EXPERT AEROTHERMODYNAMIC FLIGHT INSTRUMENTATION ENVIRONMENT AND INTEGRATION
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ABSTRACT

The paper reports on the aerothermodynamic (ATD) environment of the EXPERT configuration associated with the planned first flight (5km/sec trajectory). A status report is given on the embarked flight measurement technique developments and qualification with emphasis on the thermal protection system (TPS) integration issues. Special attention is given to the design of the flight measurement sensors themselves, their integration into the TPS as well as to the measurement of the free stream parameters during re-entry using an Air Data System (ADS).

This paper addresses the EXPERT scientific payload that consists of a series of scientific flight measurement techniques such as:
- Flush Air Data System (FADS),
- Nose heating (Pyrex),
- Catalysis measurements,
- Natural and roughness induced transition,
- SWBLI upstream of the open flap and flow reattachment on the flap,
- Shock layer chemistry using emission spectroscopy (RESPECT),
- Base pressure and heat flux measurement,
- Skin friction gauges,
- Temperature and heat flux measurement on Sharp Hot Structures (UHTC)
- Boundary layer thickness, Pitot static probe

INTRODUCTION

EXPERT is an "in flight research" test bed (CLASS 1) i.e. a generic vehicle incorporating a series of critical phenomena requiring improved understanding so as to enhance the tools for design used for demonstrators (CLASS 2) and full-scale qualification flight vehicles (CLASS 3). These tools for design incorporate numerical tools including physical modeling, ground-based facilities including associated measurement techniques as well as the flight sensors and their integration themselves. EXPERT is a generic configuration that will perform a sub-orbital flight and re-enter the Earth atmosphere. The EXPERT vehicle will be equipped with state-of-the-art instrumentation and will provide flight measurements of critical aero-thermodynamic phenomena occurring during a hypersonic flight.

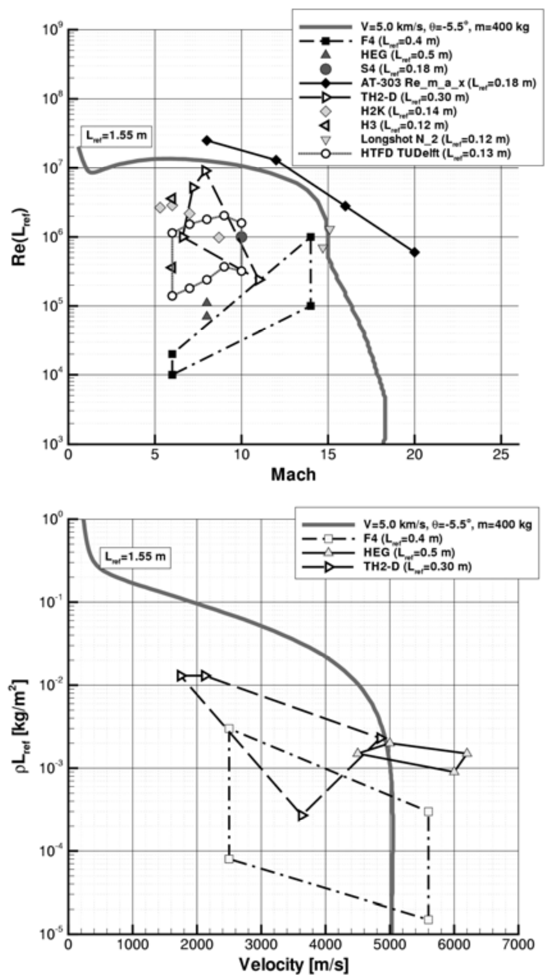

Fig. 1a and b: EXPERT trajectory with high-enthalpy- and some major perfect gas -facilities performance envelops.

The objective of the EXPERT mission is to perform a sub orbital flight for in-flight measurements of critical aerothermodynamic phenomena using state-of-the-art instrumentation.

A test bed is provided for validation of aerothermodynamic models, codes and ground test facilities in a representative flight environment, to improve the understanding of issues related to analysis, testing and extrapolation to flight. The flight data provided by the EXPERT mission will be used to study the wind tunnel-to-flight extrapolation and scaling methodologies at established high enthalpy facility and perfect gas facility crossing points (Fig. 1 a en b).

THE EXPERT VEHICLE

The EXPERT configuration has been optimized to enhance the phenomena of interest and at the same time respecting the constraints of mass and volume imposed by the VOLNA Launcher. The final configuration is shown in Fig. 2. A body of revolution with an ellipse-clothoid-cone two-dimensional longitudinal profile constitutes the basic shape cut by 4 planes incorporating 4 fixed flaps.

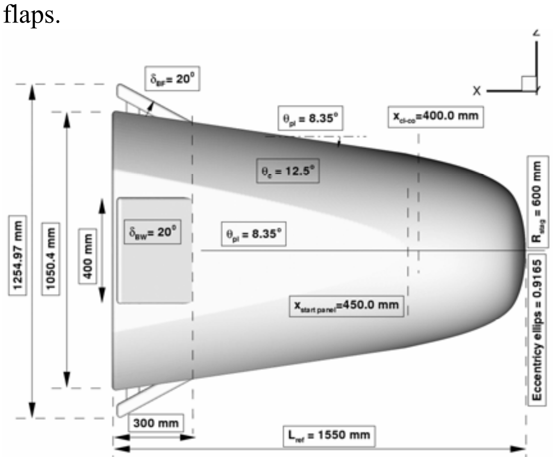

Fig. 2: EXPERT 4.5 side view.

The nose is an ellipse with an eccentricity of 0.9165 with a local nose radius of 0.60 m. The ellipse- cone junction is second order by using a clothoid to avoid pressure jumps. The cone has an angle θ_c=12.5° and features axisymmetric flow enabling two-dimensional sensitivity computations. The connection of the clothoid and the cone is located at x=0.40, exactly where the C-SiC TPS ends and PM-1000 TPS starts. So the C-SiC part covers completely the ellipse and the clothoid and the PM-1000 is just conical. The leading edge of the panels are located at x=0.45 m to avoid double curvature in the C-SiC part. The angle of the panels are θ_{pl}=8.35°. The four flaps have a width of 0.40 m and a projected length of 0.30 m and their deflection angles δ_{bf} are 20°. All flaps will be open to study 3D micro-aerodynamic effects on corners; base flow recirculation and non-convex reradiating wall effects. The reference length of EXPERT is L_{ref}= 1.55 m. with a wetted base area S_{ref}=1.1877 m^2.

THE SCIENTIFIC PAYLOADS

The EXPERT vehicle will carry state-of-the-art instrumentation for in-flight measurement of the critical aerothermodynamic phenomena: transition, catalysis, real gas effects on shock interaction, as well as blackout. Special attention will be paid to the design of measurement sensors, as well as to the gathering of the free-stream parameters during reentry.

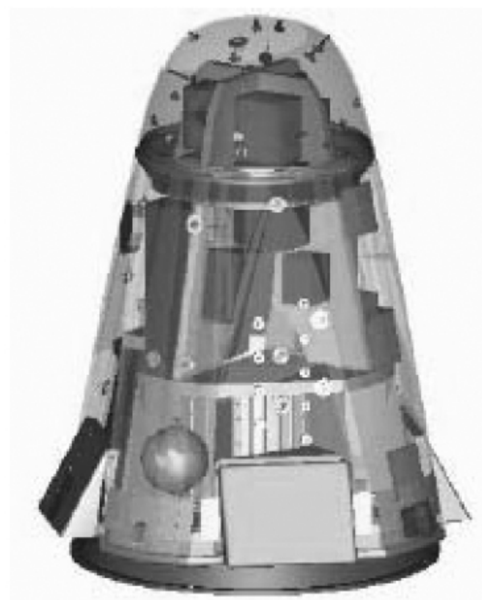

Fig. 3: EXPERT internal layout

Air Data System and Nose Heating

The nose of the vehicle, featuring high geometrical accuracy and a low surface catalicity, integrates both a Flush Air Data System and heat flux sensors PYREX (developed by IRS, Germany).

A pressure-based Air Data System (ADS) mounted on EXPERT's nose will provide free stream dynamic pressure, angle of attack and sideslip angle. Raflex gages will be used as ADS sensors featuring combined pressure and heat flux measurements. These heat flux measurements will be compared with those obtained from the PYREX measurements.

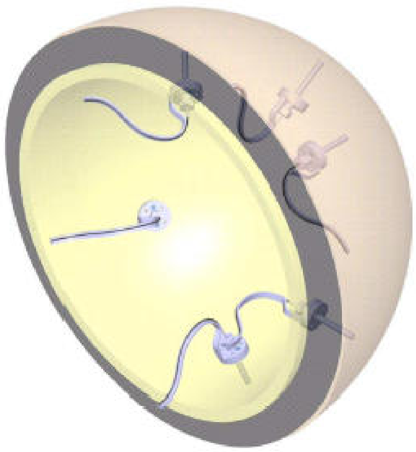

Fig. 4: Heat flux sensors (Pyrex) mounted in nose

The goal of the PYREX measurements is to determine the temperature history and corresponding heat fluxes at six locations on the nose (Fig. 4). Pyrometric sensors have been developed in the last years for temperature and consequently heat flux measurements based on collected thermal radiation intensity.

Among the pyrometric sensors developments within Europe, a particular system aimed at gathering relevant data on TPS rear surfaces, has reached an advanced design status. The experimental set-up, whose initial application was the rear surface of the X-38 Nose, is constituted by:

1) Sensor heads.
2) Fiber optics.
3) Sensor unit.

The optical signal from the sensors is led through an optical path to the sensor lens where it is focused; subsequently the fiber optics lead the optical signal to the conversion unit hosting the photodiodes and finally the electric signal is recorded by the electronic unit of the sensors

Catalysis measurements

The assessment of the catalytic gas-surface interaction is a major concern when designing a thermal protection system. The degree of catalicity of a material affects the heating of the surface (the higher the degree of catalicity, the higher the wall heat flux) and thus the design of the protection needed. Understanding this phenomenon calls for very complex modeling at the molecular level, which can be only partly validated in ground-based plasmatron facilities.

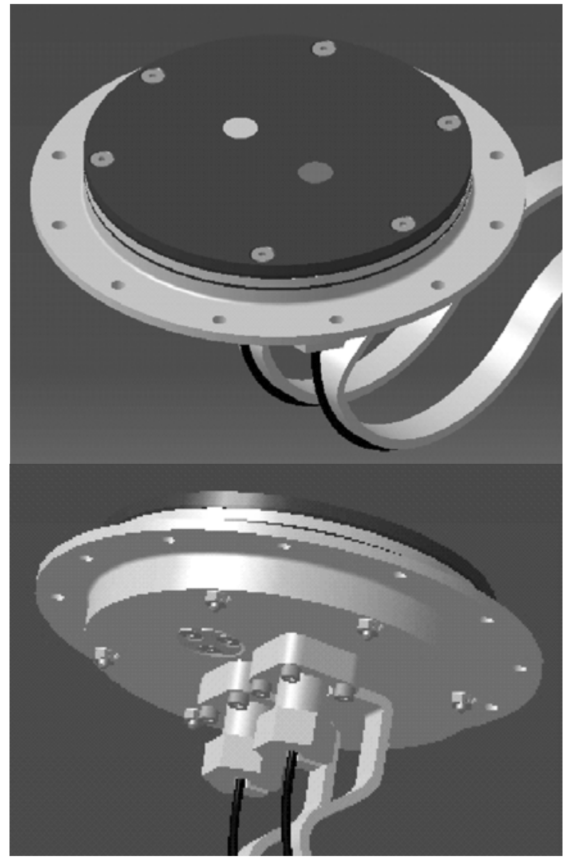

Fig. 5a and b: PHLUX sensor with thermocouples

For EXPERT the catalysis will be studied with the PHLUX sensor, which is depicted in Fig. 5.

Natural and roughness-induced transition

Laminar to turbulent boundary-layer transition is considered one of the most critical aerothermodynamic phenomena due to the associated local temperature peaks and drag increase; unfortunately, present day hypersonic methods are based on old correlations that need to be revisited. In fact, chemistry effects are difficult to simulate in ground facilities and cold hypersonic facilities are affected by external disturbances (wind tunnel related), which constitute dominant sources of perturbations for transition triggering.

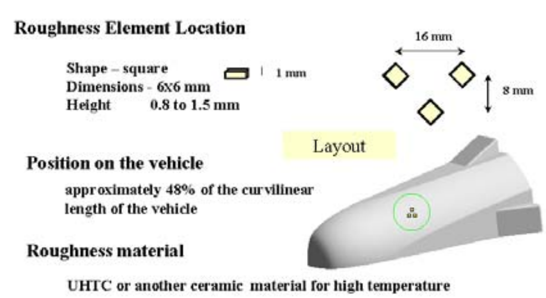

Fig. 6: Roughness elements on EXPERT

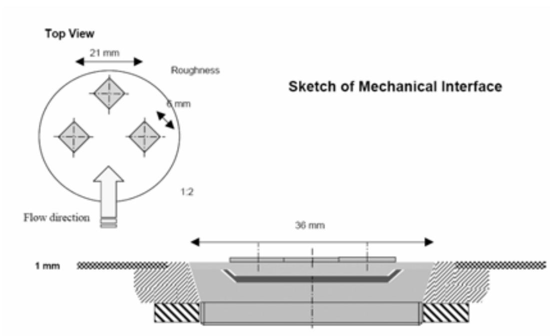

Fig. 7: Roughness elements in detail

Thus, only flight experiments with well-characterized disturbances (triggering transition where required) may provide essential information to be coupled with ground facilities data and numerical simulation results. Roughness-inducing boundary-layer transition elements will be mounted on the leading edges of EXPERT in diametrically opposite locations. Their position, size and number will be chosen such that transition occurs in the lower altitude, higher Reynolds number part of the flight. Heat flux sensors will detect transition.

The other conical edges will be kept smooth in order to have a reference clean condition to be compared against the induced transition behavior. Fig. 6 and Fig. 7 show a typical roughness element layout, whereas Fig. 8 addresses typical roughness induced transition correlations, which need to be validated via new flight data.

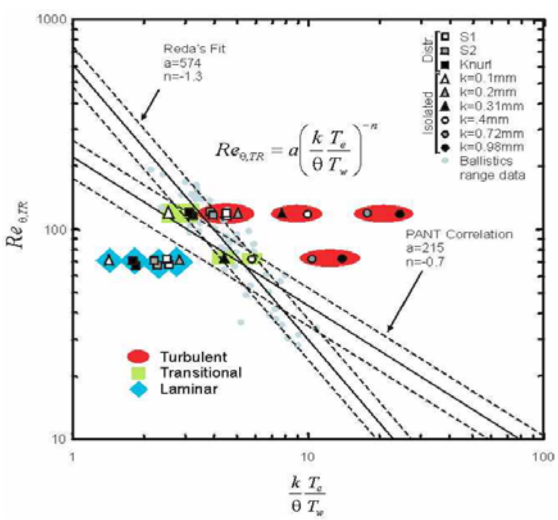

Fig. 8: Experimental activities on Roughness induced transition (courtesy VKI).

At this point, the importance of analyzing smooth surfaces has to be remarked: in fact, the experiment will be successful only if no transition is triggered by surface discontinuities upstream of the roughness elements are located. That is why this Payload addresses both surface discontinuities triggered transition and roughness element induced transition via CFD + stability analysis, wind tunnel test campaigns and flight tests.

<u>SWBLI upstream of the open flap and flow reattachment on the flap.</u>

It is widely known that boundary layer separation effects in front of deflected flap have a significant impact on re-entry vehicle controllability; moreover the heating associated with shear layer reattachment may affect to a great extent the TPS design of the relevant area.

Three dimensional effects, corner and gap heating, flow circulation, constitute critical issues that need to be addressed; the EXPERT vehicle is foreseen to be equipped with an experimental set-up including thermocouples, heat and pressure gages, strain gages in three different locations:

- Ahead of the open flap.
- Onto the open flap.
- In the cavity underneath the open flap.

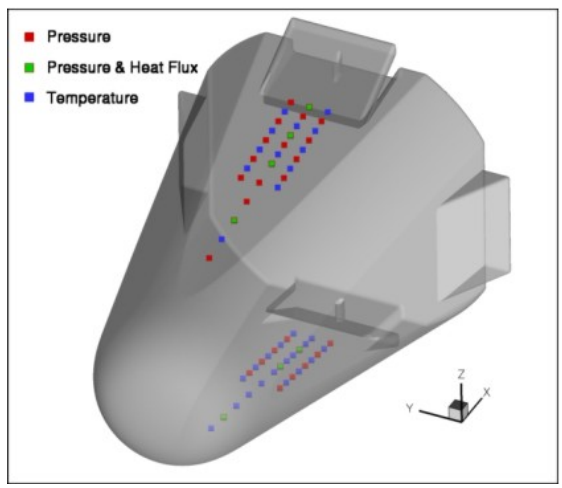

Fig. 9: Sensors located before the Open Flaps

Boundary-layer separation effects in front of a deflected flap (Fig. 9) affect not only the flap for control purposes, but also the heating associated with shear-layer reattachment. Three dimensional effects, corner and gap heating, base-flow circulation and wall cooling are all critical issues that need to be addressed in the design of control flaps. The set-up proposed for EXPERT consists of a space-vehicle ceramic flap with fixed actuator instrumented with simple but reliable devices such as thermocouples, heat and pressure gages and micro-pyrometers.

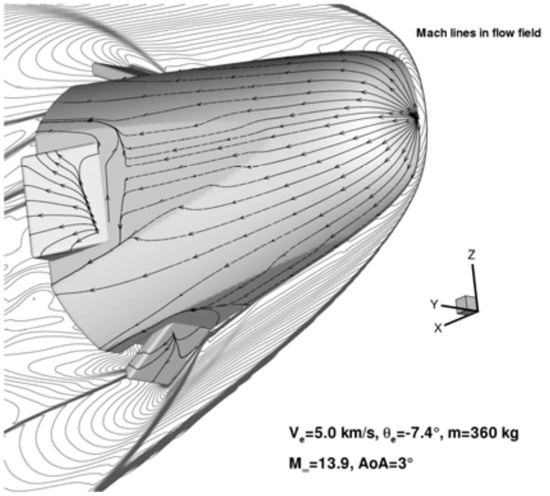

Fig. 10: Streamlines and Mach lines around EXPERT

In order to derive extrapolation-to-flight criteria able to reproduce both the mechanical and thermal loads acting on the control surface, a number of experimental tests will be performed. The EXPERT flight conditions in the flap region will be characterized by means of CFD and ground experimental activities. Also the flat faces upstream of the flap are foreseen to be instrumented.

Rear Face Infrared Thermography

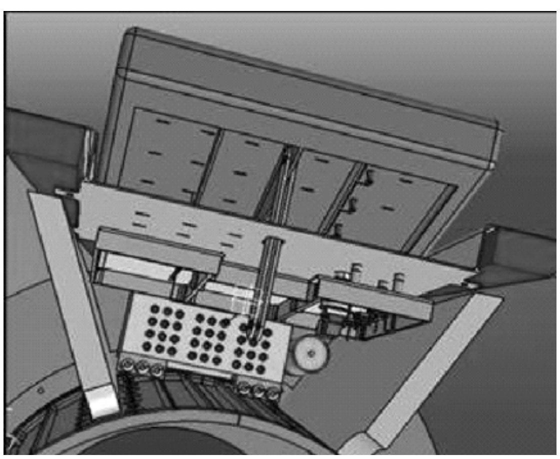

Fig. 11: Base view of the open flap.

The scientific objective of this measurement technique is to use a non-intrusive instrument based on Infrared technology to get a 3D thermal map of the rear face of a control surface evolving in time; this technique, accompanied by a validated non-linear inverse method, allows for the determination of the heat loads subjected to the flap.

Different European companies/research institutes (such as HTS, Switzerland and Onera, France) have been investigating this technique.

The selection of the operational wavelength regime coupled to the choice of the infrared camera (from the commercial market) constitutes a first step into the design of the overall experimental set-up.
One important characteristic that the camera is asked to have is the ability to feature variable exposure times, thus allowing measuring an extended range of temperatures.

At present a technical possibility would be to choose a quantum detector based on an InGaAs photodiode array operating in the NIR regime. With such a choice the achievement of a 2K-temperature resolution has been considered feasible if the integration times of the camera are adapted in the course of the measurement ranging from 700 to 1800 K.

It was found that, in order to maximize the scientific output of the assembly and to minimize the risks, the assembly needs to be equipped with a lens system allowing for sufficient coverage of the surface under investigation as well as to inhibit saturation of the detector and radiative overheating.

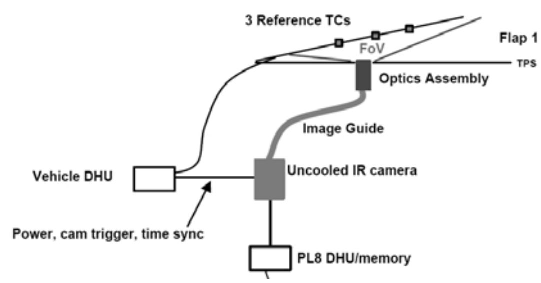

Fig. 12: Rare face infrared thermography schematics.

It is worth to highlight that the attainable accuracy on the temperature measurement is not only dependent on the selected detector but also on the intensity of the emitted radiation, which it self is a function of the temperature of the object and of the viewing angle. A rigorous calibration activity is mandatory so as to ensure reliable experimental data. To this end some "check" thermocouples in the field of view of the camera providing a calibration means have been incorporated into the flap. The overall accuracy would be a function of the thermocouples accuracy and would feature some geometrical dependence provided that the radiative properties are well known.

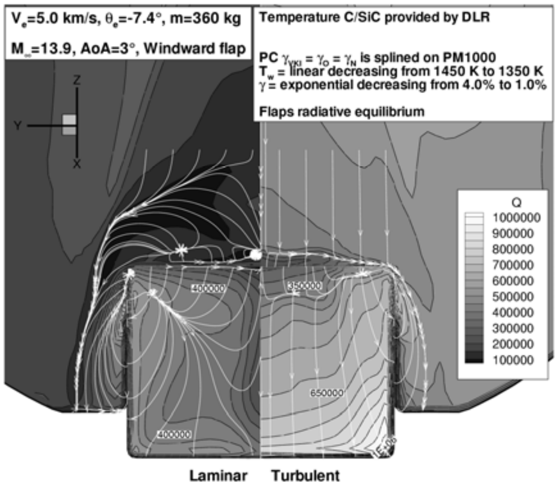

Fig. 13: Laminar and turbulent heat flux and separation bubble

Apart from the selected hardware, this measurement technique relies on the development and validation of a reliable rebuilding procedure based on a true multidisciplinary approach. Such a rebuilding procedure, currently under consolidation, is designed to take into account:

1) Convective heating of the control flap.
2) Conductive & radiative properties of the materials in the control surfaces area.
3) Re-radiative effects.
4) Flow/structure interaction.

Radiative properties of the measurement assembly affecting directly the signal to the detector (e.g. lens emissivity) will be taken into account.

The laminar and turbulent heat flux distribution on and around the leeward and windward flaps are presented in Fig. 13. The heat flux on the corner of the windward flap reaches 1.0 MW/m^2. The separation bubble is visualized with streamlines. The laminar separated bubble is much larger that the one computed assuming turbulent flow. Care should be taken, as it is known that a laminar separation combined with a turbulent reattachment provides a design case in which a transitional reattachment provides a higher heat flux than a fully turbulent case. The laminar flow show a much more complicated separated flow field then the turbulent flow, e.g. notice the secondary separation bubble. All these features hopefully will be detected in flight.

Shock-layer chemistry using emission spectroscopy: RESPECT

This instrument aims at collecting spectroscopic information during re-entry through spectrally resolved emission; the experimental data will then be compared with coupled flow field/radiation codes leading to the validation of thermo-chemical models. The RESPECT subsystem (Fig. 14 shows a two channel device) consisting of a miniaturized spectrometer, optical fibers and a lens system; the foreseen spectral range is 200-800 nm.

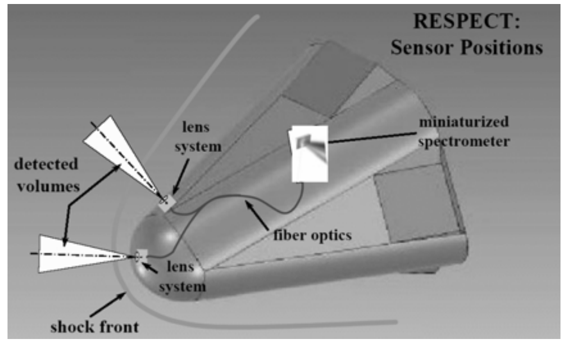

Fig. 14: RESPECT mounted on EXPERT (courtesy IRS)

The challenge of this flight instrument lies in the design of the electronics supporting the spectral measurement and the optical window through the heat shield. Preliminary activities performed at IRS demonstrated the feasibility of such a procedure.

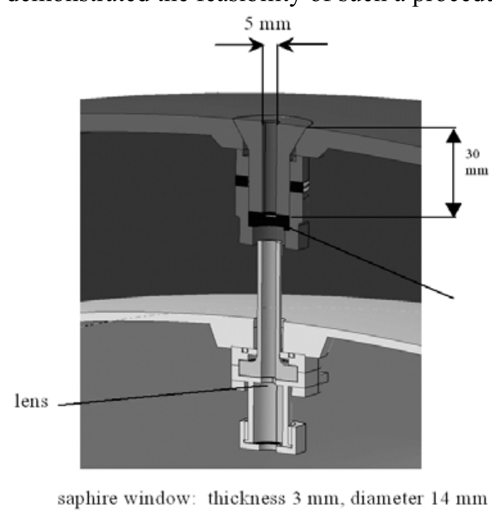

Fig. 15: Close view lens system RESPECT

Base flow measurements

This Payload aims at measuring base pressure. Local base pressure and heat flux measurements will be made to study the complex base recirculation flow field.

Skin Friction Measurements

A slip flow sensor is foreseen to be integrated in the EXPERT vehicle: this combined probe mainly designed for surface flow diagnostics in the slip- and rarefied flow regime may also be used in the laminar continuum flow regime. In the rarefied flow regime heat flux, particle flux to surface and slip speed ratio will be measured as well as surface pressure, heat flux and skin friction during the continuum regime. The slip flow sensor has been designed with two inclined pressure taps, which are integrated in one caloric copper sensor head, ensuring same temperature for the cavities of both probes.

Sharp Hot Structures

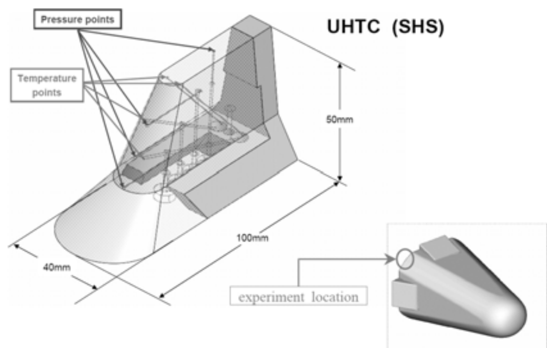

Fig. 16 Dimensions of the sharp hot structure

The objective of this payload is to fly an instrumented patch of UHTC material. The payload could be a bulk ceramic component or coated component (UHTC covered with anti-oxidation UHTC). The flight test aims at monitoring the thermal conditions of the structure. Two symmetric locations are foreseen for this Payload. The UHTC could be integrated on dummy winglets, similar to the Pitot static rakes or on a small-deflected surface at vehicle trailing edge.

Pitot static probe

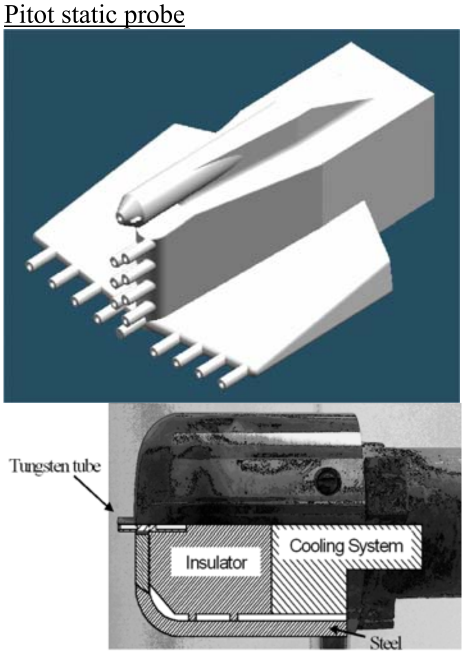

Fig. 17: Pitot static rakes and probe holder for Plasmatron testing.

EXPERT is currently foreseen to be equipped at trailing edge location with a Pitot static pressure rake in order to collect in-flight data on the boundary layer characteristics; the critical issues to be tackled are related to the conceptual design of the probe, the selection of the material, the definition of the attachment points and the location and type of transducers. The resulting characterization of the boundary layer at the trailing edge of the vehicle will further contribute to the understanding of the boundary layer laminar-to-turbulent transition phenomenon. Testing of probe elements will be performed in the VKI plasmatron; as shown in Fig 17.

CONCLUSIONS

EXPERT is an in-flight research programme, with the objective to improve our understanding of critical aerothermodynamics phenomena such as transition, real gas effects and shock wave boundary layer interactions associated with flap efficiency and heating. At present one ballistic flight (5 km/sec) is planned. If successful, it is believed that other flights are possible such as for higher speed (6 km/sec); future flights for the study of transitional flow phenomena and skipping trajectories, jet interaction, test beds for MHD/nose heat flux reduction schemes and flights for the study of advanced materials associated with high-speed re-entry.

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