SHEFEX II

AERODYNAMIC RE-ENTRY CONTROLLED SHARP EDGE FLIGHT EXPERIMENT

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ABSTRACT

In this paper the basic goals and architecture of the SHEFEX II mission is presented. Also launched by a two staged sounding rocket system SHEFEX II is a consequent next step in technology test and demonstration. Considering all experience and collected flight data obtained during the SHEFEX I Mission, the test vehicle has been re-designed and extended by an active control system, which allows active aerodynamic control during the re-entry phase. Thus, ceramic based aerodynamic control elements like rudders, ailerons and flaps, mechanical actuators and an automatic electronic control unit has been implemented. Special focus is taken on improved GNC Elements. In addition, some other experiments including an actively cooled thermal protection element, advanced sensor equipment, high temperature antenna inserts etc. are part of the SHEFEX II experimental payload. A final 2 stage configuration has been selected considering Brazilian solid rocket boosters derived from the S 40 family. During the experiment phase a maximum entry velocity of Mach around 10 is expected for 50 seconds. Considering these flight conditions, the heat loads are not representative for a RLV re-entry, however, it allows to investigate the principal behaviour of such a facetted ceramic TPS, a sharp leading edge at the canards and fins and all associated gas flow effects and their structural response.

1. INTRODUCTION

Modern Ceramic Matrix Composite (CMC) materials for thermal protection systems (TPS), like C/C-SiC (carbon fibre in carbon-silicon carbide matrix) allow for new shapes in re-entry vehicle design. These materials do not loose their mechanical strength and rigidity at elevated temperatures of 1600° or above. This qualifies them for the high loads at the edges and tips of sharp edge designs. From a technological point of view, the SHEFEX flight hardware concept is a result of combining two main ideas coming from aerodynamics and thermal protection system (**Fig. 1**). On the one hand, a vehicle design based on sharp edges offers superior aerodynamic performance in the supersonic and hypersonic speed regime compared with blunt bodies. On the other hand, a vehicle design based on flat panels made of composite ceramic offers low production costs and reduced thermal protection weight compared to corresponding classical shape designs. In particular, to take advantage of the major aerodynamic efficiency, sharp edged vehicles should fly different re-entry paths than blunt bodies, resulting in different requirements for the attitude control system. Indeed, due to their poor aerodynamics, classical blunt bodies follow a semi-ballistic re-entry flight path characterised by higher re-entry angles, resulting on strong decelerations and higher landing speed. On the contrary, vehicles with high temperature resistant materials, additionally offering lifting sustained re-entry, may present a re-entry flight path characterised by lower angles of attack, resulting in long re-entry time accompanied with low decelerations and accurately low landing speed if an appropriate re-entry control law is designed.

Figure 1: SHFEX-I Flight hardware

Thus a flight experiment devoted to test new re-entry guidance and control algorithm is of importance for future vehicle developments. Additionally, from a fluid mechanics point of view a flight experiment devoted to an actively aerodynamic controlled vehicle provides a platform to accumulate know-how on flap efficiency and flap heating due to shock-wave boundary-layer interaction and shock-shock interaction. Accounting that the SHEFEX Program is a kind of “SKY BASED FACILITY” as economical way to acquire knowledge in the physics of hypersonic flight by means of sounding rockets, reducing risks and development costs by gradually testing new concepts and qualifying new technologies and encouraged by the knowledge acquired with SHEFEX I [1], DLR decides to implement a step by step approach towards an active controlled re-entry vehicle. Therefore, the goal of the SHEFEX II experiment is to demonstrate hypersonic re-entry with an aerodynamic controlled vehicle.

2. MISSION DEFINITION

SHEFEX II will lift off using a first stage solid rocket motor of 4tons propellant mass. About 60 seconds after ignition the system will reach 54 km altitude. Within the first ballistic phase after separation of the first stage, the second stage, also a solid rocket motor will be re-pointed to a more flat attitude before its ignition. The 800 kg propellant mass of the second stage will boost the payload to an apogee of approximately 270 km. After a de-spin manoeuvre, the separation from the rocket motor will be initiated and the attitude control will orient the payload for re-entry at approximately 35°. Re-entry and so the initiation of the experiment phase will be at 100 km when the atmosphere effects became reasonable (**Fig. 2**). Indeed, for the SHEFEX-2 experiment the conventional parabolic trajectory for unguided sounding rockets has been modified with respect to a lower apogee but longer re-entry and with respect to the atmospheric flight sequence. This modifications require an exoatmospheric re-pointing manoeuvre by the ACS cod gas thruster system under spinning conditions after the first stage burned-out and has separated. The remaining vehicle will be pointed and the roll axis aligned with a low elevation angle (e.g. 0 deg to 10 deg) before the ignition of the second stage. After it burn-out the spin will be removed by a yo-yo de-spin system. The ACS will set the re-entry attitude of the experimental vehicle.

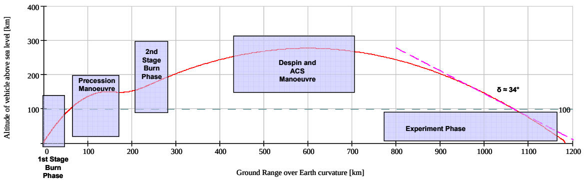

Figure 2: SHFEX-II Mission events

The experimental phase on the down-leg from 100km down to 20km comprises almost 50 seconds of experimental time providing velocities in the region of 3.1km/sec and 2.7km/sec respectively which conforms to a Mach regime between 11.0 and 9.5 (**Fig. 3**). This high Mach number will cause extreme heat fluxes at the payload tip and sharp leading edges at the canards and stabilizers. So temperatures above 1800°C may occur at these exposed locations. The dynamic pressure will increase up to 4bar at the end of entry trajectory at 20 km.

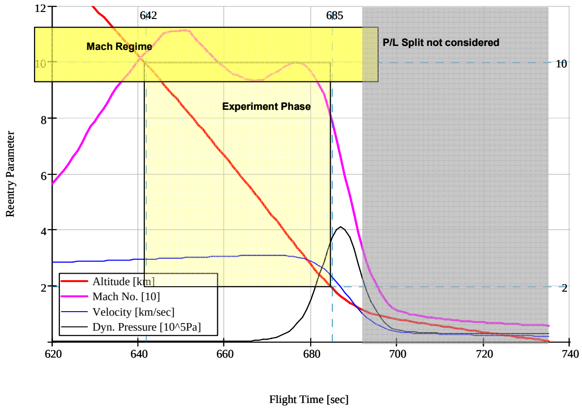

Figure 3: SHFEX-II Experiment events

As the second stage of the vehicle will be re-oriented with an active control system before ignition, a fully redundant flight termination system is necessary. This system permits the destruction of the second stage motor in the case of an abnormal flight. During the burn phase of the first stage, the system is treated as a normal unguided sounding rocket. The ignition of the second stage is effectively controlled by a number of conditions like: (i) precession maneuver achieved; (ii) ignition time window open; (iii) TC ignition inhibit not active. The onboard inertial guidance platform signals to the ignition system that the pointing of the second stage is achieved and corrected. Via telemetry, the payload engineer and safety officer can verify this information on ground and correlate with additional information such as payload GPS and radar. Should there be a failure of the attitude control system, an ignition inhibit signal can be sent to the second stage ignition system by the payload telecommand system. Should all conditions be fulfilled, the second stage will ignite at a preset time.

Finally, at approximately 15 km altitude on the descent, the payload will be separated by a manacle ring release and high velocity separation system into two sections which are inherently unstable. This will produce a tumbling motion with extremely high deceleration which results in velocities of less that 250 metres per second by the time the payload sections have descended to 4.5 km, where the heat shields are deployed and normal recovery parachute system operation is possible. Experience with the SHEFEX 1 payload has shown that aerodynamic braking is adequate provided the problem of ram air spikes is accounted for and the centres of gravity of the payload sections are correctly placed. High velocity recovery systems are installed at the aft ends of both payload sections. **Table 1** summarises the basic characteristics of SHEFEX-II with respect to SHEFEX-I mission.

Table 1: SHEFEX-I & II mission differences.

	SHEFEX I	SHEFEX II
Payload	250 kg	380 kg
Apogee	210 km	260 km
Downrange	230 km	1150 km
Max. Speed	Ma 6.5	Ma 10-12
Stages	2	2
Experiment time	20 sec	45 sec
Re-Entry angle	84 °	35°

Similar to the previous mission, the SHEFEX-II mission will take place in Andoya. As **Fig. 3** indicates at Andenes Rocket Range the 3m and the 6m monopuls tracking stations will we used to receive the payload PCM data and the video images. Both receiving chains are configured to provide polarization and frequency diversity reception. This concept will ensure good data quality during that part of the trajectory visible from the range. The ARR mobile telemetry station will be located and operated in the same way as during the SHEFEX I mission. During this flight, the station demonstrated its value at this local elevated position. With this station it will be possible to receive direct payload data down to a flight altitude of less than 100km on the down-leg part of the trajectory. The MORABA mobile telemetry station will be set up on the elevated plateau at Longyearbyen. This position enables the reception of the payload signals as soon as the vehicle is visible over the local horizon which corresponds to a flight altitude of approximately 70km on the ascent. From this point onwards the payload data is received and the demodulated PCM signal is sent back to Andenes using the submarine high data rate optical fibre link. As the ground range to the nominal landing point of the payload is in the order of 300km, the RF link can be maintained down to an altitude of ~ 4km. As the initiation of the recovery sequence will start in about 15km altitude with splitting the payload, most of the recovery events can be monitored. A second payload telecommand station will be used at this location to transmit commands which are received through the optical fibre connection from the payload engineer at Andøya as soon as a reliable downlink to the payload is achieved.

The payload telecommand system is identical to the system used for the SHEFEX 1 project. The onboard system comprises two L-Band telecommand receivers coupled to two high temperature antennas spaced at 180°. During the ascent of the vehicle, real time video data from a camera looking aft will be transmitted to the ground station using a S-Band 10W video transmitter. The RF output of this transmitter is connected to the same combining network and antennae array which is used for transmitting the payload TX1 PCM data but in this case a left hand circular polarized field (LHCP) is radiated to further decouple the transmitters. After deployment of the second stage and payload fairings, a second camera looking forward from the payload flare will use this link. At separation of the two payload sections and shortly before activation of the recovery system, the video input to the transmitter is switched to a third camera in order to monitor the recovery sequence. Further, the payload is equipped with a 400W radar transponder and an appropriate antenna system which receives and transmits with a circular polarization. In addition, the qualified DLR ORION GPS receiver will be used to obtain velocity and position data. The onboard generated IIP information is used as a backup source to the ground safety system using radar data.

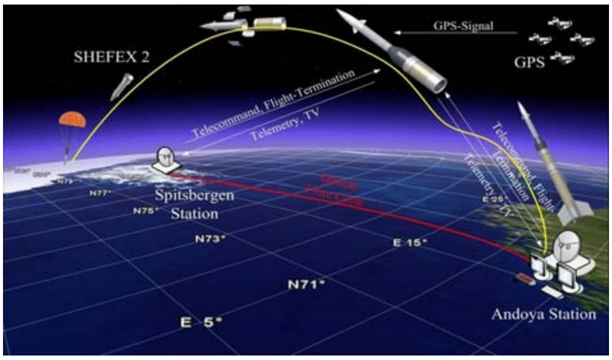

Figure 3: SHFEX-II Mission control

3. LAUNCHER LAYOUT

As a result of a trade off of different launcher configurations and examination of each possible performance and related trajectory, a final 2 stage configuration was chosen considering the Brazilian solid rocket boosters derived from the S 40 family. The vehicle was originally designed as a vacuum test bed for the S-44 apogee motor used in the Brazilian VLS satellite launcher programme. The S-40 motor is part of the VLS vehicle operating as the third stage. The S-44 motor and also the inter-stage adapters are lightweight structures built of Kevlar composites. The VS-40 was first launched successfully in April 1993 achieving an apogee of 950 km and a ground range of 2680 km with a payload mass of 197 kg and 81.8 deg of launch elevation. Up to now, two flights are recorded, both successfully.

Including the payload the overall length of the SHEFEX-II system is 12, 6 m (**Fig. 4**). The overall mass of the system is 6.7 tons. The implementation of a new vehicle with an unusual payload form, guidance system and trajectory performance criteria as well as a recovery operation requiring extreme aerodynamic braking at a low altitude has imposed a wealth of technical problems in the mechanical design. The main problem areas are the aerodynamic stability of the complete vehicle during ascent in spite of payload fins and inactive canards, active separation of the two motors after an extended coast phase, incorporation of two cold gas systems with thrusters at optimum locations and splitting the payload at hypersonic velocities for pre-recovery aerodynamic braking. In addition, a payload length of 5.5 metres and a maximum mass of 350 kg is the target. A solution for the payload fin and canard problem would be to place a fairing over the complete payload; however, the increased mass would have reduced the performance of the first stage and particularly the second stage unless it could be ejected under spin before ignition. The qualification of such a system is considered to exceed the SHEFEX-II resources. A compromise is chosen which comprises a small fairing over the payload fins which will be ejected after the second stage burnout and de-spin. The fairing will be of composite material and consist of two or four segments approximately 1.4 metres in length which is released by pyrotechnic actuators on the payload and the attachment module. The canards will be locked by retractable pins until apogee but as they are exposed, still contributes to the need for larger but lightweight fins on the first stage. These fins with a span of greater than 1 metre and an extended root chord on the motor case provide the required lift off stability.

Figure 4: SHFEX-II Launcher layout showing 1st and 2nd stage and payload experiment

In opposition to SHEFEX I the shape of the test article is chosen to create a symmetric re-entry body stabilized by tail fins and 4 movable small canards near the front area of the cylindrical pay load segments. Within the cylindrical segments all necessary subsystems like navigation platform, power cells, RCS- unit, data acquisition, parachute and recovery system, telemetry, etc. are integrated. The front tip area of the SHEFEX II re-entry vehicle is designed using the facetted shape design as used within the first mission. However, for the flight experiment a compromise between a consequent facetted shape using only a low number of plane areas, a certain inner volume for sensor integration and boundary shape of the rocket fairing has to be found. In Figure 4 the preliminary outer shape is depicted (top left).

The tip is divided within 5 sections. The front section includes a leading tip insert and an integral facetted ceramic nose cone. The primary substructure of the payload tip is similar to the SHEFEX I concept and consists of a aluminium frame created by stiff booms and spares. The free space is closed by flat aluminium panels, which create an inner mould line (IML). The panels are also used for mounting the TPS facets and experiments. Inside the frame, some measurement equipment is integrated. These items are boxes for thermocouple connection and compensation, pressure transducers, a pyrometer system, data processing boxes and subsystems for passenger experiments. As **Fig. 5** displays, the tip geometry is symmetrically divided into 8 identical facets in circular direction and consists of 5 segments along the tip to the actuator module interface. Thus, the payload tip houses 40 single flat areas. 32 of them are available for different experiment positions.

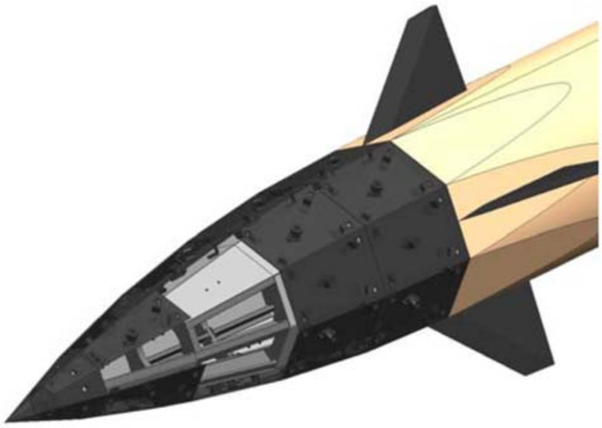

Figure 5: SHFEX-II Flight hardware drawing

4. SHEFEX-II MAJOR EXPERIMENTS

4.1. Aerodynamic/Flight Mechanic Experiment

A disadvantage of a ballistic re-entry is the limited manoeuvrability, so that it becomes difficult to cope with flight-path constrains like the heat flux or total load. These difficulties can only be overcome by actively controlling the aerodynamic forces acting during re-entry. For SHEFEX-II the first cylindrical part behind the facetted payload tip includes an aerodynamic flight control unit. The active part is an actuator system to move the 4 canards. Interaction with the RCS system at altitudes above 80 km and continuously changing aerodynamic sensitivity till payload split at 20 km require challenging advanced control algorithms and high speed actuators. Indeed, at an altitude of 80km and in a time frame of 18s the flight control unit shall damp to zero any roll and yaw anomaly. Then the vehicle will go for a pre-defined manoeuvre on angle of attack variation of 8s duration followed by a pre-defined roll manoeuvre of 6s duration. Finally the flight control unit shall recover the neutral position of the vehicle in a time frame of 3s. (**Fig. 6**).

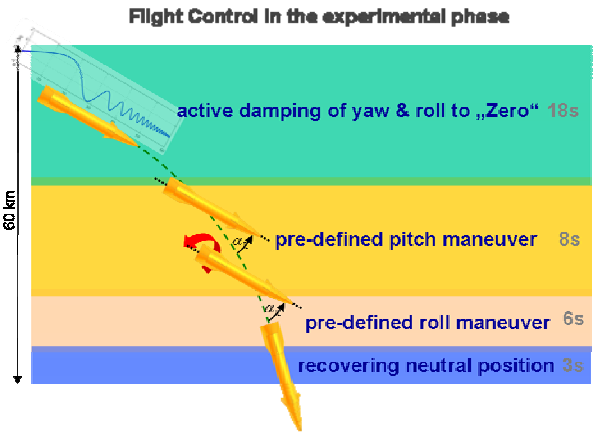

Figure 6: SHFEX-II Aerodynamic/flight mechanic experiment layout

Taking advantage of the significant technical progress in computer technology and CFD, to realize the above experiment here is proposed a direct coupling between fluid mechanics and fight mechanics which enables an immediate analysis of the projected manoeuvre. For hypersonic vehicles this is of special interest, because their layout currently requires complex aerodynamic datasets which depend on Mach number, angles of attack and yaw as well as on control surface deflections. Additionally, usually the complete trajectory from hypersonic cruise flight / re-entry until subsonic landing has to be covered. Currently, the direct coupling of CFD and flight mechanics is still too much time-consuming to consider the free motion of a vehicle along a complete trajectory. Therefore, in a first attempt it is used the flight of SHEFEX II to assess the tool resulted from the modular coupling procedure between the DLR surface inclination method SOSE and the trajectory optimization code REENT of the University of Stuttgart [2]. The modular layout of such coupling procedure is shown in **Fig. 7.** It allows the consideration of complete arbitrarily staged missions without and with propulsion, where the propulsion systems may be considered applying a bookkeeping procedure and within 6DOF simulations. While this coupling tool is well suited for the definition of staged sounding rocket experiments, in future applications more sophisticated fluid mechanic methods like the DLR Euler- and Navier-Stokes code TAU, may be easily introduced. Such extended multi-disciplinary approach, involving computational fluid dynamics and flight mechanics allows full dynamic analysis of controlled free flying vehicles.

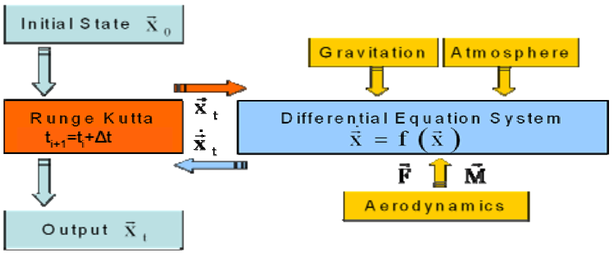

Figure 7: Fluid-Mechanics / Flight Mechanics coupling strategy.

In the frame of the DLR Project IMPULSE an independent 6-DOF motion module has been developed and coupled with the CFD-TAU code which enables time accurate coupled simulations of aerodynamic and flight mechanic. It is a stand-alone module with following properties: rigid body motion; resting flat earth (rotation and curvature of Earth is neglected); no restriction on principal axis of inertia. The control of the simulation process via a python script enables the possibility of a user intervention in each time step. So it is feasible to realize special boundary conditions, like control surface deflections. Furthermore it integrates the individual disciplines into a unified computational framework. The 6-DOF module decomposes the rigid body motion into a translation of the centre of mass and a rotation about the axis located at the centre of mass. The position of the centre of mass is updated using Newton's law of motion in the inertial frame. The rotational position of the body is specified using the Euler angles which are updated by integration of the angular velocities.

As an essential prerequisite, simulation of manoeuvres requires a consideration of vehicles control surfaces. This control surface integration provides a challenge for numerical investigations due to the treatment of the mesh, which must move with the control surface. In order to avoid a new mesh generation for each surface deflection, the technique of overlaid grids, Chimera-Technique, is utilized to integrate the control surfaces. Overset-grid methods are based on subdividing the physical domain into regions that can accommodate easily generated grids. The resulting sets of overlapping grids have to communicate with one another in order to exchange flow information. The original Chimera-Technique, accomplishes this exchange using a linear-interpolation of the primitive variables. Unfortunately this method has the disadvantage that it doesn't maintain conservation across mesh boundaries and needs furthermore an overlapping region of at least two cells. Consequently, degenerations in both accuracy and convergence may result, especially in regions of high gradients. Investigations using the original Chimera-Technique for high supersonic and hypersonic cases show an artificial shock reflection in the interface of the grid boundaries. Hence a novel Chimera-Method is implemented for the analysis of SHEFEX-II [3] where no overlapping region are needed and only a common surface between the two independent grids are used while points on the common surface can possess a displacement.

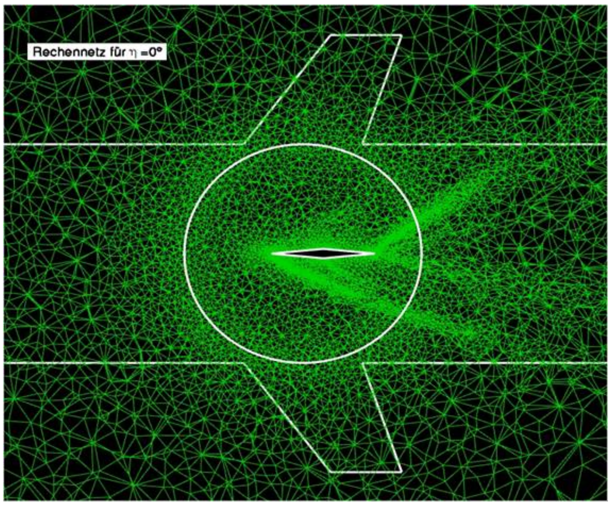

Figure 8: New chimera strategy applied to SHEFEX-II

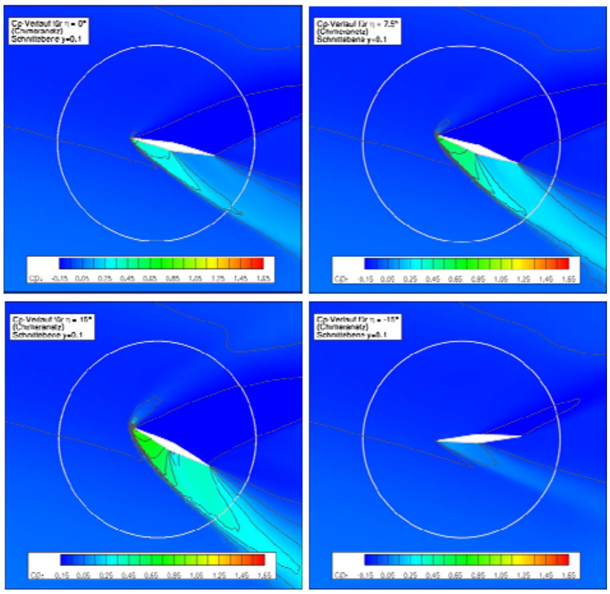

Figure 9: Pitch maneuver due to canard motion.

Efforts directed to apply the combined Navier-Stokes solver with the integrated flight mechanic equations and the new chimera strategy for the prediction of dynamic derivatives are under way. **Figure 8** presents first results for an instantaneous pitch-down manoeuvre due to a canard embedded in an extreme fine grid which moves together with the vehicle while the applied flow field is resolved in the stationary background grid. **Figure 9** shows pressure fields for a supersonic motion, Mach 2.5, nominal angle of attack 12° and canard deflection angle varying from +/-15°.

4.2. Flush Air Data System (FADS)

Within the nose cone tip some special arrangement of 8 pressure sensors will be implemented to investigate possibility of a flush air data system, which may be useful for vehicle control (pitch and yaw) against gas flow direction during hypersonic flight. However, this is a passive experiment with no interaction of SHEFEX II active control. But pressure data assessment shall allow a comparison of vehicle orientation data got by GNC platform and advanced algorithm for pressure data processing. From a structural point of view, the integration of pressure holes and tubing within the hottest area of the vehicle is a challenging issue.

4.3. Actively Cooled TPS (AKTIV)

Based on the very good experience got by DLR during development of an effusion cooled ceramic rocket engine burning chamber, it seems to be possible to transfer this technology for the design of extremely loaded sharp leading edges or flat TPS elements exposed to heat fluxes beyond materials temperature limits. First screening tests of different porous ceramic materials and cooling gases showed a promising potential for this technique. Significant cooling effects at rather low gas consumption could be demonstrated within a plasma channel test sequence at hypersonic gas flow conditions [4]. However, a large effort has to be invested to investigate and understand the responsible parameters for an optimal cooling effect considering the thermal conductivity and interactions between the surrounding gas flow and boundary layer. Active cooling systems are of special interest for use in severe thermal environments where the passive systems are inadequate. The transpiration cooling experiment uses a porous ceramic material at the outer surface through which a coolant flows into the boundary layer. Thus, transpiration cooling is effected by two physical phenomena, as there are the porous structure being convection cooled by the coolant and the coolant layer on the outer, hot surface, lowering the heat transfer from the high-enthalpy environment to the vehicle surface.

For SHEFEX-II it is foreseen in the centre of a pair of the flat thermal protection system panels, a porous probe will be inserted as is shown in **Fig. 10**. This porous probe is to be run through by the coolant and is pressed into the surrounding C/C-SiC TPS material by a compression ring. The pressure reservoir is flanged to the C/C-SiC ceramic by riveted ceramic fasteners. The reservoir itself is made of stainless steel. To this point, a numeric FE-analysis of the experiment set-up was performed. Investigations of a similar set-up were successfully completed in a plasma wind tunnel and provide a basis for the present experiment. In addition, the impact to the whole gas flow characteristic at the payload tip caused by the boundary layer interaction with the cooling gas will be simulated by CFD and wind tunnel investigations.

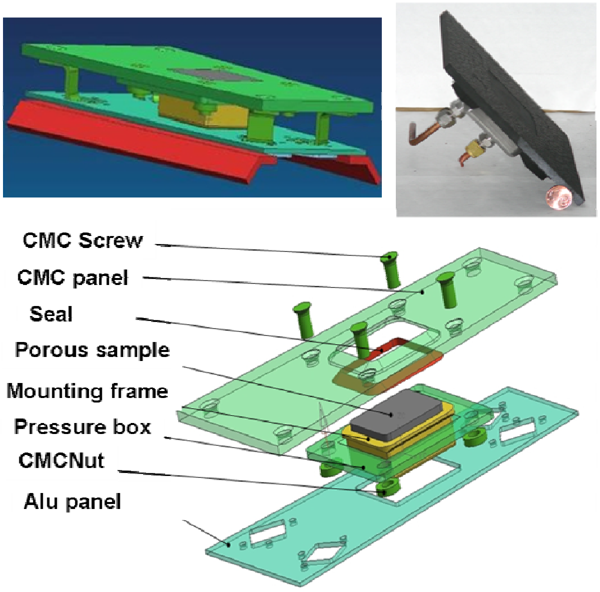

Figure 10: AKTIV Experiment layout. Top left: design layout. Top right: flight hardware. Bottom: Integration layout.

4.4. Ceramic Control Surfaces (CANARD)

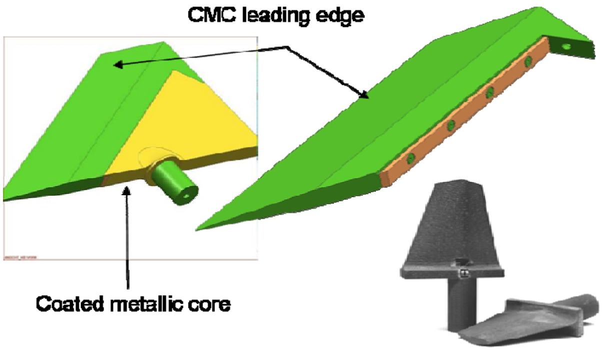

Figure 11: CANARD Experiment layout (left). Flight hardware (right).

The canards themselves are highly thermo-mechanically loaded structures. Due to limited shaft diameter and very high bending loads, a CMC/metallic hybrid structure was chosen for structural design. The leading edge structure is made from C/C-SiC fibre ceramic to withstand the expected high temperatures of 1800°C at the leading edge (**Fig. 11**). The canard main structure is made from a Titanium alloy to carry bending loads and to transfer torsion from the actuators. Special attention has to be paid for the attachment design between Titanium and CMC to balance thermal expansion mismatch.

5. FINAL COMMENTS

At present, the SHEFEX II launcher configuration, the experiment lay out and mission profile is finally defined. The mission profile will offer enough experiment time and sufficient re-entry speed to take the next step in flight testing. All key experiments are established and finally accepted. The detailed structural design and preparation of aerodynamic basic data base and determination of aerodynamic parameter for active control is completed and manufacturing of launcher and experiment hardware will be initiated in October 2008. Start of integration is planned in summer 2009 to meet the launch window in spring 2010.

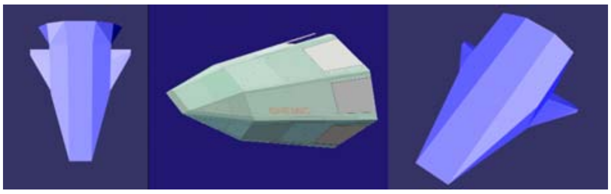

Figure 12: SHEFEX III Concept studies.

SHEFEX-II is one more step forward within DLR’s roadmap for the development of hypersonic and re-entry technology. A first application is planned within the Returnable Experiment REX [5] based on the follow on SHEFEX III experiment (**Fig. 12**). Such a system shall provide for the first time a sharp edge capsule as free flying platform with a high micro g quality for a few days. Since sharp configurations exhibit a bow shock attached to the nose, the vehicle experiences almost no high temperature effect regarding its aerodynamic performance, i.e. almost no real gas effect, resulting in a re-entry trajectory Mach number being independent of temperature and hence allowing mission re-planning according to contingencies. Furthermore, in contrast to blunt bodies, the size of the sharp edged vehicle can vary, i.e. it can be scaled upwards and downwards according to mission and launcher requirements, without change in aerodynamic performance since the bow shock does not change in position. Thus, the return capability, active aerodynamic control during re-entry and the special container technique derived from sounding rocket experiment set up shall provide a cost effective and easy access for experimenters.

6. ACKNOWLEDGMENT

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