ATLLAS: Aero-Thermal Loaded Material Investigations for High-Speed Vehicles

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ATLLAS: Aero-Thermal Loaded Material Investigations for High-Speed Vehicles

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In fall 2006, the EC kicked-off a 3 years long project called ATLLAS: Aerodynamic and Thermal Load Interactions with Lightweight Advanced Materials for High Speed Flight to initiate research on high-temperature resistant materials for sustained hypersonic flight. This includes both materials for the external geometry as well as for the internal combustor geometries. The project, lead by ESA-ESTEC, consists of a consortium of 13 partners from industry, research institutions and universities.

The objective is to identify and assess lightweight advanced materials which can withstand ultra high temperatures and heat fluxes enabling high-speed flight above Mach 3. At these high speeds, classical materials used for airframes and propulsion units are not longer feasible and need to be replaced by high-temperature, lightweight materials, with active cooling of some parts.

I. Introduction

For high-speed aircraft, material and cooling issues for both airframe and engine are one of the key elements which forces the designer to limit the flight Mach number. The expected benefits of economical, high-performance and high-speed civil-aircraft designs that are being considered for the future will be realized only through the development of light-weight, high-temperature composite materials for structure and engine applications enabling reduction of weight, fuel consumption, and direct operating costs.

When aircraft fly this fast for long periods of time, friction from the air passing over the aircraft heats up the outer surfaces of the fuselage and wings. For example, an aircraft flying at Mach 3 will experience a temperature increase of ~330ºC from this kinetic heating. The maximum temperature of the outer surface will be 350ºC. For Mach 6 the outer surface would be ~1200ºC. The extremely severe combination of component stress levels and high temperature operating conditions, as well as the requirement for an extended 25,000-cycle service-life, introduce the challenge of utilizing advanced materials without incurring excessive weight and cost penalties. Such materials' behaviour and related manufacturing processes are beyond current commercial experience and only little information is available.

Propulsion engineers are mainly confronted with increasing difficulties arising from high engine temperatures. The structural total-life requirements for the SST propulsion system are the same 30,000 hours as in subsonic commercial engines. Nevertheless, subsonic aircraft engines spend less than 10% of their mission time at the most severe engine conditions. On the contrary, SST engines will spend about 60% of the mission time under the most severe combination of component stress levels and high temperature conditions. The challenge is to utilize advanced materials to cope with the high temperatures without incurring excessive weight and cost penalties.

It brings the engine designer new problems because of the higher operating temperatures required to produce the higher thrust. At Mach 2 air will enter the intake at about -60°C, will be compressed in the intake and be at about

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130°C when it reaches the face of the engine, and will leave the high-pressure compressor at 550°C. At Mach 3 this rises exponentially to respectively 325°C and 986°C.

Viable combustors concepts, having a long life goal of 18,000 hours, depend on the development and demonstration of a new class of high temperature ceramic matrix composites (CMC) for which no previous commercial practice exists. At the same time, lightweight, high strength and high stiffness metallic, intermetallic and ceramic composite materials are being examined for the exhaust nozzle design in order to meet engine noise and weight requirements. These include gamma titanium aluminides and thin wall castings of superalloys. In general, large complex configurations must be manufactured economically and demonstrate long life under adverse operating conditions.

The major challenge arises from the total airframe configuration. To meet it the aerodynamicist has to produce a satisfactory compromise between two inherently conflicting requirements: the need for minimum drag in supersonic flight and the need for controllability and ease of handling in subsonic flight. From a design point of view, the lift-to-drag (L/D) ratio is the most important aerodynamic parameter of airliners, affecting essential economic-related performance such as maximum range, payload and fuel consumption. The primary cause of SSTs' high specific fuel consumption (SFC) is the dramatic fall in airplane's L/D ratio at supersonic speeds. Concorde, for example, experiences an L/D reduction in the order of one-half that of subsonic jets.

The main goal, therefore, is to increase the lift-to-drag ratio throughout the speed regime of the next generation SST. As a start, existing commercial and experimental vehicles are revisited to evaluate their performances and weak/strong points: the Concorde, the Valkyrie XB-70 and the Blackbird SR-71 are well known Mach 2 to 3 vehicles with public, though limited, access to technical documentation. Similarly, an existing Mach 6 HYCAT concept is used a start for further iteration loops.

Later on, methods will be evaluated which include optimisation schemes coupled with state-of-the-art computational fluid dynamic (CFD) solvers, as well as non-linear design methods. The development and application of Multi-Disciplinary Optimisation tools involving aerodynamics, propulsion, structure and flight mechanism are in the end the only way to realize an optimum integrated airframe/propulsion aircraft. It is however not the intent to evaluate new and advanced propulsion concepts as is the case for a presently running EC-project LAPCAT[1] particularly needed for the high Mach numbers (M=8). Here we start from existing engines (turbojets) or engines which are within technical range (turbo-ramjets). Potentially scramjet might be evaluated in case there is a need or a technical benefit.

The concept of boom minimization is based on suppressing the coalescence of multiple secondary shock waves caused by the SST in supersonic flight, so that the overpressure (DP) at ground level is reduced. This can be achieved through the manipulation of aircraft's design characteristics, resulting in an optimised N-wave pressure signature with significant sonic boom loudness attenuation. Recent effort was the NASA program SSBE (Shaped Sonic Boom Experiment) as a continuation of similar programs such as QSP (Quiet Supersonic Platform) and SSBD (Shaped Sonic Boom Demonstration). Advanced low-boom configurations can be achieved by a more uniform lift distribution stretched over a longer length, so that the sonic boom maintains its weaker mid-field features with lower bow shock. In order, however, to obtain adequate boom loudness suppression, the area distribution of an aircraft must be carefully determined aerodynamically. Such advanced low-boom designs induce a drag penalty, tending toward lightly-loaded but larger wing surfaces. In the proposed program we investigate eliminating the fuselage bow shock and the rear reattachment shock by careful integration with the propulsion system. Alternatively, creation of cold plasma in front of nose or leading edges allows the change of shock structure and its related strength.

II. Project Objectives

The ATLLAS project aims at providing a sound technological basis for the industrial introduction of lightweight advanced high-speed aircrafts on the long-term (15-20 years), defining the most critical RTD-building blocks to achieve this goal and finally to investigate in depth these critical technologies by developing and/or applying dedicated analytical, numerical and experimental tools.

Two supersonic aircrafts concepts are evaluated. The primary cause of the high specific fuel consumption for high-speed transportation is the dramatic fall in lift/drag ratio at supersonic speeds. The main goal is to find if the established empirical L/D barrier is fundamental or if it can be broken by careful design and in particular by close integration of the airframe and the engine. The study will investigate an aircraft configuration suited to Mach 3 flight and another for Mach 6. Areas of critical aero-thermal loads will be identified and evaluated.

Critical technologies for both the external airframe and the propulsion units are assessed. The major issues addressed will be sonic boom and heat transfer reduction, high temperature resistant materials which are both lightweight and long-duration oxidation-resistant, novel cooling techniques, particular aerodynamic phenomena related to compressibility, and fuels that have both high energy content and good heat sink capability.

Specific objectives for the envisaged concepts are related to materials and cooling. Lightweight airframe components are clearly needed for both concepts. The multi-functionality of hollow-sphere structures for aeronautical applications is evaluated for their low-density, thermal protection, acoustic absorption. Also Ultra-High Temperature Composites and oxidation resistant CMC materials for sharp leading edges and air intakes at sustained high heat fluxes typical for high-speed transport are investigated allowing the generation of a database for possible concepts and materials.

Also lightweight engine components are needed allowing the increase of the combustion liner and turbine vanes temperature resulting into lower NOx-emission and higher turbine inlet temperatures leading towards higher thermal and propulsion efficiency. Long-term oxidation and wear resistance of the combustion liner for lean combustion conditions are performed for the same reasons of setting up a database for possible concepts materials.

Despite the use of high-temperature protection systems, the imposed heat fluxes for airframe and engine still require the use of direct or indirect cooling to control material temperature. The initiation of high-temperature resistant materials automatically requires the (re)-investigation of novel cooling concepts by evaluation of various types of cooling processes (film, transpiration, effusion) within propulsion units with respect to cycle efficiency and controlling operational material temperatures. Also EHD cooling principles by altering the shock position and strength and hence the related stagnation heat flux are studied.

The emphasis in the area of loads definition is to develop and verify models to predict the combined effect of aero-thermal and material interaction on several lightweight high-temperature resistant materials. This is accomplished by integrating existing aerodynamic, heat-transfer, and structural codes. The results are then calibrated and verified with simplified experiments

The use of multi-disciplinary analysis and optimisation process (MDO) to model a sufficient complete flight mission by the inclusion of the disciplines aerodynamics, structure and flight mechanics will allow to optimise the aircraft for maximal cruise range starting from a fixed maximal take-off weight and a given fuselage. As an appropriate balance between accuracy and numerical effort, high fidelity modelling based on an Euler flow solver and a finite element solver is intended for the high-speed cruise part of the mission using the disciplines aerodynamic and structure.

ATLLAS is carried out by a 13-member consortium. As major European manufacturers in the highly competitive high-tech field of aeronautical high-speed flight design and manufacturing, ASTRIUM (D), MBDA (F) and EADS-CRC (D) will provide the technical needs and application-specific expertise. One SME industrial partner, GDL (UK), has developed a design method particularly suited to highly integrated engine/airframes and is applying the method to the Mach 3 aircraft design. Another SME, ALTA (I), has developed renowned skills and expertise the field of high-speed experiments. The groups belonging to research centres (ESTEC (NL), DLR (D), ONERA (F), FOI(S)) and universities (Stuttgart(D), Munich (D), Southampton (UK) and UPMC at Paris (F)) are all working for long-time on specific issues of propulsion, combustion and aerodynamics with close contact to industry in bilateral, national and international collaborations. They provide basic knowledge, investigation means and testing facilities.

III. Novel Concepts for High-Speed Flight

To allow a direct calculation of the cruise efficiency, a global approach is applied. The vehicle is enclosed in a control volume, with the conservation equations for mass, momentum and energy being applied to the steady flow system as is shown in the Figure below.

With respect to sonic boom, it has been found that carbon dioxide relaxation absorption could affect the propagation of sonic boom at the altitudes of interest here. Since aerodynamic shaping might not be sufficient to achieve the required sonic boom performance for a Mach 6 aircraft, additional approaches related to shock wave manipulation by means of nose attachments have been selected to be tested as shown in Fig. 1.

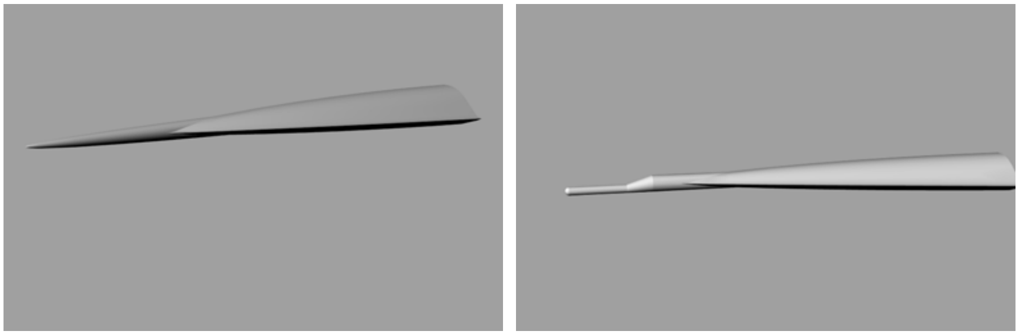

Figure 1 : nose shaping for sonic boom alleviation

For the Mach 6 configuration, from a set of available designs, the partners decided to depart the study from the HYCAT configuration. First analysis of trim capability, stability and controllability for the derived configuration, ATLLAS Mach 6 (Fig. 2) indicates vehicle trim ability during cruise and enough range-capability.

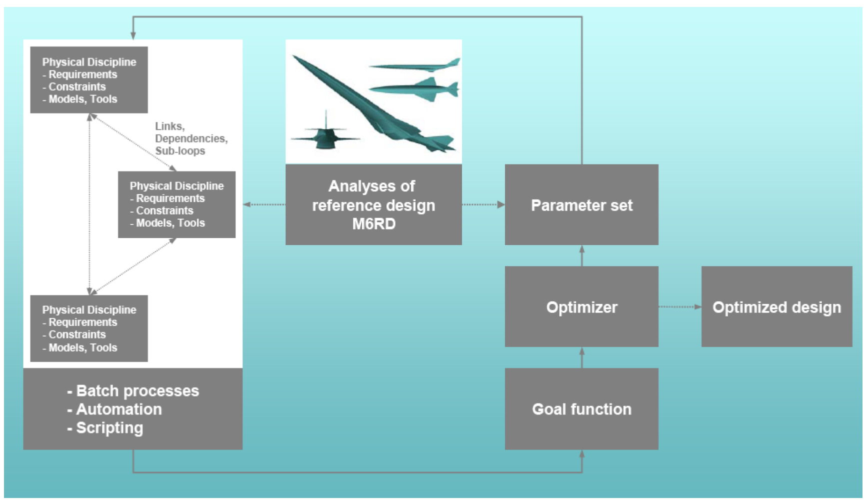

Figure 2: Multi-disciplinary integration tool

IV. Lightweight Airframe Materials for Sustained High-Speed Flight

High-speed aircrafts are exposed to high thermal and mechanical loads. Especially the nose structure, wing leading edges, air intakes etc. will reach temperatures which require special heat resistant materials, structural concepts and optional cooling devices. The expected leading edge temperatures for the ATLLAS reference vehicles are relatively low. At Mach 6 the temperatures is expected to be around 500 K up to an altitude of 30000 m for sweep back angles of 65° and a radius of 1 mm. For the Mach 3 vehicle they are lower. The intended materials should all be applicable to leading edges due to their high operational temperatures. Even the application on the nose and air intakes, where higher temperatures are expected, should be possible but requires more refined verification.

The requested aerodynamic performance for an aircraft takes focus on a high aerodynamic lift to drag ratio requiring sharp leading edges and rather thin wing or stabilizer structures. The focus will be on investigation of lightweight airframe materials including material design, coatings and determination of basic material properties. This includes different tests on material samples to determine temperature stability, chemical resistance to the expected operational environment, mechanical stability and required additional physical properties.

ONERA assesses to demonstrate the principal feasibility utilization of metal hollow sphere based components for high-speed transport vehicle and propulsion systems on engineering test sample level. Various routes for fabrication of cellular solids, mostly foams have been investigated in the past. Most effort has been spent in the field of aluminium foaming processes. A totally different concept to manufacture cellular solids is the approach via hollow spheres. Employing the hollow sphere technology, structures can be designed virtually to application needs. In contrast to classical foaming processes, there are no restrictions with regard to material selection (melt viscosity and stability). The powder metallurgical approach is applicable to any metal or even high performance alloys. The hollow sphere technology allows high degrees of porosities, reproducible properties and fair process control, structural regularity, excellent noise absorption and low weight.

The efforts on the development of lightweight metallic Hollow Sphere Structures shall be adapted to specific needs for lightweight airframe/TPS/tank systems. That is, fabrication techniques for hollow sphere structures will be adapted to the application requirements with regards to materials, densities and thermal properties. In parallel, fabrication technologies for panels with hollow sphere cores will be developed. This includes screening of suitable joining techniques (brazing, diffusion bonding) and relevant test methods thereof. Establishing suitable joining techniques for hollow sphere structures is a crucial step to supply components in sizes relevant for the envisaged application. A second axis will aim at determining the mechanical and acoustic absorption properties of lightweight high strength structural panels for high temperature structures in nickel based microsphere panels.

A FE-based model has been developed to characterize the mechanical behaviour under compression of hollow spheres packings[2]. On the experimental side, quasi-static compression tests have been performed on cylindrical samples (Fig. 3). The shape of the stress-strain curve obtained is quite similar with the one generally observed for metal foams, i.e., a densification plateau is observed. In agreement with first calculations, local plasticity due to stress localisation appears in the meniscuses and in the contact area between compression plates and samples. Viscosity seems to have any significant influence on the overall mechanical behaviour of packings.

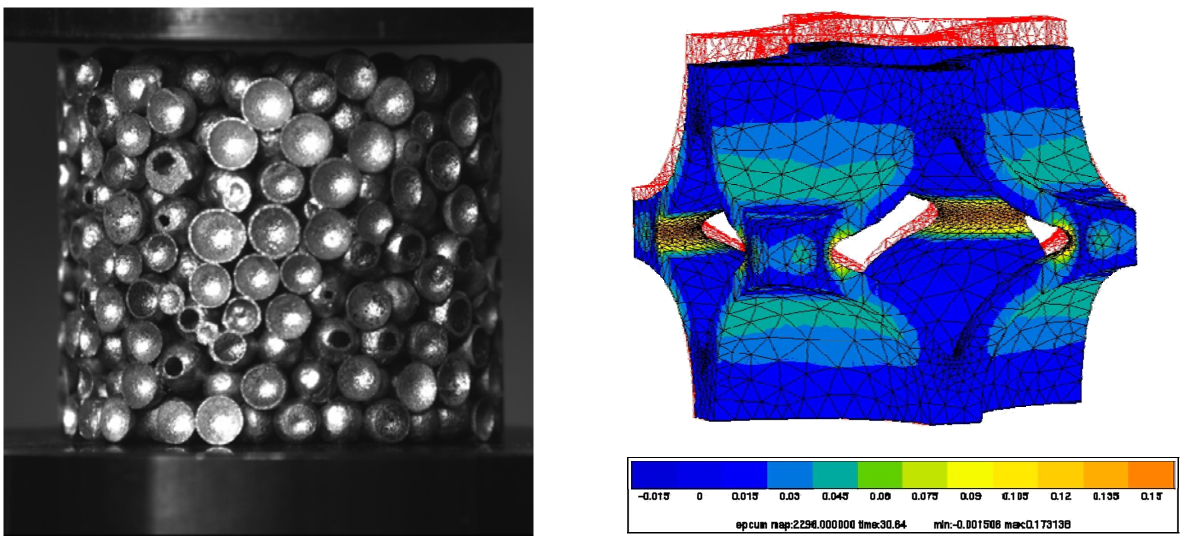

Figure 3: Cylindrical non-regular packing for quasi-static compression tests (left) and numerical simulation on a FE-based model.

ONERA also deals with the manufacturing and investigation of ultra high temperature composites. The materials are based on mixture between transition metals borides and carbides. The interest of such association is to promote the formation on surface of dense refractory oxides like ZrO_2 and HfO_2. The most suitable way to produce sharp edges is to manufacture monolithic parts using hot pressure sintering of appropriate mixture of powders. Monolithic UHTC inserts could be also added in composite structures. Another challenge is to achieve a sufficient level of toughness to overcome the brittleness of ceramic materials.

The interest in UHTCs is grown since several years, especially in the US and in Italy. Oxide materials are, at best, intrinsically resistant to oxidation. But the application on flight vehicles is rather low. Just two experiments under real flight conditions were undertaken with the Sharp Hypersonic Aero-thermodynamic Research Probe-Ballistic experiments 1 and 2 (SHARP-B1, 1997, and SHARP-B2, 2000).

A preliminary choice of three compositions has been made which are feasible by Hot Pressing (Fig. 4-5). First data on the resistance to oxidation and thermal shock of our compounds have been obtained. Oxidation rate slows with time and total weight variations are small. SEM observations of the cross-section of this oxidized material revealed the formation of a thin multilayer oxide scale in which the outermost coat (~7 µm) is a SiO_2 rich glass. Successful electrical discharge machining (EDM) trials have been made on hot pressed materials. The manufacturing was accompanied by a detailed thermodynamic analysis of the stability of the three compositions.

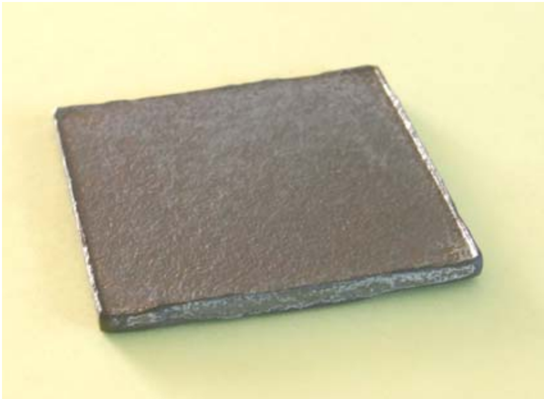

Figure 4: Appearance of a hot pressed $HfB_2/SiC/TaSi_2$ plate (36 x 36 mm)

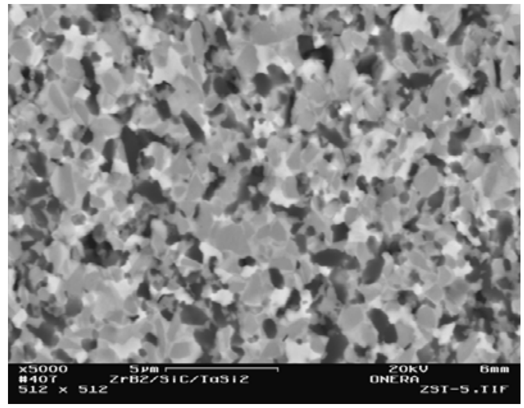

Figure 5: SEM photography of a hot pressed $ZrB_2/SiC/TaSi_2$ composite

Three DLR institutes and FOI collaborate on the application of ceramic matrix composites on leading edges and air intakes. Its application demands a high density, a high thermal conductivity and emissivity of the material. Chosen CMC's are C/C-SiC, OXIPOL and WHIPOX. Structural tests at DLR will focus on a generic but representative design and manufacturing of a sharp leading edge including interface to an adjacent structure. This sample shall consider structural and system aspects like joining technique to a cold substructure and sensor integration. One major objective is to fit this structural sample within an arc jet test facility for a test within high-speed gas flow conditions.

The application of C/C-SiC or C/SiC to re-entry vehicles is state-of-the-art to the material's excellent thermo-mechanical behaviour. But here the service-life is low in comparison to the requirements for hypersonic aircrafts, e.g. extended 25,000-cycle service-life. WHIPOX was just once tested during SHEFEX as thermal protection system of a hypersonic experiment (Fig. 6). In general, oxide ceramic based materials, intrinsically better oxidation resistant, offer a wider framework to tune their material characteristics to the envisaged application.

Preliminary mechanical tensile tests were conducted with focus on fixture and clamping at room temperature. As leading edge geometries demand for a higher fibre orientation along the leading edge axis, WHIPOX with a $\pm 15°$ fibber-orientation was manufactured and respective samples were cut. As the emissivity of WHIPOX is low in comparison to C/C-SiC high emissive coatings with $\varepsilon \geq 0.8$ are developed. The coating is basically a reaction bonded alumina which contains dark and high emissive particles. Two candidates were chosen as dark particles: SiC and a black spinel phase. Preliminary tests with coated samples were performed in plasma wind tunnel.

Figure 6: Left: Tensile samples, on the right with aluminium plate for better load application; Right: FEA of tensile samples (s_x = 100MPa within measuring section)

V. Increased Engine Thermal Efficiency: Novel Cooling Concepts

Novel active cooling techniques need to be addressed when applying advanced high-temperature resistant materials for engine components. The major goals aim to assess & investigate advanced materials and cooling concepts to increase combustion temperature in high pressure combustion chambers. Laboratory scale tests are performed to evaluate characteristic behaviour and performance of these materials and cooling concepts. These materials and cooling techniques are then compared and evaluated wrt to overall engine performance.

Different fuels are investigated required for the studied aircraft concepts: kerosene and cryogenic fuels. Both high-pressure (aerojets) and ramjets based combustion chambers are used as a testbed to deal with realistic operational gas flow conditions. Different cooling techniques will be investigated under a wide parameter range. The thermal performance will be investigated and a comparison to the simulation results will be performed. The cooling techniques are evaluated with respect to overall engine performance (e.g. specific impulse and thrust), and the production of NOx emissions.

Based on experience obtained from a transpiration cooled ceramic combustion chamber for rocket engines, it seems to be possible to use a similar cooling technology for high speed airbreathing engines. With less air used for cooling combustion liners, more air is available for use in the combustion process thereby reducing the NOx levels. NOx reduction in advanced combustor concepts requires reducing combustor cooling levels by half of the required amount for metal liners. This results in higher combustor liner temperatures in the order of 1500°C. CMC turbine vanes with the same temperature capability will be required to achieve turbine inlet temperatures compatible with higher combustor exit temperatures resulting into increased thermal efficiencies.

Main focus will be ceramic based materials for combustion chambers. Besides their high temperature stability, the specific weight and their possibly oxidising stability offer a wide range of possible applications. In addition to the very high gas temperatures and pressure within the engine (combustion chamber, expansion nozzle etc.) the chemistry and gas composition (O2, H2O, CO2, H2, N, CH...) affects the structure of the material. Within this area, oxide based CMCs combined with active cooling are promising candidate materials.

The principle of this cooling technique is to create a gas flow from the cold substructure to the hot surface directly through the porous material itself. Thus, in addition to the direct cooling effect, the boundary layer at the surface will be influenced to reduce convectional heat transfer and chemical reactions. In contrast to the above mentioned current development of the C/C based transpiration cooled burning chamber for a H2/O2 rocket engine with fuel rich burning conditions, engines for high-speed aircrafts will be designed for optimised efficiency resulting in a lean, oxidiser rich burning condition. Thus, oxidising stable materials are of prime concern.

The test facility at TUM, allowing for high pressure combustion, was updated to meet the different requirements[3]. Two new cooling feed systems were designed – one for cooling with kerosene and one for nitrogen – with respect to the requirements posted by the project partners. A new combustion chamber was designed and built. A carrier for the fundamental investigations of cooling concepts and CMC material was designed and manufactured (Fig. 7). This specimen comprises a new injector, a new combustion chamber and the film-cooling applicator ring.

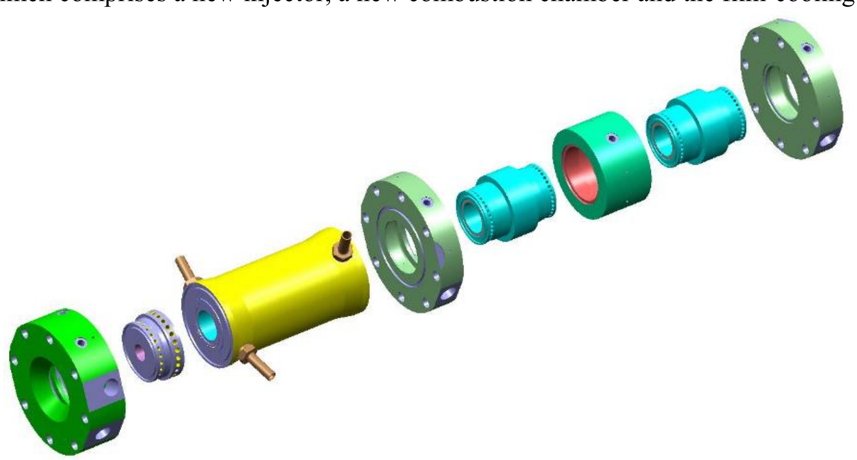

Figure 7: Sketch of CMC material sample and test configuration

Regenerative cooling (PTAH-SOCAR[4] existing cooled structure concept for example), transpiration cooling (for example through DLR porous materials C/C, OXIPOL and WHIPOX), film injection cooling are investigated.

State of the art and existing models are used to define the configurations to be tested. Test results will allow characterizing the structures to be tested and to headline the possibilities and the limits of existing models, leading to enhance them afterwards. To measure directly wall heat flux a new sensor concept is under calibration with a black body source and heat fluxes up to 500 kW/m^2 (Fig. 8).

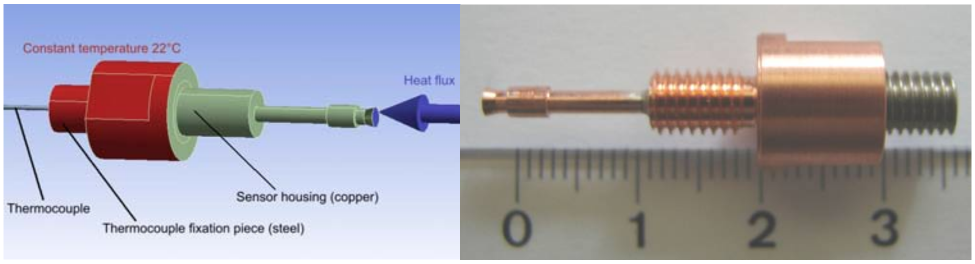

Figure 8: DLR-AS-WK heat flux sensor

To cover possible applications for ramjets as well as scramjets, experimental investigations on transpiration/effusion cooling are performed in a continuous running test facility at ITLR (University of Stuttgart). The main air flow is electrically heated up to 1500 K stagnation temperature and several actively cooled wall structures will be investigated. Thereby the main flow will range from subsonic speed up to Mach numbers of about 2.5. A test device for material characterisation was designed, manufactured and materials are tested in flow-through experiments. For the ram-based facility the used test channel was modified for installation of the composite material samples and a new plenum for medium temperature characterisation was built (Fig. 9). Furthermore, software for measurement and IR-image evaluation was modified to the ATLLAS requirements. First preliminary hot-gas tests with C/C samples at sub- and supersonic flow conditions are performed in the medium temperature range.

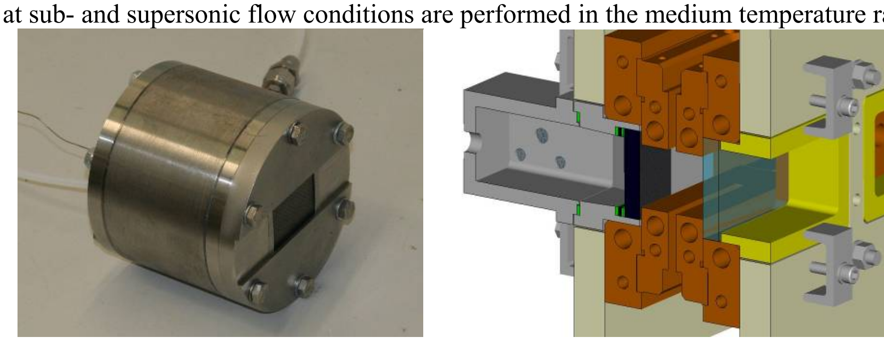

Figure 9: ITLR Through-Flow Pressure Tank and Ram-based test channel with new coolant plenum

VI. Material-Aero-Thermal Interaction Modelling

In parallel to the above described experimental investigations, the modelling aims at enhancing and testing the coupled aero-thermal phenomena in the ATLLAS type high speed flows. The phenomena to be studied are shown in Fig. 10. These coupled phenomena are simulated with different approaches (CFD, semi-empirical, commercial or in-house codes …). Comparisons have been performed with analytical and experimental results from literature, and some numerical cross-checks are planned.

An ESTEC-MBDA common used CFD tool, CFD-ACE, is used to simulate multi-physic flow with porous media. On the basis of the commonly-stated computational plan, first test cases, i.e. mainly porous plate and combustion, have been computed. Test cases have been completed to validate the software porous media model and to understand its implementation. A first reactive computation of the TUM new combustion chamber was performed by MBDA. ONERA, on the other hand, checks the feasibility of the numerical approach for multi-perforated cooling systems. A successful 3D computation of the coupled problem with in-house CEDRE computational tool at ONERA is performed on an experimental test case. It entails a full geometry (10 half holes arranged in a staggered manner) with 2 blowing ratios (0.25 and 0.65) and 2 main flow turbulence intensity levels (18% and 0.5%) (Fig. 11).

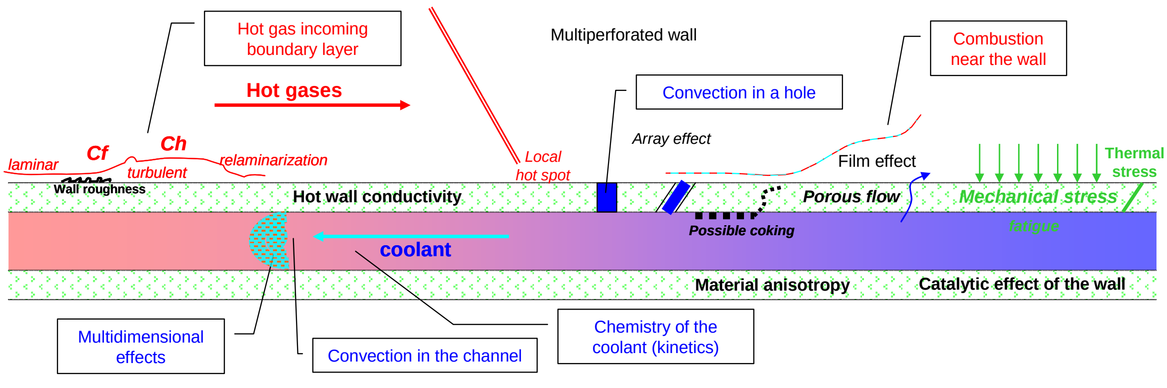

Figure 10: sketch of coupled phenomena considered for modelling

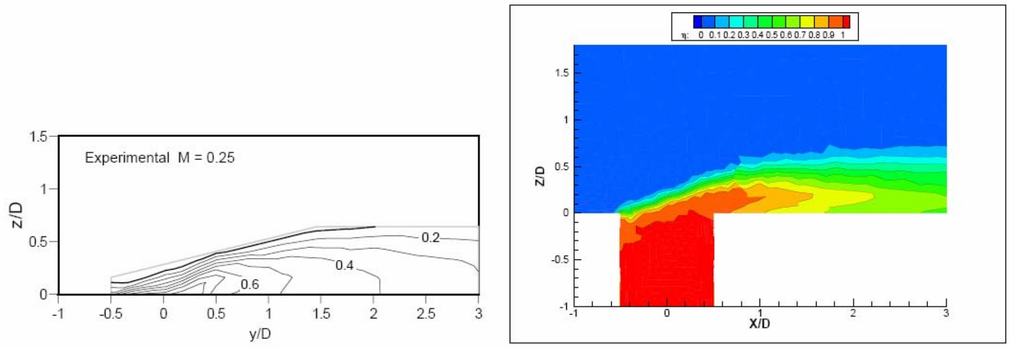

Figure 11: comparison between experimental data (left) and computational result for M=0.25 adiabatic

The performance of intakes and high-speed aircrafts are largely determined by the transitional behaviour of boundary layers. Ample knowledge is however available for the combined effects of hot walls, compressibility and roughness on the extent of the transition zone. Therefore dedicated experiments and advanced simulation tools investigate these combinations.

The definition of the new supersonic and hypersonic transition experiment conditions are driven by the ATLLAS vehicles in terms of Reynolds and Mach number. The design of a new contoured Mach 3 quiet nozzle and of a modular instrumented test body for spot detection is in progress at ALTA (Fig. 12).

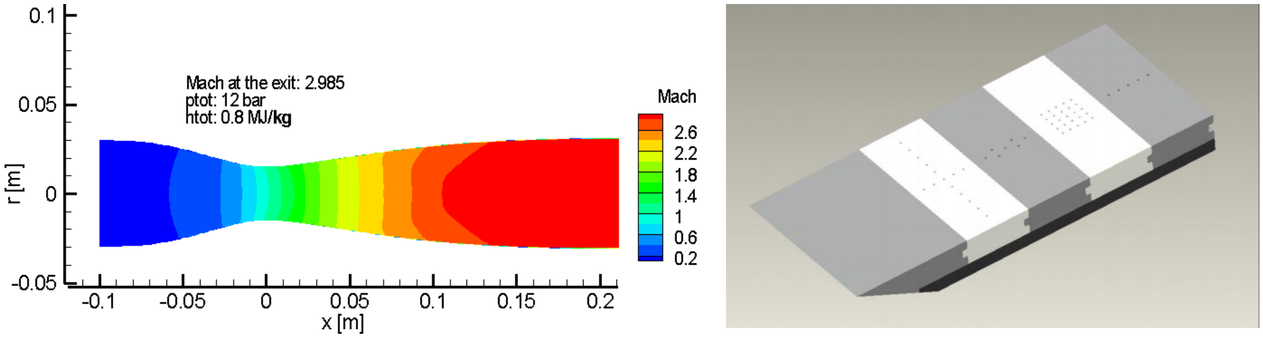

Figure 12: New Mach 3 nozzle design (left) – Modular test body for transition spot detection (right)

SOTON realizes Large Eddy Simulation computations for the Mach 3 conditions, for cold or adiabatic wall conditions (Fig. 13). A reasonable match was found with previous adiabatic wall Direct Numerical Simulation. Cold and hot wall spots have similar propagation velocities while cold wall spots have slightly reduced spread angle.

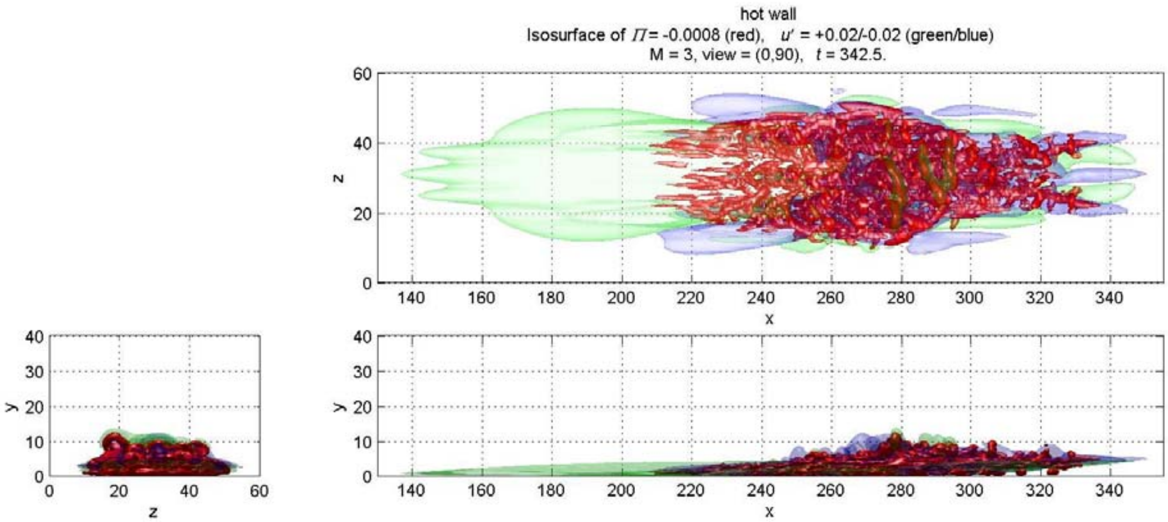

Figure 13: calculated spread angle of transition spot at Mach 3 (SOTON)

VII. Conclusions

Overall design for high-speed transports at Mach 3 and 6 are revisited to increase the lift/drag ratio and volumetric efficiency through the 'compression lift' and 'waverider' principles, taking into account sonic boom reduction. Within this MDO process, the need of lightweight and heat resistant materials will be a prerequisite for a successful design.

Therefore, the prime focus of the ATLLAS project is on assessment of materials, cooling techniques and their interaction with the aero-thermal loads for both the airframe and propulsion components. The former will focus on sharp leading edges, intakes and skin materials coping with different aerothermal loads, the latter on combustion chamber liners. After material characterisation and shape definition at specific aero-thermal loadings, dedicated on-ground experiments are conducted. Both Ceramic Matrix Composites (CMC) and heat resistant metals are tested to evaluate their thermal and oxidiser resistance. In parallel novel cooling techniques based on transpiration and electro-aerodynamics principles will be investigated.

Combined aero-thermal experiments will test various materials specimens with a realistic shape at extreme aero-thermal conditions for elevated flight Mach numbers. Dedicated combustion experiments on CMC combustion chambers will allow the reduction of combustion liner cooling resulting into NOx-reduction and overall thermal efficiency increase. Particular aero-thermal-material interaction influences strongly the aerothermal loadings. Therefore conjugate heat transfer, transpiration cooling and compressible transition phenomena are investigated and modelled. Similarly, the interaction of hot walls on high-speed transition is of utmost importance for intake efficiency and hence engine performance. This particular phenomenon is investigated experimentally and numerically for both flight Mach numbers.

Acknowledgments

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