Utilization of Infrared Thermography to Investigate Atmospheric Entry Aerothermodynamics of Space Vehicles at von Karman Institute

by C. O. Asma*, J. Thoemel*, S. Paris* and O. Chazot*

**Aeronautics and Aerospace Dept – von Karman Institute for Fluid Dynamics, Brussels, Belgium*

Abstract (Arial, 9pt, bold)

Space vehicles that are making an entry through the atmosphere of a planet suffer tremendously because of extreme heating of the vehicle. The design of thermal protection systems for space vehicles involves multi-disciplinary topics and is a very critical stage of space vehicles. The qualification of thermal protection systems on ground is very important for a safe space flight and the protection of critical payloads. At von Karman Institute, several ground facilities are used for the characterisation and qualification of thermal protection systems and materials. Infrared thermography is one of the most important measurement techniques used to monitor surface temperature and heat flux imposed on the thermal protection material, thus enabling the researchers to analyse the structural and thermal behaviour of tested materials. This should not be more than 100 words (Arial, 9 pt, justified).

1. Introduction (Arial, 9pt, bold)

When a space vehicle is to make an entry into the atmosphere of the destination planet, it has to be protected from severe aerodynamic heating. The extremely high amount of kinetic and potential energy that the space vehicle has at the beginning of its atmospheric flight should have been completely transformed into thermal energy when the space vehicle finally lands down. Thermal protection system (TPS) materials are used to shield hypersonic aerospace vehicles from the severe flow heating encountered during atmospheric entry. Proper design of TPS is one of the most critical stages of the design of the space vehicles as it is indeed a complicated optimisation problem between many scientific topics. On one hand, the TPS has to be light enough, but on the other hand it has to guarantee the protection of the vehicle and its payloads from extreme temperatures. The aerodynamic constraints on the external shape of the space vehicle bring additional difficulty on designing the TPS.

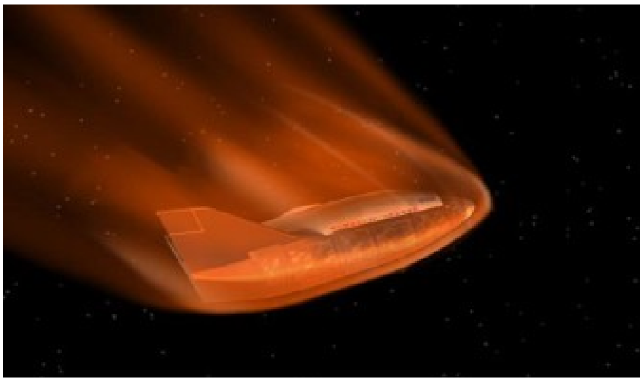

Fig. 1. *Artistic view of the X38 Crew Re-entry Vehicle (NASA / ESA)*

The characterisation of the thermal protection material (TPM) is very important prior to the flight. Emissivity and catalycity at elevated temperatures are the two most important properties of the TPM [1]. The determination of emissivity and catalytic properties of TPS materials is a major issue for the aerospace vehicles. These properties strongly affect the heat transfer to the materials with up to a factor of two greater heat flux for a fully catalytic material compared to a non-catalytic material. Knowledge of TPS catalytic properties is extremely important for designing aerospace vehicles that have very stringent mass budget, for reusable launch vehicles the problem is even more critical. They require operating in a suitable ground facility with measurement techniques developed for high enthalpy flows. An appropriate methodology is also mandatory to allow for flight extrapolation.

For these reasons, many experimental investigations are carried out in ground facilities that are able to simulate the high enthalpy condition of atmospheric flights [2]. Performing tests under harsh thermal conditions is not easy. Suitable measurement techniques have to be applied carefully to be able to monitor the thermal and aerothermodynamic properties of the free-stream and the test model. Among several measurement techniques, infrared thermography is one of the most useful techniques to observe the temperature history of the test specimen. The fact that the surface temperature of the test specimen reaches values above 1000C, radiative heat flux becomes significant, thus employment of infrared camera or pyrometers result in more precise temperature measurements compared to other techniques such as thermocouples.

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2. High Enthalpy Facilities of von Karman Institute (Arial, 9pt, bold)

The experimental simulation of real flight situation in a laboratory is a very complex issue. The complete simulation of the aerodynamic and thermal loads encountered during re-entry flight is not possible within a single facility. New concepts of high-enthalpy facilities are being studied, such as the radiatively driven hypersonic wind tunnel using non-isentropic heating process [3] or very large scale arc-jet facility [4]. Those facilities approach better the reality but still address only one part of the trajectory and the main problem remain about the reacting flow produced by electrical discharge and not by shock waves as it occur in a real flight. At von Karman Institute, the atmospheric entry flight is simulated in two different facilities, one high-enthalpy facility (Plasmatron) and another facility (Longshot) that can simulate the high air velocity.

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2.1. The Longshot Facility (Arial, 9 pt, underligned)

The VKI Longshot free piston tunnel (Fig. 1) is a short duration facility operating with nitrogen or carbon dioxide and designed for the attainment of very high Reynolds number hypersonic flows. It has a Mach 14 contoured nozzle of 0.43 m exit diameter and a 6 degree conical nozzle of 0.60 m exit diameter which can be used throughout the Mach number range from 15 to 20 using nitrogen and 10 to 15 using carbon dioxide. Typical Reynolds numbers at Mach 15 range from $5x10^6$ to $20x10^6$ / m.

A high precision incidence mechanism for pitch, roll, and yaw is mounted in the open-jet 4 m^3 test section. Instrumentation includes a force/moment balance, accelerometers, thin-film and coaxial thermocouples for heat flux measurements, piezoresistive pressure transducers, and a Schlieren system; 64 channels of transient recorders with a 50 kHz sampling rate are controlled by a PC.

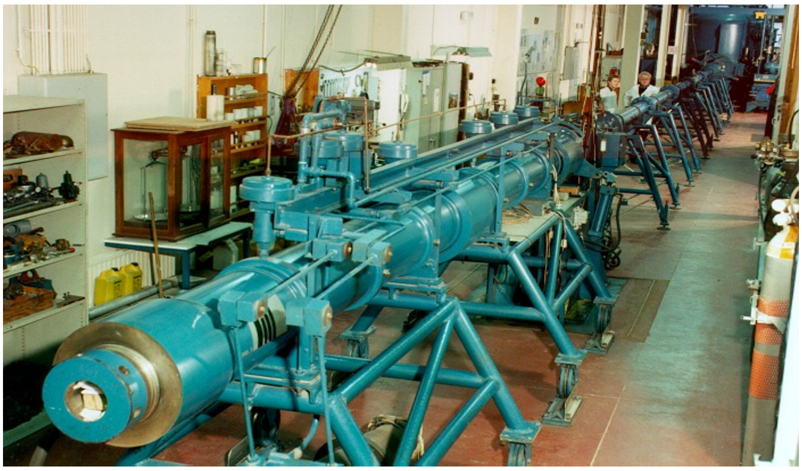

Fig. 2. *VKI Longshot Facility*

2.2. The Plasmatron Facility (Arial, 9 pt, underligned)

The facility used at VKI for the testing is a Plasmatron-type using an Inductively Coupled Plasma (ICP) torch (Fig. 3). A sketch of the basic test configuration can be seen in Figure 4. VKI Plasmatron working principle and operation are presented in [5]

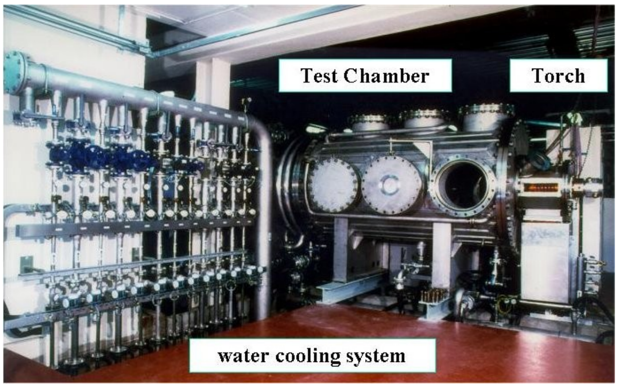

Fig. 3. *The VKI Plasmatron facility.*

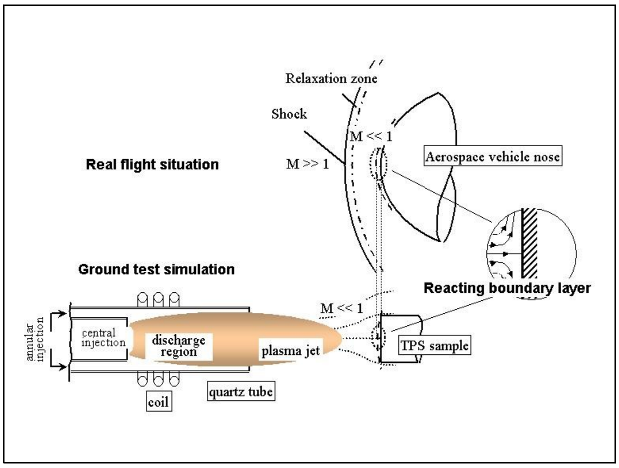

Fig. 4. *Concept of local heat transfer simulation at VKI Plasmatron facility.*

The main control parameters are the mass flow injected in the torch, the pressure in the test chamber and the generator power imposed. In the context of TPS testing and catalycity determination it could be relevant to mention that it is an appropriate facility for those purposes. It allows testing in a subsonic plasma jet, where LTE conditions are more likely to be verified produced by an ICP torch, which provide chemical purity. This last point has been checked by spectroscopic measurements for the most powerful emission line of copper, silicon and iron [12]. It is equipped with two interchangeable ICP torches, one of 80 mm diameter for the test of small samples and one of 160 mm diameter suited to samples as well as to full TPS tiles. Each torch is mounted inside a support enclosure, which is fixed on a side of the test section, a 2.5 m long, 1.4 m diameter vessel equipped with multiple portholes and windows to allow maximal flexibility and unrestrained optical access for plasma diagnostic techniques. Inside the enclosure, the samples and probes are mounted on a fast-injection system.

The jet of plasma is collected at the outlet of the enclosure and cooled in the heat exchanger to a maximum temperature of 50°C to protect the vacuum plant from overheating damage. The vacuum plant consists of three volumetric vacuum pumps, which allow operating pressures between 1 hPa and atmospheric pressure with a maximum flow rate of 3000 m3/h. A Roots pump can be inserted in the circuit to bring the pressure down. Exhaust gases are vented to the atmosphere through a stack.

The Plasmatron is equipped with a 1.2 MW, 400 kHz, high-frequency generator of the new solid-state technology, using thyristors and MOS inverters instead of vacuum tubes. A huge closed circuit cooling system using de-ionised water protects all facility parts from melting due to the plasma heat, which is evacuated through three dry air coolers located on the roof. For air plasma, the facility is connected to the VKI compressed air supply. For test with CO2, rakes of bottle of compressed gas are used. The full facility is computer-controlled from a remote cabin.

Main measurement techniques applied at the Plasmatrin facility are temperature, heat flux and pressure measurements. For the characterization of the free-stream, laser diagnostics and spectroscopic techniques are utilized [7]. Infrared camera and two-color pyrometers are used to detect the surface temperature of the test specimen.

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3. Atmospheric Entry Aerothermodynamics (Arial, 9pt, bold)

The thermochemical non-equilibrium encountered in real flight is hard to duplicate in ground facilities. Only the conditions based on the local characteristics of the flow in the regions closest to the vehicle surface are considered. This is the basis of the Local Heat Transfer Simulation (LHTS) method, a hybrid numerical-experimental methodology. This local simulation methodology was developed at the Institute for Problems in Mechanics of Moscow (IPM). A detailed description can be found in [1, 8, 9] and it has been previously applied at the VKI [10, 11, 12].

The LHTS is based on the pioneering work of Fay & Riddell and Goulard on the similarity solution of the heat flux at the stagnation point of a chemically reacting boundary layer. It requires that the local conditions at the boundary layer edge around a stagnation point in the laboratory conditions and in real flight conditions are equal. For an accurate simulation, wall catalycity and emissivity should be the same in ground tests and in flight. The heat flux will be equal in the two cases if the boundary layer outer edge enthalpy He, chemical compositions, pressure p_e and velocity gradient be are the same in the wind tunnel and in flight:

$$H_e^f = H_e^g \qquad p_e^f = p_e^g \qquad \beta_e^f = \beta_e^g$$

where subscript e refers to the boundary layer edge, superscript f and g refer to the flight and ground conditions respectively. Refer to Figures 4 and 5 for a schematic of the local simulation concept.

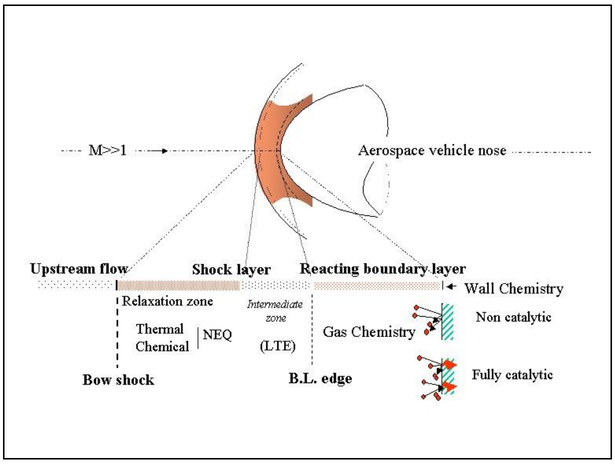

Fig. 5. *Aerothermodynamics of real flight situation*

For complete simulation of flight conditions, these three parameters should be duplicated in ground facilities. The problem is that only the stagnation pressure can be measured directly. To overcome this, two flow parameters are measured: the Pitot pressure and heat flux at the stagnation point. These are then related to the unknown enthalpy and velocity gradient at the boundary layer edge by means of an iterative process hence the hybrid numerical-experimental nature of the methodology [13]. The boundary layer edge characteristics are obtained via this iterative process. Measurements taken with a reference material (fully catalytic) are necessary to establish the properties of the flow in the laboratory conditions. For air, extensive experience has led to the use of copper as a good approximation to a high catalytic surface material.

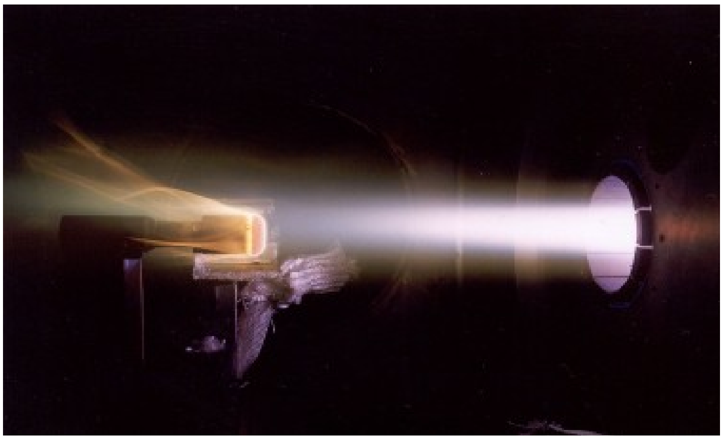

Fig. X. *Test of ablative material in the VKI Plasmatron facility*

4. Utilisation of Infrared Thermography for Atmospheric Entry Applications (Arial, 9pt, bold)

Infrared thermography and pyrometers. Measuring surface temperature. Need for calibration. Thermocouples to measure back wall temperatures.

Picture showing the sample installed.

Show how emissivity is determined using infrared results and pyrometer results

Heat flux trajectory simulation. Infrared observation is important, shows details that can not be seen with bare eye.

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5. Conclusion (Arial, 9pt, bold)

6. Margin

Documents are limited to 10 pages. Please use A4 paper with different odd and even pages and mirror margins. Margins set at 1.7cm (top), 8.7cm (bottom), 2cm (inside), 6.5cm (outside) and 0.5 cm (gutter).

7. Figures and tables

All figures in colour of black and white (i.e. graphs, data plots, illustrations, photographs, …) are to be numbered in the order that they are introduced and referred to as figure 1, figure 2, etc. Authors may choose to insert the figures in the text as they occur (full or part width of the page) or to put them all at the end of the paper after references. In both cases, each figure should have title under it in the style shown below (figure 1).

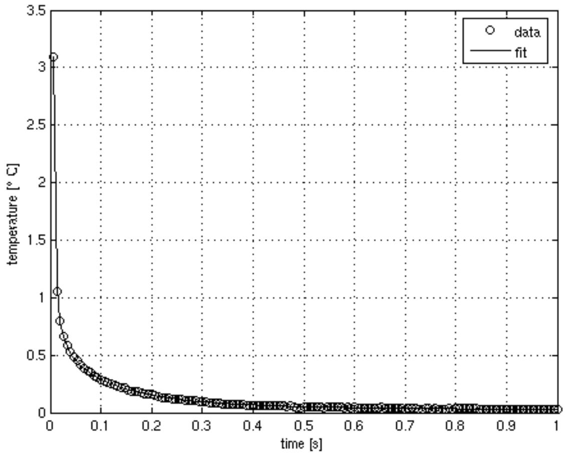

Fig. 1. *Title (Arial, 9 pt, centered, italic)*

Tables may also be in the text (full or part width of the page) or after references (and before the figures if placed at the end of the paper). The title of the table should be put on top of the table. Tables have to be referred to in the text as table 1, table 2, etc.

Table 1. *This is what table caption looks like (Arial, 9 pt, centered, italic)*

Column 1	Column 2
Text 1	Result 1
Text 2	Result 2
Text 3	Result 3

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