surface catalycity.

Usually designers assume a fully-catalytic wall\(^1\) because that’s the “worst case scenario” for surface heating but experiences in very different facilities had proved that for common TPM the value can

\(^1\)And sometimes even Super Catalytic Wall
be 3 orders of magnitude lower [12, 13, 7]. Classical references like Anderson [3] usually admit that, for common reentry scenarios, the heat flux to a fully-catalytic wall is approx. twice the one to a non-catalytic wall. This puts a lot of weight penalty in an “end of line” space application because a reentry vehicle should always do the complete mission, from Earth to Earth (generally speaking: from planet to planet). This ‘dead weight’ (= “dead budget”) can be avoided with a better knowledge of the reentry conditions in general and GSI phenomena in particular.

Catalycity is also a fundamental parameter that need to be accurately introduced in CFD codes in order to correctly “connect” the flow to the surface. To complicate a little bit, usually catalycity isn’t a single number but, instead, a variable dependent on surface temperature and boundary layer edge parameters. This is referenced in several works like [7, 14, 15, 16] and again proved in this work (see chapter 6). That’s why a correct ATDB, both in data and concept, is very important for the design of future space missions.

2.2 Passive-to-Active Oxidation Transition in TPM

Since the first heat shields designed for reentry applications, reusability is an important concern for the design engineers. For high speed reentry ablative heat shields are necessary so reusability is out of question. On the other hand, for low speed reentry, specially when large gliding and skipping reentry vehicles are used, reusability is a main concern, for economic reasons. We all remember the financial disaster of the US Space-Shuttle Program, primary due to the expensive maintenance of the SSO between flights.

So, it is essential for future designs to know if a certain material will be preserved or degraded during a reentry maneuver. Used in the SSO and Buran (Буран), Silicon Carbide (SiC) composites or coatings are one of the main material in study for future missions and many investigations about it were already done in the past. It is known [7, 17, 18, 19, 20] that for high pressures and low temperatures, SiC undergoes in a passive oxidation process that generates a net mass gain due to the creation of a protective layer of Silica (SiO\(_2\)) in the exposed surface of the material. The chemical reaction occurring is

\[
\text{SiC(s) + } \frac{3}{2}\text{O}_2(g) \rightarrow \text{SiO}_2(s) + \text{CO(g) in a molecular oxygen atmosphere}
\]

or

\[
\text{SiC(s) + 3O(g) \rightarrow SiO}_2(s) + \text{CO(g) in a atomic oxygen atmosphere}
\]

For higher temperatures/lower pressures, the material go through an active oxidation process which conducts to a net mass loss and degradation of the material. The chemical reaction is

\[
\text{SiC(s) + O}_2(g) \rightarrow \text{SiO(g) + CO(g) in a molecular oxygen atmosphere}
\]

or
SiC(s) + 2 O(g) \rightarrow SiO(g) + CO(g) in a atomic oxygen atmosphere

The frontier between this two regimes is called Passive-to-Active (PA) transition.

Despite the fact that it only became a primary issue with the start of the space-shuttle program, the first studies about oxidation transition in SiC based materials date from the 50s, when Wagner proposed a model that relates the transition with the partial pressure of oxygen in the mixture bulk and surface temperature [21]. Later Turkdogan et al. [22] developed the “smoke theory” for the vaporization of Si.

Later also Gulbransen and Jansson [23], Singhal [24], Hinze and Graham [25], Nickel [26], Keys [27], Narushima et al. [28], Heuer and Lou [29] and Balat [17, 18], among others, also published studies about this topic.

Particularly, Gulbransen and Jansson provided 3 possible thermodynamic equilibrium equations for the transition:

\[
\begin{align*}
\text{SiC}(s) + 2 \text{SiO}_2(s) & \rightarrow 3 \text{SiO}(g) + \text{CO}(g) \\
\text{SiC}(s) + \text{SiO}_2(s) & \rightarrow 2 \text{SiO}(g) + \text{C}(s) \\
2\text{SiC}(s) + 2 \text{SiO}_2(s) & \rightarrow 3 \text{Si}(g) + 2 \text{CO}(g)
\end{align*}
\]

Laboratory tests indicated the third equation as the one that best fits the results.

Balat [17, 18], based on the work of Wagner [21], developed a model that predicts the transition partial pressures of oxygen as function of the diffusion coefficients $D_i$.

As we can see in figure[2.2] it is difficult to find results in accordance between the different research groups. This is why research programs about this topic are still going on, like the one that supported part of this work.
Figure 2.2: IXV Surface Temperature and PA Transition Lines. The solid line represent the evolution in the temperature of the most heated point in the windward side of the vehicle.
Chapter 3

Experimental Facilities and the LHTS Methodology

3.1 Plasmatron: The VKI’s ICP Windtunnel

The Plasmatron facility was designed in the early 90s in order to support the design process of Hermes, a spacecraft also known at the time as the European Space-Shuttle. Although the main project got cancelled, the Plasmatron project continued in order to reinforce the european knowledge in the the fields of reentry aerothermodynamics and plasma physics. The facility was first ignited in July 18th, 1997 and it’s still the most powerful of its kind in the world. Figure 3.1 presents the complete facility system.

Since then, a long list of lessons were learned by all the people that worked in this facility and the most important was that nothing is easy in a Plasmatron experiment, mainly because of the extreme temperatures and complexity of the facility. The facility and the experimental setups are continuously being updated in order to increase the Plasmatron capabilities and the results’ quality.

To produce plasma, this facility uses a physical principle called inductive-coupled plasma generation (ICP). Conceptually it consists in a quartz tube surrounded by a coil in which a gas is injected. The coil is connected to a high power generator that provides high alternate voltage with an high frequency. The current in the coil induces a powerful oscillatory electro-magnetic field inside the tube with the field lines coaxial it. The residual charged particles in the gas are than accelerated because of the magnetic field and additional Foucault currents appear.

This makes the gas to heat up because of Joule’s effect promoting an increase on the gas ionisation degree, increasing the Foucault currents and making the flow entering into an heating “snowball” effect that results in high temperature, highly ionized gas (plasma) that exits the torch in form of a jet (see figure 3.1).
The high power generator is capable of providing 1.2 MW at 2 kV and 400 kHz and it's a solid state MOS technology generator. The torch as 160 mm of diameter and exits to a test chamber at low pressure with 2.5 m long and 1.4 m diameter and the whole facility is cooled by deionized water in a close circuit. The facility is computer controlled using a 719 I/O lines PLC and two PC’s for monitoring the operation. The envelope of operation of the facility is presented in figure 3.3.

3.2 The Local Heat Transfer Simulation method in VKI

In order to correctly duplicate the reentry flight conditions in a ground test facility it’s mandatory to use similitude relations. It is known that practical ground test facilities can’t totally reproduce the freestream of flight conditions with Mach numbers higher than 8 [30]. In order to overcome this problem, several different types of facilities were developed to address different parts of the problem.

For the Mach number simulation Blow-Down windtunnels and Shock Tubes are used. Blow-Down windtunnels are cold gas facilities so no chemistry can be reproduced but Shock Tubes can actually reproduce the complete aerothermodynamic environment for reentry vehicles. The problem with these facilities is that they only allow testing for a fraction of second. This short amount of time is not
This facility was the Plasmatron pilot facility.

Figure 3.2: ICP Torch - VKI Minitorch Facility

Figure 3.3: Plasmatron Operation Envelope
enough to properly test TPM due to thermal inertia.

To solve this problem, high enthalpy facilities were developed and in the western countries and
the most used were diffusion reactors [31, 32, 17, 18] and Arc-Jet facilities [13, 33, 34, 35]. Arc-Jets
provide the correct testing setup but several problems arise from their operation like jet instability,
flow contamination and lack of an exact knowledge of the operation conditions. Meanwhile in Soviet
Union, at IPM-RAS, Kolesnikov and his colleges developed the LHTS methodology based on ICP
plasma generators. This method allows to know with accuracy the boundary layer edge conditions
and those condition can then be used to extrapolate the test to a flight condition.

The base for the LHTS method are the analytical formulas developed in the 50s by Fay & Riddell
[36] and Goulard [12]. Both based their work in the pioneer work of Lees [37].

Fay & Riddell proposed the following formula for the stagnation point heat transfer on the nose
of a hypersonic vehicle with a fully-catalytic surface.

\[
q_w = 0.763 Pr^{-0.6}(\rho_e \mu_e)^{0.4}(\rho_w \mu_w)^{0.1^{0.5}}(H_e - h_w)[1 + (Le^{\alpha} - 1)(h_{D,e}/H_e)]
\]  

(3.1)

were

\[
h_{D,e} = \sum_{i,e} y_{i,e} h_{F,e}
\]

(3.2)

and \(\alpha\) is 0.63 for frozen boundary layer and equal to 0.52 for equilibrium boundary layer.

Goulard proposed a similar formula, more simplified and applicable only to frozen boundary layers,
but it allows to study walls with an arbitrary catalycity, using the factor \(\phi\).

\[
q_w = 0.664 Pr^{-0.6}(\beta_e \rho_e \mu_e)^{0.5}H_e[1 + (Le^{\frac{2}{3}} \phi - 1)(h_{D,e}/H_e)]
\]

(3.3)

\[
\phi = \frac{1}{1 + 0.47Sc^{-0.5} \sqrt{2/\beta_e \rho_e \rho_w}}
\]

Analysing these two formulas, Kolesnikov [38] concluded that to simulate the reentry aerother-
mochemical environment at the stagnation point only three parameters at the boundary layer edge
need to be equal to the flight condition: total enthalpy, total pressure and velocity gradient.

\[
H_e^F = H_e^{GT} \quad P_t,e^F = P_t,e^{GT} \quad \beta_e^F = \beta_e^{GT}
\]

(3.4)

Conceptually, these 3 parameters represent the conditions behind the bow shock wave that appears
in the front of an hypersonic vehicle (see figure 3.4).

Than, using the 3 parameters, it is possible to extrapolate the ground test to the hypersonic flight
of a vehicle with certain geometric characteristics using the Kolesnikov’s method [30, 38]. It uses the
following formulas:
The $h_F^\infty$ and $p_F^\infty$ can be neglected because we are dealing only with hypersonic speeds, so $(V_F^\infty)^2 >> h_F^\infty$ and $\rho_F^e \cdot (V_F^\infty)^2 >> p_F^\infty$.

At this point, the density can be used to, through an atmospheric model, know all the remaining parameters in flight like altitude, static pressure, static temperature and speed of sound and through that also the flight Mach number. In this work the U.S. 1976 Standard Atmosphere model \[39\] was used.

Then the boundary layer edge velocity gradient ($\beta_{GT}^e$) can be determined using $\Pi_2$ (NDP2, see section 3.8.2) together with model radius and, using the thin shock layer theory \[40\], we can relate it with flight conditions:

\[
\beta_{GT}^e = \frac{1}{R_{eff}^F} \sqrt{\frac{8 \rho_F^e - \rho_F^\infty}{3 \rho_F^\infty}} = \frac{V_F^\infty}{\sqrt{\frac{8 \rho_F^e}{3 \rho_F^\infty}}} \quad (3.7)
\]

Knowing that $\rho_e$ can be considered a function of $H_e$ \[30\] we can substitute $\rho_F^e$ by $\rho_e^{GT}$, which is a result of the enthalpy rebuilding process and the formula comes:

\[\text{An alternative to the thin shock layer theory is to use the modified Newtonian theory, in which the factor \[8/3\] in equation \[3.7\] is substituted by \[2\, \[3\].}\]
\( R_{\text{eff}}^F = \frac{V_F}{\beta G T_e} \sqrt{\frac{8}{3} \frac{\rho_F^c}{\rho_G^c T}} \)  

(3.8)

To know the test parameters in the Plasmatron chamber, also the methods presented by Kolesnikov are used in VKI but with some differences introduced in-house. The general methodology is address next in section 3.2.1 and again in 3.8.4 and the differences between the methods used in IPM-RAS and VKI are described in [41].

3.2.1 Experimental Methods for Reentry Simulation in Plasmatrons

To extrapolate the test of a TPM sample exposed to plasma to a flight condition a multi-step methodology is used.

First, after the test and knowing \( \dot{m} \), \( p_s \) and \( PW_{cl} \) is possible to calculate the corresponding Non-Dimensional Parameters (NDPs, see section 3.8.2).

During the test, a calorimeter (see section 3.5.1) is injected into the jet and the heat flux and surface temperature are recorded, being the surface catalycity estimated by the Minimax method in a different experiment [6, 42, 43, 7].

With all these results, we can than use the the CERBOULA code (see section 3.8.3) in order to calculate the boundary layer edge enthalpy (\( H_e \)) and other relevant properties in the boundary layer and in its edge.

At this point, we can extrapolate the results to flight conditions using equations 3.5, 3.6 and 3.8.

If one is also interested in the TPM catalycity, the process can than be reversed: The boundary layer edge parameters are now known, plus the surface temperature and heat flux (by optical methods, see section 3.6) so the CERBOULA code can be run in order to determine the surface catalycity. Also the famous Kolesnikov’s abacus (see section 3.3) can be calculated and used for the same propose.

An important remark should be done about the way how the transferred heat flux is calculated. It is done by performing an energy balance at the surface of the sample:

\( q_w^i = q_w^\downarrow \)  

(3.9)

\( q_{\text{cond}} + q_{\text{diff}} + q_{\text{rad.in}} = q_{\text{rad.out}} + q_{\text{loss}} \)  

(3.10)

\[ \left( -\lambda \frac{\partial T}{\partial y} \right)_{w,fl} + \sum_{i=1}^{NS} h_i \vec{T}_i \cdot \vec{n}_w + q_{\text{rad.in}} = \sigma \varepsilon T_w^4 + \left( -\lambda \frac{\partial T}{\partial y} \right)_{w,sol} \]  

(3.11)

In which the term \( q_{\text{rad.in}} \) is usually neglected based on the previous experiences and the term \( q_{\text{loss}} \) can be neglected [6, 7] in the experiments presented in chapter 5 but is measured by a calorimeter in the experiments presented in chapter 6.
The term $q_{\text{rad, out}}$ can be calculated using the Stephan-Boltzmann law ($q_{\text{rad}} = \varepsilon \sigma T_w^4$) being $T_w$ measured by the pyrometer and $\varepsilon$ calculated from the comparison of the pyrometer data with the radiometer data (see section 3.6.3).

At the wall, $\vec{J}_{i,w} \cdot \vec{n}_w = \dot{w}_i$ and the catalytic boundary condition is written as:

$$\dot{w}_{i,\text{cat}} = m_i \mathcal{M}_{i,\text{cat}} = m_i \gamma_i M_i^j$$  \hspace{1cm} (3.12)

If a Maxwellian distribution with the Chapman-Enskog perturbation term is used, the result for the impinging flux of atoms comes:

$$M_i^j = n_i \sqrt{\frac{k_B T_w}{2 \pi m_i}} + \frac{1}{2 m_i} \vec{J}_{i,w} \cdot \vec{n}_w$$  \hspace{1cm} (3.13)

Applying equation 3.13 in equation 3.12 the final expression comes [11]:

$$\dot{w}_{i,\text{cat}} = \frac{2 \gamma_i}{2 - \gamma_i} m_i n_i \sqrt{\frac{k_B T_w}{2 \pi m_i}}$$  \hspace{1cm} (3.14)

A complete and comprehensive picture of the complete methodology is presented in section 3.8.4.

3.3 Recalling the Abacus – The Temperature Problem

The Heat Flux Abacus for catalycity determination come originally from the work of Kolesnikov [38] and it is well known as a method for catalycity determination in Plasmatrons. A typical abacus can be seen in figure 3.5. Nevertheless, it is usually misunderstood as a general picture for the behaviour of catalycity as a function of temperature. In fact, people sometimes think that when the surface temperature changes, the point of determined catalycity moves inside the graphic to another point and that’s not true at all.

In fact, in all the experiments made so far, the temperature of the sample was only determined for an unique condition: the radiative equilibrium case. So we can’t compare results from tests at two different temperatures because the free-stream conditions, and so the boundary layer edge conditions, are different and for different conditions we have different abacus! Also, heat flux can change due to emissivity changes and/or aerothermodynamic factors like catalycity differences and all that must be taken into account.

The main propose of this work is to determine the catalycity for two different temperatures and for the same boundary edge conditions in order to plot, in the same abacus, two temperature points and then extract information that will hopefully help the design and selection of different types of TPS in the future, as explained in section 1.2. Results are presented in chapter 6.

As a final remark for this section the author would like to remember again that the abacus never closes a loop: For a given flight condition/boundary layer edge condition, a specific abacus is addressed and it allow us to relate three parameters: $T_w$, $\gamma$ and $q_{\text{rad}}^i$. Knowing two of them, we can know a third.
20 Experimental Facilities and the LHTS Methodology

Figure 3.5: Example of an Heat Flux Abacus

<table>
<thead>
<tr>
<th>Probe Name</th>
<th>Symbol</th>
<th>$R_{b}$, mm</th>
<th>$R_{c}$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>ST</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>EQ</td>
<td>57.5</td>
<td>5</td>
</tr>
<tr>
<td>Frozen</td>
<td>FR</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 3.1: Plasmatron Probes Dimensions

3.4 Sample Holders

The sample holders are presented in figure 3.6. Three different shapes (FR, ST and EQ) are available in VKI and their dimensions are presented in table 3.1. The difference in shape allow us to address different velocity gradients keeping all the remaining test conditions constant. This difference in velocity gradients is equivalent to changing the Damköhler number of the test $Da = \frac{\tau_{fl}}{\tau_{ch}}$ and that’s why this probes are also called Damköhler probes. In figure 3.7 is possible to see the old location of the calorimeter that read the $q_{loss}$ term (see section 3.2.1) in the classical setup.

Previous experiments [6] show that this quantity is negligible thanks to the thick layer of Procelit™ 180 placed in the back of the sample, so the calorimeter wasn’t used in this setup for the test campaigns presented in this work.

A new setup for the sample holder is presented in section 3.7.1

3.5 Intrusive Measurement Techniques

3.5.1 Heat Flux Probes

Copper heat flux calorimeters have been used for years in high enthalpy facilities in order to precisely measure the heat flux to an high catalytic surface. In fact, despite the first experiments using the LHTS principle used the assumption of a fully catalytic surface for copper, later on it was concluded
Figure 3.6: Sample Holders (Extracted from [7])

Figure 3.7: Sample Holder - Radiative Equilibrium Setup
that this isn’t a corrected assumption. Several campaigns were conducted in VKI to estimate the true copper catalycity for the different test conditions and nowadays it is possible to use catalycity tables to correct the copper catalycity used in the enthalpy rebuilding process \[6, 7, 42, 43\]. Some extensive information about this topic can be found in [7].

There are two types of calorimeters available in VKI: the water cooled calorimeter and the slug calorimeter. The later one was used in the past as reference and validator of the water cooled one \[6\] and it wasn’t used in this work. From now on, the water cooled calorimeter will be just referenced as calorimeter. The calorimeter work with a steady-state energy balance principle:

$$q_{cw} = \frac{\dot{Q}}{A} = \frac{\dot{m} \cdot c_p \cdot (T_{out} - T_{in})}{A}$$ (3.15)

In reference \[44\] an abacus is provided for the mass flow rate necessary in order to avoid water boiling. In \[44\] and \[45\] uncertainty quantifications are done for the probe and the latter one proposes the following formula for the relative error:

$$\frac{\delta q_{cw}}{q_{cw}} = \sqrt{\left(\frac{\delta \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\delta c_p}{c_p}\right)^2 + \left(\frac{\delta (T_{out} - T_{in})}{(T_{out} - T_{in})}\right)^2 + \left(\frac{\delta A}{A}\right)^2}$$ (3.16)

According to the uncertainties presented in [7], for typical values of \(q_{cw} (100 \sim 2000 \text{ kW m}^{-2})\) the error vary between 7% and 12%.

### 3.5.2 Pitot Probes

A Pitot probe with the same geometry of the heat flux probe is used to perform stagnation pressure measurements. The Plasmatron chamber is equipped with an absolute pressure transducer (Member-anovac DM 12, Leybold Vacuum, OC Oerlikon Corporation AG, Pfäffikon, Switzerland) that measures the static pressure with ±0.7 hPa accuracy. The Pitot line is connected to a Validyne variable reluctance pressure transducer (DP15, Validyne Engineering Corp., Northridge, CA, USA) and the output is amplified and corrected by a voltage demodulator (CD-15, Validyne Engineering Corp., Northridge, CA, USA). Validyne and amplifier are calibrated by means of a Betz water manometer, leading to an
uncertainty of ±0.2% in the dynamic pressure (information extracted from [7]). In figure 3.10 one can see an example of a pitot probe used in the Plasmatron.

3.6 Optical Measurement Techniques

3.6.1 Two-Colour Pyrometer

The two-colour pyrometers had proven to be one of the most reliable methods for practical radiative temperature measurement. They measure the spectral radiance in two different, but close, wavelengths. It is allowed to assume that, between the two wavelengths, the body emissivity does not change (gray body assumption). Then, the ratio between the spectral intensities allow to calculate the temperature independently from the emissivity.

In the Plasmatron equipment, two two-color IR pyrometers (Marathon Series MR1SB and MR1SC, Raytek Corp., Santa Cruz, CA) are available. They are selected according to the expected measured
temperature: the MR1SB operate between 700 and 1800°C and the MR1SC operate between 1000 and 3000°C. They work around 1µm wavelength, with a view angle of ∼35° relative to the sample normal and through a 1cm thick quartz window. The acquisition rate is 1Hz and the overall uncertainty is estimated to be ±10K. More information about these equipments and a mathematical description of the working principle of a two-colour pyrometer can be found in [7].

3.6.2 Broadband Infrared Radiometer

A broadband IR radiometer (KT19, HEITRONICS Infrarot Masstechnik GmbH, Wiesbaden, Germany) is placed with a view angle of ∼47° relative to the sample normal and it’s in front of a 1.8cm thick window made of KRS-5. This material provides a 70% transparency over the whole range of the operating waveband (0.6-39 µm). More information about this material can be found in [7]. The output is the integrated thermal radiation over the operational spectrum, within a temperature range of 0 to 3000°C and an acquisition rate of 1Hz was selected.

3.6.3 In-Situ Emissivity Determination Method

The in-situ emissivity measurement method currently used in the Plasmatron was introduced by Panerai [7, 19] inspired on the work of Balat at al. [46]. In essence, the method is very simple. The out-coming radiation from the sample is measured by the radiometer between the wavelengths 0.6 µm and 39 µm.

This radiation is than divided by the integrated blackbody radiation over the same wavelength interval (the temperature is known from the Pyrometer reading) and the result is emissivity.

\[
\varepsilon \equiv \varepsilon(T) \equiv \varepsilon_{0.6-39 \mu m}(T) = \frac{W_{0.6-39 \mu m}(T)}{W_{0.6-39 \mu m}(T)}
\]  

(3.17)

The Planck’s law, equation 3.18 gives the spectral radiance as function of temperature and corresponding wavelength and is integrated using the method proposed by Widger and Woodall [47] that results in equation 3.19 with \(W^0_{0-\lambda}\) coming in \(W^1 \text{ m}^{-2} \text{ sr}^{-1}\).

\[
W^0(\lambda) = \frac{2hc^2}{\lambda^5} \left( e^{\frac{2hc}{\lambda kT}} - 1 \right)
\]  

(3.18)

\[
W^0_{0-\lambda} = \frac{2k^4T^4}{h^3c^2} \sum_{n=1}^{\infty} \left( \frac{3\zeta^2}{n^2} + \frac{6\zeta}{n^3} + \frac{6}{n^4} \right) e^{-n\zeta} \text{ with } \zeta = \frac{2\pi hc}{\lambda k_B T}
\]  

(3.19)

For the numerical calculation of the series, \(\infty\) is substituted by \(n_{\text{max}}\) and using the relation \(n_{\text{max}} = \min(2 + 2/\zeta, 512)\) one can guaranty, at least, a 10 digit precision in the integration.
3.6.4 Optical Emission Spectroscopy

The equipment for optical emission spectroscopy is described in [7] and following information is adapted from there.

Optical emission spectroscopy is used to obtain qualitative information on the gas phase composition in front of the samples and detect the presence of relevant chemical species compared to freestream conditions. The emitted light is collected through a variable aperture and focused by a 300 mm focal length converging lens (LA4579, Thorlabs GmbH, Munich, Germany) into the entry of a 600 µm diameter optical fiber (Premium Fiber, Ocean Optics, Dunedin, FL). This lead to a broad range (200-1100 nm) spectrometer (HR-4000, Ocean Optics, Dunedin, FL). An acquisition rate of about 1 Hz provides real time acquisition spectra. In the present campaign the line of sight is maintained fixed in the stagnation line in 3 locations between 1mm and 9mm from the sample surface. The calibration of the system in relative intensity is performed with a deuterium lamp in the UV range (< 400 nm) and with a ribbon tungsten lamp in the visible (> 400 nm). The repeatability of the measurements has been checked, ensuring the relative uncertainty on the total integrated emission of the radiative signature to be less than 10%.

3.7 New Techniques Developed in the Context of this Work

3.7.1 Cooled Sample Setup

To achieve the objective of study the wall temperature effect on the catalycity of a TPS sample, a new experimental setup was developed to be used in the Plasmatron. Recalling the equation 3.10 that is repeated were for commodity

\[ q_{\text{cond}} + q_{\text{diff}} + q_{\text{rad,in}} = q_{\text{rad,out}} + q_{\text{loss}} \]
we can conclude that in order to change the surface temperature without changing the aerothermochemical environment we must change the amount of incoming radiation (3rd term in LHS) or change the conductive loss term (2nd term in RHS).

Reducing the amount of the incoming radiation will not allow reducing the wall temperature because the incoming radiation effects are already negligible and it’s very difficult to achieve in a practical way (probably only with help of cryogenic cooling). Besides all that, changes in the plasma properties could happen because, above a certain temperature, plasma can be considered a radiative participating medium. Any of the points listed above are enough to discard the incoming radiation option. However, to increase the wall temperature this method is applicable but a super-heated surface doesn’t have any real interest in the current frame of research. The remaining option is changing the $q_{\text{loss}}$ term.

Almost since the beginning, the idea for cooling the sample was to use a calorimeter in the back of the sample. The calorimeter serves two proposes: First it acts as an heat sink allowing the reduction of the sample surface temperature through thermal conduction across the sample. Second because it allows the measurement of the amount of $q_{\text{loss}}$ which is necessary to rebuild the surface catalycity.

The initial target was to use the same setup to cover the complete range of temperatures from the radiative equilibrium temperature (the highest possible) to a temperature near the cold wall calorimeter temperature (approx. 350K). Another requirement was to do it with the technical solutions available because of the short calendar for testing and budget limitations.

In order to simulate the envelope of operation of the calorimeter, a small 1D simulator, called heat1D, was programmed using the MATLAB™ environment. This program basically receives as input the geometry, the working fluid, the $Nu = f(Re, Pr, geometry)$ correlations and the boundary conditions used and it allows to investigate the range of temperatures experienced by the different components of the calorimeter cooling system. More details about this program can be found in section 3.8.1.

Two test cases were selected from the data available in [7]: one representing an high HF environment and another representing a low HF environment. Details can be found in table 3.2.

The first working fluid tested was water because it has been used for years in the calorimeters used in VKI and so the technical readiness level of such setup is quite high. The problem faced
was that it basically only allows a very narrow range for the wall temperature around 400K due to the excellent properties of water as cooling fluid. This lead to the simulation of several different alternative configuration by varying mass flow rate, inlet pipe diameter, materials and working fluids in order to acess to different temperature levels. Also the idea of using a thin layer of high temperature insulation in the back of the sample was introduced. This allow temperature levels that would be impossible to achieve otherwise.

This finally conducted to a multi-mode solution that appears to be the optimal considering all the constrains. An example of an operational map for this setup can be found in table 3.3. The final design for the calorimeter is presented in figure 3.12.

Besides Water, also Air, Argon, Helium and Carbon Dioxide were tested as working fluids. Air revealed to be the best in performance and technical simplicity for the situations were water is not functional. Helium revealed to be an extremely good cooling fluid for this kind of applications but in this particular case it is just “to good” because will conduct to results similar to water but with technical and economical disadvantages. Carbon Dioxide as properties similar to air but it is interesting for applications around 800K of calorimeter inner wall temperature because it has an abortion window coincident with the radiative peak of a blackbody at the same temperature (approx. 4µm, see figure 3.13). Argon presents weak properties for this kind of application. In the end, Air and Water were selected as working fluids.

The design of this calorimeter was quite challenging because of all constrains applied like maximum metallurgic temperature, maximum outlet temperature and constructibility of all the components. For future developments, the author recommends the reading the work of Zuckerman & Lior [48] because of the very complete set of correlations available for jet impingement heat transfer.

Because of a heavy load of work in the VKI workshop, it was impossible in practical time to prepare the new calorimeters needed for the original planed experience. The solution to overcome this problem was to create an adapter to transfer the heat from the sample to an existent calorimeter with the lowest temperature gradients in the sample as possible. The existent calorimeter can only be used with water because of metallurgical constrains.

The final apparatus used in chapter 6 is presented in figure 3.14.
28 Experimental Facilities and the LHTS Methodology

Figure 3.13: CO$_2$ Absorption Spectrum in Absorption Length Unit

<table>
<thead>
<tr>
<th>Wall Temperature [K]</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>900</th>
<th>1100</th>
<th>1200</th>
<th>1900</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition I</td>
<td>Water</td>
<td>Air</td>
<td>Air</td>
<td>-</td>
<td>Water + Radiative Thin Insulation</td>
<td>Equilibrium</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Condition II</td>
<td>Water</td>
<td>Air</td>
<td>Air</td>
<td>Air</td>
<td>-</td>
<td>-</td>
<td>Water + Radiative Thin Insulation</td>
<td>Equilibrium</td>
</tr>
</tbody>
</table>

Table 3.3: Example of an operational map for the High Temperature Calorimeter for the two test cases from table 3.2

Figure 3.14: Sample Holder - Cooled Sample Setup
3.7.2 New Correlation for Dynamic Pressure Estimation

Continuing the work of Marotta in VKI [15] it was noticed that the static pressure influence on dynamic pressure was not explicit in the previous available correlations. To avoid time lost when post-processing long lists of data with linear interpolations that can’t even guarantee a correct representation of the static pressure effect, it was decided to create a “single” formula of the type \( p_d = f(q_{cw}, p_s) \) using the previous database compiled by Marotta and also including some Plasmatron data that wasn’t included in the previous work.

A non-linear least squares surface fit was done with help of a MATLAB™ script and several different formulas were tested in order to achieve the best possible fit on the data. The data and the fitted surface is represented in figure 3.15 and the final formula in equation 3.20. In this formula, \( q_{cw} \) should be introduced in kW m\(^{-2}\).

\[
p_d = A(1 + B q_{cw}) p_s^C + D
\]

\[
A = 31877.02 \\
B = 0.004857 \\
C = -0.935972 \\
D = -0.832394
\]  

(3.20)

A study of the errors involved in the process was done and the conclusions are summarized in figure 3.16. Despite some punctual measurements which have high relative deviations with respect to the correlation (some times higher than 90%), one can see that the average relative error is lower than 15% and the average absolute error is lower than 10 Pa. The \( r^2 \) factor in this fit is
> 0.998. This is considered acceptable considering the experimental problems in the acquisition of this data and fluctuations on the jet. According to Panerai [7], the typical uncertainty for the dynamic pressure measurement in the Plasmatron is 20%, so the average error in the correlation is inside the experimental uncertainty.

3.8 Brief Note on the Computational Methods Used

3.8.1 The heat1D script

This program was created to simulate the temperature of the sample, calorimeter, intermediate insulation and coolant fluid inside the calorimeter, as a first approximation to check if the idea of cooling a sample was possible or not. With the idea of simplicity in mind, the big challenge was to create a easy method to have, at least, approximate values for the boundary conditions at the sample. In this case, even the most complete methods can’t be trusted because the boundary conditions at the wall of the sample exposed to plasma are in fact the ultimate target of this experiments.

A first rough method was tried by using convection coefficients between plasma and sample but the final solution was found by analysing the work of Panerai [7]. In the experiments conducted there, the heat flux transferred to the wall ($q_{w}$) was determined with precision through a radiative equilibrium method. In this method the terms $q_{rad.in}$ and $q_{loss}$ from equation 3.10 are neglected: the first because of the low temperature of the test chamber and the second because of the thick Procelit™ insulation placed in the back of the sample [6]. So lets consider that at the edge of the

---

2In reference [7], $q_{w}$ is called $q_{w}$
boundary layer the conditions \((H_e, p_e, \beta_e)\) i.e. the test conditions) remain constant with respect to the radiative equilibrium test, ideally by submitting the two samples, in radiative equilibrium and cooled configurations, to the same plasma jet and with the same probe geometry.

For this kind of testing, only the conditions at the wall and inside the boundary layer will change. Let’s then analyse the conditions one by one. At the wall, the variables playing are three: Temperature, Catalycity and Emissivity. Temperature influence directly the conductive \((q_{\text{cond}})\) and the “loss” \((q_{\text{loss}})\) terms as it can be checked in equation [3.11] and in combination with catalycity also the diffusion term \((q_{\text{diff}})\) through the species production rate at a catalytic wall (equation [3.14]).

Temperature also influences the radiative heat flux \((q_{\text{rad,out}})\) in combination with emissivity. Emissivity is known to be a weak function of temperature [7, 49] but for this approximation it was considered constant and equal to 0.8.

The main point of the approximation done was to consider that \(q_{\text{w}}\) does not change with wall temperature. This is of course false but gives the “worst case scenario” for a first dimensioning of the experience. What happens is that the \(q_{\text{diff}}\) term decreases with the reduction of \(\dot{w}_{\text{catal}}\) which decreases with the reduction \(\sqrt{T_w}\) and \(\gamma\). \(\gamma\) itself appears also to decreases with temperature which was reported by different authors like Panerai [7] or Fourmond et al. [16].

Despite the fact that the decreasing of the wall temperature increases the conductive term \((q_{\text{cond}})\) it is known, specially for walls with an high catalycity, that this term is smaller compared with the \(q_{\text{diff}}\) term so a global reduction of \(q_{\text{w}}\) is expected or at least a no increase of it.

The first step done in the program is to calculate the \(q_{\text{loss}}\) term. That is made, using the hypothesis explained above, simply by subtracting \(q_{\text{rad,out}} = \varepsilon\sigma T_w^4\) from \(q_{\text{w}}\).

Then, using simple relations for 1D conduction and convection in the sample and in the calorimeter (from Incropera et al. [49]) and imposing the calorimeter bulk temperature, all the temperatures can be calculated.

To calculate the Nusselt number, three different correlations were used: The first come from an old technical report written during the design phase of the Plasmatron equipment [44]. It was result of numerical simulations and has the advantage that it was created directly for application at the problem in study but it is only available for water. The other two are design correlations for confined jets available in Li & Garimella [50], which result from experiments and are available for a wide range of fluids. These last two correlations were preferred but the results from the first one are very similar.

The formula extracted from [44] is:

\[
\overline{\text{Nu}} = 2.047 \text{Re}^{0.5} \left( \frac{\mu_w}{\mu_{\text{in}}} \right)^{0.1} + 5.848
\]  

(3.21)

The formulas extracted from [50] are:
Experimental Facilities and the LHTS Methodology

\[ \overline{\text{Nu}} = 0.676 \text{Re}^{0.555} \text{Pr}^{0.441} \left(\frac{l}{d}\right)^{-0.071} \left(\frac{D_c}{d}\right)^{-0.276} A_r \]
\[ + 1.133 \text{Re}^{0.637} \text{Pr}^{0.441} \left(\frac{D_c}{d}\right)^{-1.062} (1 - A_r) \]  
for Water (3.22)

\[ \overline{\text{Nu}} = 1.826 \text{Re}^{0.473} \text{Pr}^{0.441} \left(\frac{l}{d}\right)^{-0.071} \left(\frac{D_c}{d}\right)^{-0.312} A_r \]
\[ + 0.501 \text{Re}^{0.724} \text{Pr}^{0.441} \left(\frac{D_c}{d}\right)^{-1.062} (1 - A_r) \]  
for Air (3.23)

where \( l \) is the length of the inlet pipe, \( d \) is the inner pipe diameter, \( D_c \) is the diameter of the area cooled by the confined jet and \( A_r \) is the area of the jet impingement region normalized with the total area and is calculated using \( A_r = (1.9d/D_c)^2 \).

A typical output of the code is presented in figure 3.17.

### 3.8.2 The ICP code and NDPs

As explained before in section 3.2.1, after the test being complete, a lot of information is still missing and we need a "bridge" that is provided by CFD. Knowing the operation conditions of the Plasmatron, one can than use the VKI ICP code to know the non-dimensional parameters (NDPs) for the corresponding test. This solver will not be discussed in detail in this work but it is important to say that it is a viscous reactive flow solver coupled with an electro-magnetic solver. It uses a second-order accurate pressure-stabilized discretization on a collocated mesh that simulates the ICP.
torch and part of the test chamber. For more details about this solver the reader is addressed to specific literature [51, 52].

The solution depends on the power transmitted to the coil, static pressure, mass flow and swirl angle (being this usually fixed). The power transmitted to the coil (also called ICP value) is related with the power imposed on the High Frequency Generator by the generator efficiency. The generator efficiency was estimated in the past as 50% [53] and recent sensitivity analysis shown that efficiencies between 40% and 60% give a maximum difference in $H_e$ with respect to the nominal efficiency bellow 0.6% [7].

To save CPU time and results processing time, the solutions for the ICP code are in a database. Currently, solutions are available for mass flows of 16 g/s and 8 g/s. Only 16 g/s conditions were used all along this work. The solutions for each NDP for all pairs $(PW, ps)$ calculated in the past were fit with polynomials. These correlations are valid for power values between 60 and 120 kW, ICP value, and static pressures between 1500 Pa and 20000 Pa [7]. For all the NDPs, the regression formula is

$$\Pi_i = C_0 + C_1 \cdot ps + C_2 \cdot PW + C_3 \cdot ps \cdot PW + C_4 \cdot ps^2 + C_5 \cdot PW^2$$

(3.24)

Notice that in this formula the power should be in kW and the constants $C_i$ are available in table 3.4.

Each NDP as a physical meaning that is explained in the following list:

- Non-dimensional Thickness: $\Pi_1 = \frac{\Delta}{R_m}$
- Non-dimensional Velocity Gradient: $\Pi_2 = \left( \frac{du}{dx} \right)_e \frac{R_m}{v}$
- Non-dimensional Velocity Gradient Derivative: $\Pi_3 = \frac{d}{dy} \left( \frac{du}{dx} \right)_e \frac{R^2_m}{v}$
- Non-dimensional Velocity: $\Pi_4 = \frac{V_e}{v}$
- Modified Non-dimensional Velocity: $\Pi_5 = \frac{V_e}{V_{e,c,d}}$

Table 3.4: Constants for the NDPs Correlations

<table>
<thead>
<tr>
<th>NDP</th>
<th>$C_0$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>$C_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Pi_1$</td>
<td>+5.295E - 01</td>
<td>+2.095E - 07</td>
<td>-2.249E - 03</td>
<td>-3.637E - 08</td>
<td>+4.790E - 11</td>
<td>+0.125E - 06</td>
</tr>
<tr>
<td>$\Pi_2$</td>
<td>+7.799E - 01</td>
<td>-1.724E - 05</td>
<td>-8.034E - 03</td>
<td>+9.231E - 08</td>
<td>+2.824E - 11</td>
<td>+3.521E - 05</td>
</tr>
<tr>
<td>$\Pi_3$</td>
<td>+1.320E + 00</td>
<td>-3.090E - 05</td>
<td>-1.263E - 02</td>
<td>+1.824E - 07</td>
<td>+4.679E - 10</td>
<td>+5.528E - 05</td>
</tr>
<tr>
<td>$\Pi_4$</td>
<td>+9.341E - 01</td>
<td>-1.817E - 05</td>
<td>-1.924E - 02</td>
<td>+6.531E - 08</td>
<td>+3.473E - 10</td>
<td>+4.486E - 05</td>
</tr>
<tr>
<td>$\Pi_5$</td>
<td>+5.563E - 01</td>
<td>+2.126E - 06</td>
<td>-2.092E - 03</td>
<td>-7.657E - 09</td>
<td>-6.877E - 01</td>
<td>+8.847E - 06</td>
</tr>
</tbody>
</table>

Notice that in this formula the power should be in kW and the constants $C_i$ are available in table 3.4.

In fact, thanks to this correlations, the author never had to “lose” time running the ICP code in the cluster or studding it.

Recently, the values used in the adimensionalization of NDPs have changed slightly so the following formulas should be used very carefully.
The CERBOULA code

The code CERBOULA is in fact a code in two distinct parts: CERBERE and NEBOULA\(^5\). The program that is executed is CERBERE and this one iteratively calls NEBOULA. Each one of them will be shortly described in the next sections.

NEBOULA

This code is a solver for stagnation point axisymmetric boundary layers under the assumption of thermal equilibrium and chemical nonequilibrium. It is assumed that the flow is laminar and only steady-state is considered.

It was developed by Barbante \cite{Barbante11} and it uses the PEGASE library developed by Bottin \cite{Bottin54} for thermodynamic and transport properties. The equations are discretized by Hermitian polynomials and thanks to that the solution is forth order accurate. No more detailing about this code will be done in this work being the reader advised to consult specific literature \cite{Barbante11, Dunn55}.

Nevertheless, is important to say that the primary inputs for the program are the conditions at the BL edge (\(H_e, p_e, \beta_e, v_i,e, H_{ie}, \) etc.) plus the conditions at the wall \((T_w, \gamma)\) and the main outputs are \(q_{\text{cond}}, q_{\text{loss}}, \) and \(q_{\text{down}}\) plus the temperature and species distribution inside the boundary layer.

This program is written in C and during all this work a seven species Air mixture model (Air-7\(^6\)) was used for the flow. For the gas phase reaction constants, the Dunn & Kang chemistry model \cite{Dunn55} was used for all the calculations except in the sensitivity analysis in section 7.2.1.

CERBERE

This code acts essentially as a pre and post processor for NEBOULA.

The user has several options available like, for example, enthalpy rebuilding, catalycity rebuilding or abacus plotting, among others \cite{Cerber}. For enthalpy rebuilding the user gives all the BL edge parameters available (NDPs, \(p_d\) and \(p_s\)) plus the probe radius, wall conditions at the calorimeter and the measured heat flux \((q_{cw})\). The code will than iterate the BL edge temperature (and consequentially also \(H_e\)) with a Newton loop until the numerical heat flux calculated by NEBOULA (that is executed in each iteration) matches the experimental one.

For catalycity rebuilding, the process is similar but instead of \(H_e\) (that is now known), the iterated variable is \(\gamma\).

To plot the heat flux abacus, the user just need to input the BL edge conditions and the NEBOULA will calculate, for user selected pairs \((T_w, \gamma)\), the corresponding heat flux.

\(^5\)Sometimes this code is referred in the literature as “VKI Boundary Layer Code”
\(^6\)This model include the following species: O\(_2\), N\(_2\), NO, NO\(^+\), O, N and e\(^-\)
3.8.4 The Complete Experimental-Numerical Frame

In figure 3.18 we try to give a complete view of how the data from the experiments is processed until the final results are obtained, as explained in the previous sections.
Chapter 4

Numerical Simulations

In order to have a first feeling on the 2D effects in the cooled sample experiment a series of thermal simulations were done using ANSYS™. It uses the finite element method and the element type chosen for this work was a quadratic triangle and a serendipity quadratic quadrilateral. No further considerations will be done about this method being the reader addressed to specialized literature like Reddy [57]. The simulations were done in 2D axisymmetric mode and the symmetry axis is the left vertical on the images. Because of the fallback of the original planned temperature campaign (see section 3.7.1) also a quick simulation of the calorimeter adapter was made.

4.1 Cooled Sample Setup Simulation

As already explained in section 3.7.1 two different test cases were studied: one corresponding to low HF and the other corresponding to high HF, respectively Condition I and Condition II. For simplicity, the emissivity was considered always equal to 0.8 for the reasons already explained in section 3.8.1. These two conditions were used to test three configurations of sample holders: without cooling, with cooling and with cooling and intermediate insulation.

In figure 4.1 we can see an example of a mesh for the configuration with cooling. The meshes for the other configurations are equivalent. The boundary conditions used were a convective surface in the back with a bulk fluid temperature of 350K and a convection coefficient\(^1\) of 7000 W m\(^{-2}\) K\(^{-1}\), the sample and cover being submitted to a constant HF and radiating to an enclosure at 400K. The initial temperature was set to 300K. Details and results for the different configurations will be presented next. Temperature fields for all the simulations are presented in Appendix A and Temperature vs. Time graphics can be found in Appendix B and are from points along the symmetry axis.

\(^1\)A value typical for the water calorimeters was used because no data is available for the cooling system of the holder itself.
4.1.1 ST Sample Holder Without Cooling

This configuration was tested to access the validity of the approximations made in section 3.8.1. The cover material used was the same used in the tests, Silicon Carbide (SiC).

4.1.2 ST Sample Holder With Cooling

The main objective of these simulations was to find if the lateral heat flux to the calorimeter could “pollute” the measured heat flux across the sample. The Temperature vs. Time graphics show that the steady state for the sample area is achieved in less than 10 s. The holder in general only achieve steady state after 75 s. Heat Flux fields can be found in figures 4.2 and 4.3.

The geometry simulated is very rough because, at this point, the final experimental setup was not it fully defined/known which lead to the need of an extra simulation presented in section 6.2. Also a small insulation was planed to be placed between the sample and the cover but it does not exist in the final setup.

The conclusions for these simulation are that the lateral heat flux only has a negligible effect on the final measurement for the two conditions.
Figure 4.2: HF Field - Cond. I

Figure 4.3: HF Field - Cond. II
4.1.3 ST Sample Holder With Cooling and Insulation

In the same way as the simulations in the previous section, the objective of these simulations was to find the lateral heat flux to the calorimeter. According to the Temperature vs. Time graphics, the steady state for the sample area is also achieved in less then 80 s. Heat flux fields are presented in figures 4.4 and 4.5.

The conclusion for these simulations are equal to the ones in section 4.1.2.

4.2 Calorimeter Adapter

As explained in section 3.7.1, there was the need of designing a calorimeter adapter.

The simulations done were similar to the simulations in section 4.1 with the exception that only the sample and the adapter were simulated for simplicity and lack of time for modelling. Simulations were made first for pure copper (\( \lambda = 400 \text{ W kg}^{-1} \text{ K}^{-1} \)) and then for commercial bronze (\( \lambda = 50 \text{ W kg}^{-1} \text{ K}^{-1} \)) and for thicknesses of 5 and 3 mm. The results show that with 5 mm it’s possible to obtain a maximum surface temperature difference lower then 4K for an adapter made of commercial bronze with 5mm thickness for condition I which is more than acceptable for the proposed experiments.
Figure 4.5: HF Field - Cond. II

Figure 4.6: Temperature Field - 5mm adapter
Figure 4.7: Temperature Field - 3mm adapter
Chapter 5

Oxidation Campaign

The objective of this campaign of tests was to establish the transition between Passive and Active Oxidation in C/SiC TPM and also the identification of the operational limits of such material through the investigation of the phenomena known as “temperature jump”.

The tests were done under the framework of the IXV project for the expansion of the ATDB in order to help the design phase of this vehicle and were financed through an ESA’s Technology Research Programme (TRP).

5.1 Testing Procedures

The testing procedure were similar for all the samples tested. Inside the Plasmatron test chamber were installed a Pitot probe, an HF probe and the sample holder. Most of the tests were done using the ST geometry for Pitot, HF probe and sample holder, but in the end of the test campaign some were done using the FR geometry. These last tests are described in section 5.2.6.

The measurements with the intrusive probes were acquired before the sample injection into the plasma and used to calibrate the jet. Afterwords, the optic instruments allow the measurement of the sample temperature and emitted radiation. Besides that, also optical spectrometry data was acquired from 3 points in or near the boundary layer region and the test was recorded with an High Definition Camera. All the steps of the tests are listed below:

→ Chamber vacuum and pressure stabilization;
→ Plasma and data recording start-up;
→ Standard heat flux probe injection and power adjustment to the target heat flux;
→ Heat flux probe retraction and Pitot probe injection;
→ Pitot probe retraction and sample holder injection;
Oxidation Campaign

Table 5.1: Test Conditions for HER samples

<table>
<thead>
<tr>
<th>Test</th>
<th>Sample</th>
<th>$T_{\text{w}}$</th>
<th>$T_{\text{w,j}}$</th>
<th>$q_{\text{exp}}$</th>
<th>$P_{\text{a}}$</th>
<th>$P_{\text{d}}$</th>
<th>$m_{\text{prex}}$</th>
<th>Time</th>
<th>$P_{\text{W_{exp}}}$</th>
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<td>[K]</td>
<td>[kW m⁻²]</td>
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<td>1.956</td>
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</table>

* Preliminary data to be verified.
** Jump temperature. Before jump, steady state was achieve with $T_{\text{w}}$=2095K.
*** Jump temperature.

Two different kinds of TPM were tested. Both are CMC C/SiC manufactured by Herakles and MT Aerospace, that will be referred from now on as HER for the material manufactured by Herakles and MTA for the one from MT Aerospace. Both are identical materials and they consist in a Silicon Carbide matrix reinforced with Carbon Fiber so they can be classified as CMC. MTA also owns an extra SiC layer coating the surface, deposited by chemical vaporization methods. HER will be used to construct the nose and windward side of IXV and MTA will be used for the construction of the control flaps of the same vehicle.

The test conditions are presented in the tables 5.1 and 5.2.

5.2 Results

The results of this testing campaign will be presented in this section together with results from literature for comparison.

In this section, the notation $q_{\text{w}}$ will be used to represent $q_{\text{exp}}$ ($= q_{\text{w,exp}}$).
Oxidation Campaign

5.2 Test Conditions for MTA samples

Table 5.2: Test Conditions for MTA samples

<table>
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<tr>
<th>Test</th>
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<th>$\epsilon$</th>
<th>$T_E$</th>
<th>$s$</th>
<th>$P_{W_{el}}$ kW</th>
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* Preliminary data to be verified.
** Jump temperature.

5.2.1 General Results (ST geometry)

First, in tables 5.3 and 5.4, we present the rebuilt quantities calculated using the LHTS methodology, more specifically using the ICP code results and running the CERBOULA code, and also some other important quantities as, for example, mass loss rate. At the end of each table the estimated oxidation regime is presented. The complete rebuilding results, including the NDPS used and the species concentration at the boundary layer edge are presented in Appendix C.

To determine the oxidation regime, 3 criteria were used: visual inspection, mass loss rate (MLR) and presence of a Silica layer detected using Scanning Electron Microscopy (SEM).

As a first approach, the visual appearance of the samples allow to roughly say if a sample went through a passive, active regime or a temperature jump. The previous work of Panerai [7, 19] was used as reference.

Description of the samples and images are presented in section 5.2.3. In the future, this is will
oxidation campaign

Table 5.4: Summarized Test Results - MTA

probably be helpful for spacecraft maintenance routine checks.

The MLR allow a more scientific approach. It is known, from previous experiments which used a real-time weight measurement, like the work done by Jacobson & Myers [20], that the mass loss rate varies dramatically between passive and active oxidation and that fact is used as transition criteria. Results are presented in figures 5.1 and 5.2. The letter A mark the samples that were submitted to active oxidation.

We can clearly see a large increase in the MLR of the samples subjected to active oxidation with respect to the ones subjected to the passive regime. One can also see that lower static pressures are more destructive for the samples.

The SEM was used as a verification measurement, which allowed to confirm the presence/absence of a glassy silica layer over the exposed surface, hence, cross-checking the predicted regime by the other methods. The SEM analysis were performed at PROMES, France.

An uncertainty analysis was done for the MLR determination. Knowing that the MLR is given by the formula

\[
MLR = \frac{m_{\text{post}} - m_{\text{pre}}}{A \Delta t}
\]

than it can be deducted that the relative uncertainty is given by

\[
\frac{\delta MLR}{MLR} = \sqrt{\left(\frac{\delta m_{\text{post}}}{m_{\text{post}}} + \frac{\delta m_{\text{pre}}}{m_{\text{pre}}}\right)^2 + \left(\frac{\Delta t}{\Delta t}\right)^2 + \left(\frac{2\pi D}{4D}\right)^2}
\]

The uncertainty for the temperature is given by the pyrometer specifications and it is equal to \(\pm 10\,\text{K}\).

The observation, using SEM, of samples without a SiO\(_2\) layer which didn’t went through a temperature jump, together with the analysis of the results of the visual inspection and the MLR, can be used to declare, with relative confidence, that the temperature jump can’t be used as a marker of the transition.

An interesting result can be found plotting the surface catalycity as function of the boundary layer edge enthalpy. It can be observed in figure 5.3 that the catalycity has a relative increase during the
transition and such result goes in the same direction as the theory: active oxidation is equivalent to a more reactive wall.

This sudden increase in $\gamma$ can be used for determination of the PA transition but is not recommended by the author. It implicate a very long measurement chain, subjected to several different errors, which in the end conducts to an high uncertainty. In fact, previous UQ studies done by Villadieu et al. \cite{58} and Panerai \cite{7} point to uncertainties that can be bigger than the vertical range of this graph. Plus, chemistry models involving Si in the gas phase are still missing in the code, including the important exothermic reaction $\text{Si} + \text{O} \rightarrow \text{SiO}$. Nevertheless, this method is valid but needs an higher number of tests to guarantee its validity.
5.2.2 Passive-to-Active Oxidation Transition Line

In this section we present our results together with our proposal for a PA oxidation transition line, based on the same trending of the result from the experiments done at PROMES using the MESOX set-up using CVD SiC on C/SiC composites under microwave-excited air and presented by Balat (fig. 11 in [18]).

As we can see, our results are in very good agreement with the reference. The results are presented in figures 5.4 and 5.5 as function of the oxygen partial pressure and reciprocal wall temperature. The differences in the results can be attributed to the uncertainties and differences in the tested samples.

5.2.3 Visual Inspection of the Samples

Despite that the samples were submitted to scanning electron microscopy (SEM), a simple visual inspection of them can deliver interesting information. In figure 5.6 we can see pictures of samples that undergone different oxidation regimes for the same static pressure level (in this case 5000 Pa). For the sample that undergone passive oxidation a yellow/brown/blue appearance can be observed and it is associated to the existence of a thin silica layer in the surface. The colours change according to the thickness of the silica layer. After active oxidation, the surface has a shiny look and one can notice the reduction of the coating protection that makes the carbon fibres more exposed. After a temperature jump, the surface is completely eroded and the black appearance is due to the residuals of the carbon combustion. Also an appreciable reduction in thickness is noticeable.

Similar conclusions can be extracted for the MTA samples, with the pictures presented in figure 5.7.
Figure 5.4: Passive-to-Active Transition - HER

Figure 5.5: Passive-to-Active Transition - MTA
Figure 5.6: Examples of HER samples tested with $p_s=5000\text{Pa}$
Figure 5.7: Examples of MTA samples tested with $p_s = 5000 \text{Pa}$
5.2.4 The Temperature Jump

The temperature jump is a phenomena observed in TPM containing SiC and submitted to extreme reentry environments. It was first reported by Lacombe & Lacoste [59] and after by other scientists [60, 61].

More recently, I. Sakraker et al. [62], Marshall et al. [63] and Panerai [7] found the same phenomena in experiments done in the Plasmatron at VKI. In this work we are going to avoid detailed comments or explanations on this topic being the reader advised to consult Hald [64] or Marshall et al. [63].

In figures 5.8 and 5.9 one can observe the difference in temperature evolution between a test without jump and one with the jump. One should also notice that after the jump the temperature is several hundreds of Kelvin above the cases without jump. These extreme temperatures, in an enough long reentry manoeuvre would conduct to the destruction of the TPM and consequently of the spacecraft.

In figure 5.10 we can see the evolution of emissivity for the two jump examples presented in figures 5.8 and 5.9. One can notice that after the jump, emissivity is reduced with respect to the condition pre-jump. This was noticed to be a common behaviour for all jump cases.

The emissivity peaks that appear in the graphics are just an artefact generated by the measurement system. The pyrometer is measuring the temperature in a circle with a diameter of ~ 3mm concentric with the sample. On the order hand, the radiometer is measuring the radiation from almost all the sample. This correspond to an advance/delay in the two measurements due to the slow propagation of the "jump front" across the sample.

In figure 5.11 one can see the visual recording of the "jump front" and the corresponding temperature evolution.

Only when the surface is completely immersed into the jump state, the emissivity measurement is reliable again. In conclusion, the emissivity data recorded during the jump should be ignored.
(a) TEST 28 - No Jump

(b) TEST 32 - Temperature Jump

Figure 5.9: Temperature History During Two Different Tests - MTA

(a) TEST 7 - HER

(b) TEST 32 - MTA

Figure 5.10: Integrated Spectral Radiance and Emissivity History

Figure 5.11: Temperature Jump - Evolution in Time
5.2.5 Optical Spectrometry Results

As referred before, optical spectrometry data was took during the tests. The spectrometers were aligned in order to record the emission from 3 points in the boundary layer, at 2mm, 5.5mm and 9mm from the sample along the stagnation point axis. In figure 5.12 one can see the spectra recorded with the flow already calibrated for the desired conditions with and without the sample in place. The data was obtained with the same spectrometer, pointed 1.5mm away from the sample.

5.2.6 Frozen Geometry Tests

This tests, presented in figure 5.13, show the evolution of one Si emission line (with $\lambda=288$nm) during a temperature jump. One can observe that the increase in emission starts before the measured temperature jump because of the diffusion of Si in the boundary layer during the jump evolution and the fact that the spectrometer doesn’t measure the emission in a single point but instead in a line in front of the sample. In the last image we can see that in the last 20 sec. a jump started but the jump front didn’t reach the centre of the sample before the end of the test.
Figure 5.12: Spectra took during Test 21 (Active Oxidation). One should also notice the Si peaks that appear in the presence of the sample. The arrows in the bottom figure indicate the reduction in intensity due to the recombination of the species in the BL and/or temperature reduction.
Figure 5.13: Emission Line Si288 Intensity Evolution During a Temperature Jump
Chapter 6

Temperature Campaign

This campaign had the objective of investigate the effect of temperature in surface catalycity and heat transfer on C/SiC TPM. The experience consist in fixing all the parameters in the BL edge \((H_e, p_e, \beta_e)\) and change only the surface temperature. This allow us to “isolate” the surface temperature effects. On the original test campaign was programmed to investigate several temperature levels but in consequence of issues in the manufacturing of the lab equipment\(^1\) only 2 temperature levels were investigated as explained in section 6.1. The samples tested were manufactured by Snecma Propulsion Solide.

6.1 Testing Procedures

Three tests were done in this experiment and all followed the same testing sequence which is described below. In each test two samples were tested: one with the cooled setup, already described in section 3.7.1 and one with the conventional insulated setup (see section 3.4). From now on the sample installed in the cooled setup will be referred as cooled sample (CS) and the other as radiative equilibrium sample (RS). In all the tests the geometries of the sample holder and the heat flux probe were the ST one. Each test correspond to a different pair of \((p_e, \beta_e)\) because we tried to keep \(H_e\) constant and equal to 10MJ/kg.

→ Chamber vacuum and pressure stabilization;
→ Plasma generator and data recording start-up;
→ Heat flux probe injection and power adjustment to the target heat flux;
→ Heat flux probe retraction and cooled sample injection;
→ Cooled sample exposure to plasma for approx. 8 minutes;

\(^1\)One of the drawbacks of doing an experimental simulation is that it doesn’t depend only of our will
Temperature Campaign

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<th>Sample</th>
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</table>

Table 6.1: Test Conditions for the Temperature Campaign and Reference [7]

- Cooled sample retraction and radiative equilibrium sample injection;
- Radiative equilibrium sample exposure to plasma for approx. 8 minutes;
- Plasma off and chamber ventilation;
- Stop of data recording;
- Samples recovery after system cooling;

In table 6.1 the test conditions are presented as well as some reference results extracted from [7]. The target HF was calculated before the tests using the NEBOULA code in order to match a BL edge enthalpy of 10MJ/kg. Unfortunately, it is always impossible to match exactly the the desired condition as consequence of uncertainties in the HF measurement, because the power is “tuned” in real time but the real average value of HF is only acquired in post-processing and also because in the preparation only an approximate value for the power was used. Nevertheless, the difference with respect to the target $H_e$ obtained in tests T1 and T2 was 6% and in test T3 was 13%. The error in T3 is higher because of lack of accurate power estimations during the preparation of the test campaign, which was caused by a “last-moment” change in the test condition related with Plasmatron operation constraints.

6.2 Results

The results of the campaign are summarized in table 6.2. As for the oxidation campaign, the complete rebuilding results are presented in Appendix C and some considerations on the degree of dissociation of the flow and on the temperature profile across the BL are presented on section 7.3.

During the experiments was noted that the HF measurement of $q_{\text{loss}}$ recorded by the DAC was much higher than expected. It was found that there was two reasons for that. First there was a question of concept in the the HF determination: the calorimeter probe doesn’t measure directly the HF, it measures the heat rate, this value is then divided by the area of the calorimeter and the result is the output value of the DAC. But, in fact, the area of the sample is higher than the area of the
calorimeter but the heat rate that crosses the surface of the sample is the same that crosses the surface of the calorimeter (conservation of energy principle), than the heat rate should be divided by the sample area, because that is the input for the 1D catalycity rebuilding process used in the CERBOULA code (see section 3.8.3).

Second, it was found that the SiC sample holder was exchanging a huge amount of heat with the sample ($\dot{Q}_{\text{lat}}$), i.e., the insulation created by the surface contact was too low to properly insulate the sample, as it was expected prior to the experiment. In order to overcome this issue, a new numerical simulation of the experiment was done, this time using the exact geometry tested\footnote{During the design phase simulations, presented in chapter 4 there were several unknowns like the exact samples to be tested and the exact way the sample and the calorimeter would be installed.}. A sketch of the simulated geometry is presented in figure 6.1.

The calculation of the heat rates was done performing the heat flux integration over the area using the HF results from the FEA considering cylindrical coordinates. The imposed heat flux in the wall was the value obtained by measuring the radiative equilibrium sample. The final formula to correct the measured heat flux at the calorimeter surface\footnote{Output of the DAC.} was again based on the conservation of energy principle and it is

\[
\dot{Q}_{\text{loss}} = \dot{Q}_{\text{cal}} - \dot{Q}_{\text{lat}} \iff \\
\iff \dot{Q}_{\text{loss}} = \dot{Q}_{\text{cal}} \left(1 - \frac{\dot{Q}_{\text{lat}}}{\dot{Q}_{\text{cal}}} \right) \iff \\
\iff q_{\text{loss}} = q_{\text{cal}} \frac{A_{\text{cal}}}{A_{\text{sample}}} (1 - F)
\]

in which $F$ is equal to 0.6894 and the numerical simulations shown that this value is a weak function of the imposed heat flux for the ranges of this experiment. Using this method it is possible to obtain a corrected value for the $q_{\text{loss}}$ term.

Table 6.2: Test Results From the Experiments and Reference [7]

| Test | $\dot{Q}_{\text{cal}}$ | $T_{\text{in}}$ | $\beta_e$ | $\gamma_{\text{cal}}$ | $\gamma_{\text{ref}}$ | $\gamma_{\text{exp}}$ | $\gamma_{\text{rad}}$ | $\gamma_{\text{loss}}$ | $\gamma_{\text{exp}}$ | $\gamma_{\text{rad}}$ | $\gamma_{\text{loss}}$ | $\gamma_{\text{exp}}$ | $\gamma_{\text{rad}}$ | $\gamma_{\text{loss}}$ |
|------|----------------|-------------|---------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| T1-CS | 6925.0 | 1375 | 0.82 | 167 | 43.7 | 210 | 4223 | 1440 | 9.3777 | 0.0000677418 | 0.10 | 0.026205 |
| T1-RS | 6925.0 | 1375 | 0.86 | 257 | 0.0 | 257 | 4223 | 1440 | 9.3777 | 0.0000677418 | 0.10 | 0.026205 |
| T2-CS | 2168.5 | 1374 | 0.78 | 157 | 52.8 | 210 | 4354 | 5000 | 9.4236 | 0.0032728925 | 0.10 | 0.005751 |
| T2-RS | 2168.5 | 1374 | 0.82 | 254 | 0.0 | 254 | 4354 | 5000 | 9.4236 | 0.0032728925 | 0.10 | 0.005751 |
| S10 [7] | 2097.8 | 1400 | 0.86 | 172 | 0.0 | 172 | 4440 | 1300 | 10.2487 | 0.0008190640 | 0.10 | 0.007280 |
| T3-CS | 935.2 | 1374 | 0.79 | 157 | 40.2 | 197 | 4085 | 10000 | 8.6575 | 0.0070697653 | 0.01 | 0.040872 |
| T3-RS | 935.2 | 1374 | 0.86 | 235 | 0.0 | 235 | 4085 | 10000 | 8.6575 | 0.0070698046 | 0.01 | 0.011544 |
| C2a [7] | 916.7 | 1515 | 0.90 | 269 | 0.0 | 269 | 4306 | 10000 | 9.1462 | 0.0066631346 | 0.01 | 0.023190 |
Figure 6.1: Geometry tested and Simulated

Figure 6.2: Steady State Temperature Simulation
Figure 6.3: Steady State Heat Flux Simulation

Figure 6.4: Heat Flux History of Test T1
6.2.1 Catalycity

The final output of the rebuilding process can than be obtained using the CERBOULA code and/or the HF Abacus. The graphics are presented in figures 6.5, 6.6 and 6.7 and in the abacus of T2 (figure 6.6) one can observe some important HF quantities. These quantities are also presented in section 7.3.

We can also plot the result in a 3D graphic including all the boundary condition variables (except enthalpy that is considered constant) and the result is presented in figure 6.8 together with the results from [7]. A 2D version of the graph can be also plotted to increase the readability but one should remember that $p_c$ and $\beta_c$ are independent parameters [14] and in order create the plot the $\beta_c$ values were approximated (the approximation error is around 10%).

Appears that the slope of $\gamma$ vs. $T_w$ in a log scale doesn’t evolve with $(p_c, \beta_e)$, which means that $\gamma$ is more sensible to $T_w$ for (low $p_c$, high $\beta_e$) values. On the other hand, the slope of HF vs. $T_w$ seems to be independent of $(p_c, \beta_e)$. 
Figure 6.6: Abacus of test T2 - (a): Reduction on the experimental heat flux due to the reduction on the surface temperature

Figure 6.7: Abacus of test T3
Figure 6.8: $\gamma$ as function of the BL edge parameters
Temperature Campaign

Figure 6.9: Experimental HF as function of the BL edge parameters
Chapter 7

Discussion of Results

7.1 Analysis of the Numerical Simulations

Taking into account the assumptions and approximations done for the boundary conditions and material properties, it is clear that very good results in terms of temperature values can be obtained using a finite element analysis specially for steady state.

Looking to the results of the simulation of the holder without cooling for condition I we can observe that the holder reaches steady state after approx. 150s and the maximum temperature is about 1070K. Considering that the time for steady state observed in the experiment was around 1min and the temperature recorded was 1200K we can see that the numerical results are not in perfect agreement with the experiment. Anyway, for steady state, the temperature relative error is 11%, which is acceptable for this preliminary analysis.

The same doesn’t happen for condition II were the values are much more close to the experimental values: time for steady state around 50s and temperature with a relative error of 0.7%. Specially for steady state conditions, the approximation seems to give better results for higher heat flux.

For the simulation with cooling a comparison was done between the steady state results from ANSYS™ and the results from heat1D. The values taken from the 2D simulation are from the symmetry axis. The results can be found in tables [7.1] and [7.2] and one can conclude that there is a good agreement between the two methods, despite the fact that in the ANSYS™ simulations the materials are non linear and, surfaces exchange heat through radiation with an enclosure at 400K instead of deep space (0K) in heat1D and the convection coefficient is fixed.
7.2 Analysis of the Oxidation Campaign

7.2.1 Sensitivity Analysis

To assess the reliability of the method, a sensitivity analysis was done in the catalycity determination process. That was done by calculating the HF Abacus using three different sources for the gas reaction constants: Dunn & Kang \[55\], Gupta et al. \[65\] and Park \[66\].

Two tests were selected (Test 1 and Test 28) and the results are presented in figures 7.1 and 7.2. One can notice that, for the temperatures and HF, the differences in the catalycity results are negligible.

7.2.2 Flight Extrapolation

Using the LHTS methodology (see section 3.2), it is possible to extrapolate the tests done in the Plasmatron to actual flight conditions. In figure 7.3 one can see the trajectory of the IXV vehicle and the reconstructed tests. The IXV trajectory was obtained from \[7, 67\]. It appears that the vehicle starts in an active oxidation region and then evolves to a passive region but that’s only an illusion.

In fact, in the experiments we simulate a steady-state condition, what would be equivalent to a cruise condition at the same speed and altitude. A reentry manoeuvre is typically a transient condition and as we can see in figure 2.2, the temperature in the surface starts by being relatively low due to the fact that the spacecraft comes from the “outer space”. Afterwords, during the surface warming up, the pressure is also increasing keeping the vehicle in a passive oxidation regime. After critical conditions being achieve, it goes into an active oxidation region and finally, with the increasing pressure, back to passive again.

\[^1\]The BL edge condition were rebuilt using always the Dunn & Kang reaction constants.
Results Discussion

Figure 7.1: Abacus from Test 1

Figure 7.2: Abacus from Test 28
Besides, one should take into attention that the BL edge velocity gradient is not the same that in the IXV flight condition as it can be seen in figure 7.4 so some of the tests correspond to a vehicle with a different effective nose radius. The effective nose radius can be calculated using equation 3.8. One should also note that the tests simulate better the IXV case for the higher pressures. In [7], Panerai showed that the EQ geometry is better for IXV simulations at low pressure.

Future work should be directed into the development of “transient flight extrapolation” capabilities for the Plasmatron.

### 7.3 Analysis of the Temperature Campaign

In this section, some considerations on the boundary layer of the samples tested in this campaign will be made.

First, let’s look into the species present at the BL edge (figure 7.5). One can observe that almost all the $O_2$ is dissociated and also that small quantities of atomic N appear, specially for low pressures.

Looking now to the differences between the temperature profiles in the BL (figure 7.6), one can notice that the difference in the shape of the curves is small near the wall, despite the difference in the wall temperature. This only results in a tiny increase in the $q_{\text{cond}}$ term (figure 7.7).

In figure 7.7 one can also see that the behaviour predicted in section 3.8.1 was correct: Cooling the sample (reducing $T_w$) conducts to an increase in the $q_{\text{cond}}$ term but also to a major decrease in the $q_{\text{diff}}$ term, due to catalycity decrease, which results in a global reduction of $q_{\text{loss}}$.

#### 7.3.1 Sensitivity Analysis

A sensitivity analysis on the catalycity rebuilding process was done considering that errors on $q_{\text{loss}}$ measurement and correction can occur. Experiment T1 was selected for the sensitivity study and the results are presented in table 7.3. One should note that even if the $q_{\text{loss}}$ term had been underestimated by half of its value, the value of $\gamma$ would still be lower than the value measured in the RS.

A complete UQ of the experiments was impossible in practical time because of the complexity of the software DAKOTA+CERBOULA [7] together with the need of modifications to accommodate the latest version of the CERBOULA code developed in the context of this work. Nevertheless the author consider that it is a mandatory step in future work.

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<th>Variation in $q_{\text{loss}}$</th>
<th>$q_{\text{loss}}$ [kW m$^{-2}$]</th>
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<th>$\gamma$ Rel. Error [%]</th>
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Table 7.3: Sensitivity Analysis for Test T1
Figure 7.3: Extrapolated Flight Conditions - Oxidation Campaign
Figure 7.4: Extrapolated Velocity Gradient - Oxidation Campaign

Figure 7.5: Mass Fractions at the BL Edge
Figure 7.6: Temperature Evolution Inside the Boundary Layer - Test T1

Figure 7.7: Heat Flux to the Wall
## Results Discussion

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<th>Static Pressure [Pa]</th>
<th>Static Temperature [K]</th>
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Table 7.4: Extrapolated Flight Conditions

![Figure 7.8: Extrapolated Flight Conditions](image)

### 7.3.2 Flight Extrapolation

In figure 7.8 and table 7.4 one can see the reconstructed flight conditions and the values of the effective nose radius of an hypothetical cruise vehicle which nose stagnation point would be subjected to the same aero thermodynamic environment as the tested samples.

### 7.4 Stagnation Point ATDB Algorithm

The ultimate target of TPS testing is to help the decision process and dimensioning of the TPS to be installed in future space missions.

Nowadays, very old and conservative formulas to estimate the heat transfer to the wall are still in use (see section 2.1.2). This happens because design engineers like to have very simple formulas in order to introduce them in the fast optimization loops used during the preliminary-design phase of a project. The objective is always to know the heat flux from the plasma to the wall and it’s known that it depends on 4 parameters: \( H_e, p_e, \beta_e, T_w \) besides surface material and gas mixture. In fact, for a given material and gas mixture the HF dependencies can be summarized in the following formulas.
\[ q_{w}^{\downarrow} = q_{w}^{\uparrow} \]  

\[ q_{w}^{\uparrow} = f(H, p, \beta, T) \]  

\[ q_{w}^{\downarrow} = f(T_{w}, \lambda \frac{\partial T}{\partial y}, \varepsilon(T_{w})) \]  

In equation [7.2] we can also include the term \( \gamma = f(T_{w}, \ldots) \) but it is a characteristic of the material.

Using the current setup in the Plasmatron, it is possible to make complete reconstruction of stagnation point boundary layer of a body immersed in an hypersonic flow. Then, knowing the conditions in the boundary layer edge, it is possible to obtain all the other relevant properties. One should remember that the cooled setup allows to define the surface temperature and also that catalycity depends on wall temperature.

With all this in mind, the correct way to construct a steady-state ATDB seems to be the one presented in the figures 7.9 and 7.10. For each flight condition, should be done a set of tests to access different velocity gradients (it varies with nose radius and flight conditions). For radiative equilibrium TPS types this is enough and the wall temperature is also a result but for active-passive or active TPS types (see section 1.2), additional tests for several wall temperatures must be conducted.

All the information can then be stored in tables and allow a fast and easy method to know heat flux or catalycity to be implemented in future design or CFD codes.

In the figures, the thick boxes represent the inputs for the ATDB and the thick dashed boxes the results from the ATDB.
Figure 7.9: Flowchart for ATDB Algorithms - Hot or Insulated Structure TPS

Figure 7.10: Flowchart for ATDB and Algorithms - Generic TPS
Chapter 8

Conclusions and Future Work

8.1 Conclusions

In this work, the Passive-to-Active oxidation transition of C/SiC TPM in Earth’s reentry aerothermochemical environment was determined by experimental methods and the results are in good agreement with the data available in literature. Also it was proved that the temperature jump phenomena can’t be considered a indicator of the PA transition.

Also the method used to estimate the heat flux to cooled walls presented in section 3.8.1 and its applicability to 2D thermal simulations, without direct fluid simulation, proved to be a valuable method for quick estimation of heat transfer rates for Plasmatron equipment or even for reentry spacecraft design whenever data for the TPM in radiative equilibrium conditions is available.

A new method for TPS testing was developed, allowing now the tests of Convective Cooling, Heat Pipe and Heat Sink Structure TPS in the VKI’s Plasmatron. This new method also allows the correctly study of the wall temperature effect on catalycity for fixed flight conditions. With this method it was discovered that both catalicity and heat flux to the wall decrease by decreasing the surface temperature. It was also discovered that $\gamma$ is more sensible to variations in $T_w$ for (low $p_e$, high $\beta_e$) values and that the sensitivity of the heat flux to variations on $T_w$ seems to independent of $(p_e, \beta_e)$.

Efficient computational methods for construction and use of stagnation point aerothermodynamic databases are also presented.

8.2 Recommendations for Future Work

Further theoretical investigations must be done to understand better the temperature jump phenomena and it’s causes. Introduction of more chemical reactions and models is also important, specially in the boundary layer code (NEBOULA).
A redesign of the sample holders is mandatory to decrease the errors associated with the lateral heat flux in the cooled sample configuration. Expanding the Temperature Campaign to different velocity gradients by using the frozen and equilibrium holders in a cooled sample configuration could be also an important improvement.

Also, further improvements are necessary to correctly simulate reentry conditions in terms of velocity gradient and transient effects. New probes are necessary to achieve a time continuous complete simulation of TPS in the Plasmatron.

Careful radiation analysis are also important for future work. Inside the test chamber the sample faces the torch gas which irradiates large amounts of energy because of it’s high temperature. This doesn’t happen in flight so must be taken into account during the calculation of the experimental heat flux. Maps for the incoming radiation could maybe be constructed using the radiation transport capabilities of the ICP code.
References


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Appendix A

Figure A.1: Temperature Field - Section 4.1.1 - Condition I
Figure A.2: Temperature Field - Section 4.1.1 - Condition II

Figure A.3: Temperature Field - Section 4.1.2 - Condition I
Figure A.4: Temperature Field - Section 4.1.2 - Condition II

Figure A.5: Temperature Field - Section 4.1.3 - Condition I
Figure A.6: Temperature Field - Section 4.1.3 - Condition II
Appendix B

Figure B.1: Temperature vs. Time - Section 4.1.1 - Condition I
Figure B.2: Temperature vs. Time - Section 4.1.1 - Condition II

Figure B.3: Temperature vs. Time - Section 4.1.2 - Condition I
Figure B.4: Temperature vs. Time - Section 4.1.2 - Condition II

Figure B.5: Temperature vs. Time - Section 4.1.3 - Condition I
Figure B.6: Temperature vs. Time - Section 4.1.3 - Condition II
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Table C.1: NDPs and Rebuilt Quantities - Oxidation Campaign (HER)
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<th>NDP2</th>
<th>NDP3</th>
<th>NDP4</th>
<th>NDP5</th>
<th>T(h)</th>
<th>P(h)</th>
<th>(K)</th>
<th>Pa</th>
<th>kg s(^{-1})</th>
<th>(\times 10^{10}) J kg(^{-1}) m s(^{-1})</th>
<th>(\gamma_{\text{ref}})</th>
<th>(\mu_e)</th>
<th>(\mu_s)</th>
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<td>0.3595</td>
<td>0.3935</td>
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<td>2900</td>
<td>1.008E-06</td>
<td>3.197E-01</td>
<td>4.201E-01</td>
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<td>4.310E-01</td>
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<td>0.3909</td>
<td>0.3400</td>
<td>0.3444</td>
<td>0.3772</td>
<td>2000</td>
<td>2900</td>
<td>1.019E-06</td>
<td>3.262E-01</td>
<td>5.126E-01</td>
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<td>4.201E-01</td>
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**Table C.2: NDPs and Rebuilt Quantities - Oxidation Campaign (MTA)**

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<th>NDP4</th>
<th>NDP5</th>
<th>T(h)</th>
<th>P(h)</th>
<th>(K)</th>
<th>Pa</th>
<th>kg s(^{-1})</th>
<th>(\times 10^{10}) J kg(^{-1}) m s(^{-1})</th>
<th>(\gamma_{\text{ref}})</th>
<th>(\mu_e)</th>
<th>(\mu_s)</th>
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<td>4.201E-01</td>
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<td>3.197E-01</td>
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</tbody>
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**Table C.3: NDPs and Rebuilt Quantities - Temperature Campaign**