PTAH-SOCAR FUEL-COOLED COMPOSITE MATERIALS STRUCTURE : 2011 STATUS

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NOMENCLATURE

e	wall thickness (m)
hg	heat convection coefficient (W/m²/K)
K	permeability (m²)
Mf	Flight Mach number
P	Pressure
Pduct	Hot gas pressure
Pcooling	Pressure in cooling channel
S	frontal area (m²)
Taw	Adiabatic wall temperature (K)
Tw	Hot wall temperature (K)
ρ	density (kg/m^3)
µ	dynamic viscosity (Pa.s)
ΔP	Pressure difference

ACRONYMS

CVI	Chemical Vapor Infiltration
DMR	Dual-Mode Ramjet
EADS-ST	ASTRIUM-EADS Space Transportation
FEM	Finite Element Method (structures)
ISP	Fuel specific impulse
LRE	Liquid Rocket Engine
LSI	Liquid Silicon Infiltration
03S	One Side Straight Stitching
PAO	Protection Against Oxidation
PSD	PTAH-SOCAR Duct
PSR	PTAH-SOCAR Rocket duct (37 mm diameter axisymetric cooled duct)
PSS	PTAH-SOCAR sample (flat panel)
PST	PTAH-SOCAR Tube
PTAH	Paroi Tissée Application Hypersonique
RBCC	Rocket Based Combined Cycle
RCVI	Rapid CVI process
RLV	Reusable Launch Vehicle
SOCAR	Simple Operational Composite for Advanced Ramjet
SSTO	Single Stage to Orbit
TSTO	Two Stage to Orbit
TUM	Technical University of Munich

INTRODUCTION

Advanced cooled structures have been studied worldwilde for application to heat exchangers, high speed vehicles, scramjets and dual-mode ramjets (DMR) (subsonic then supersonic combustion)[1],[2],[3] as well as future liquid rocket engines (LRE)[4]. They use high temperature materials, metallic and more and more composite (C/SiC, SiC/SiC, …). Different cooling techniques are used. To achieve performance and to limit the risk, the cooled structures are combining these different existing possibilities, leading often to complicate and costly structures.

The propulsive performance (thrust, consumption) of the DMR have to be optimised, computed and at-best demonstrated. But another major concern is the capacity to build such an engine, and to estimate its robustness and its weight. Light high performance metallic or composite fueled-cooled structures are needed, at least, for the combustion chamber[5]. Several circuits of active cooling systems had been compared to ensure good behaviour of the engine walls, with respect of the combustion-required fuel mass flow. Many configurations of cooling are envisaged, such as series of channels of rectangular shape or pin fins channels. The pin-fin circuit (Figure 1) was confirmed as more efficient[6] than the more classical machined-channels.

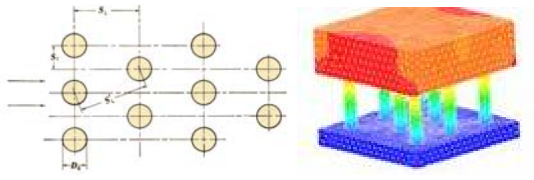

Figure 1 : pin fin configuration of cooling channel

One of the interest of the pin-fin circuit is the easy management along the walls of the DMR combustor, which is often diverging.

The interest of using composite structures (able to operate at temperature over 1800 K in oxidizing environment and with a typical density of 2) have been demonstrated thanks to several analytical and

computational studies and to actual technology experimental testing (benefit in weight, benefit in thermal capability, benefit in injection strut drag, …)[5]. The mass comparison between a metallic and a carbon/carbon structure for the same dual-mode ramjet has been evaluated [7, 8] showing 30% benefit in weight.
In 1993 began this innovative cooperation on cooled high temperature composite structures between what are now EADS ASTRIUM and MBDA-France, up to the test of the St-Elme[9] injection strut in 1997. Several manufacturing process can be used for the transformation of the preforms to composite complete structures (C/C or C/SiC, CVI, LPI, LSI routes, …). LPI and LSI routes are mostly development in the German part of EADS[10]. Besides material and process development, this ceramic-LRE-oriented project[11] also encompasses the development of special metal/ceramic and ceramic/ceramic joining techniques as well as studying and verifying NDI (Non Destructive Investigation) processes for the purpose of testing components.

The PTAH-SOCAR technology takes benefit of this background and takes most of the advantages of the different techniques with minimizing the drawbacks.

COMPOSITE PTAH-SOCAR TECHNOLOGY

This work is a cooperative effort between MBDA France (Le Plessis Robinson and Bourges), EADS-ASTRIUM- Space Transportation in Ottobrunn and Bordeaux, EADS-“innovative works” (formerly “CRC”) in Ottobrunn, Toulouse and Suresnes, with some laboratories and subcontractors.

PTAH-SOCAR genesis

This In-house Effort of MBDA FRANCE and EADS-ST leads to Low cost, highly reliable, effective Fuel-Cooled Structure Technology. The patented idea has been to develop and preliminary check a concept of C/SiC structure with the following advantages :

- no bonding system (nor brazing, nor gluing…)
- complete combustion chamber structure in one part ("monobloc")
- limitation of connecting problems
- no problem for realizing corners of a 2D combustor
- limitation of possible leakage problems
- no need of machining internal channels
- easier integration of specific systems (injectors, flame-holders..)

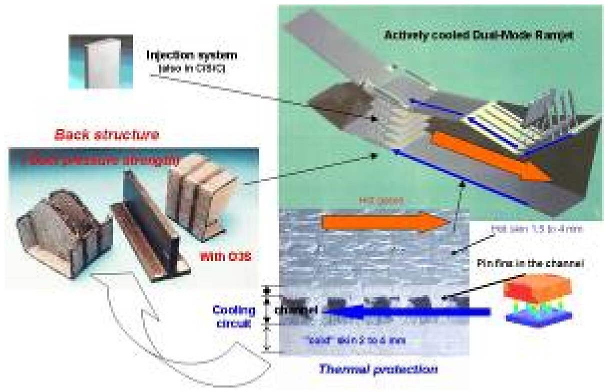

Figure 2 : general idea of PTAH-SOCAR

As shown on Figure 2 the main ideas for the manufacturing of a whole DMR engine with PTAH are the following :

- Monobloc actively cooled combustion chamber obtained at preform state before its densification process (whatever this one : C/C or C/SiC, CVI or LSI)
- Linking by stitching of complex woven preforms
- Hot and cold skins linked together by stitching with carbon yarn
- Stitching treads go through the cooling channel
- Back Structure needed to hold the combustion chamber pressure (may be external or integrated at preform state, based on carbon honeycomb , corrugated skin or a system of O3S assembled stiffeners).

The PTAH-SOCAR specific weight for the heat protection system is lower than 10 kg/m2 (density of this CMC material is closed to 2000 kg/m3). With the back structure, the total specific weight is 30% lighter than metallic advanced cooled structures.
The necessary models of the cooled structure and the associated feasibility were checked on the basis on gazeous densification, leading to C/C or C/SiC cooled structures. The period 1999/2001 was used to check with limited amount of funding and aggressive time schedule the key-points of the PTAH-SOCAR technology
Details on these results and further analysis have been presented in the hypersonic conference held in Orleans, France, in October 2002[12].
In 2002, the PTAH technology began to be investigated with EADS Germany partners with the cost-effective technology based on Liquid silicon infiltration. First technological results obtained essentially with the Liquid Route were presented[13] in 2003.
A baseline LSI route has been defined, preliminary characterized and refined with two simultanate targets : to simplify the process (low risk, low cost) and to check the complete manufacturing

capability on a monobloc duct able to be hot tested.
This optimized RCVI-LSI process is currently the reference densification method for PTAH-SOCAR structures, the readiness of this technology is given in details in the paper presented at the 2005 Hypersonic Technologies Conference[14].
The LSI route was combined with the PTAH idea and investigated at different levels, from plate sandwich samples up to complete subscale cooled ducts. The baseline process has been combineing rapid-CVI densification followed by siliconizing obtained thanks to a liquid surface deposit.

For the PTAH technology, several system "paper" studies have been performed, mainly on dual-mode ramjets (with hydrogen or hydrocarbon as fuel). Preliminary investigation has also been performed on Liquid-Rocket Engines. The corresponding models, for example implemented in the NANCY code[15], have been consolidated with data acquire during mechanical characterization on one hand and PSS cooled panel testing on the other hand.

First experimental demonstration : PSS testing

This first experimental program aimed at developing and testing several small cooled panels, called PSS (PTAH-SOCAR Samples, 130x80 mm²), in order to :

- tune and validate the manufacturing process,
- check the mechanical resistance of the technology,
- precisely evaluate the accessible performance in term of cooling capacity
- estimate the leakage with nitrogen or kerosene during hot test.

So, the PSS takes the simple shape of a plane rectangular current part of the cooled structure PSS is placed in a water-cooled stainless steel frame, which supplies the PSS with nitrogen or kerosene, to be tested at the exit of a scramjet.
The thermal behaviour of a PTAH-SOCAR cooled panel has been checked during hot test, with decreasing mass flows of coolant (gaseous nitrogen, air, regular liquid kerosene). Maximum wall temperature was over 1800 K without damage and the cumulative duration of hot tests was 5 minutes for each PSS.
These results have been complemented with permeability data and mechanical characterization.

If additional panels are tested since PSS4 panel test, some results maybe presented in the full length paper.

Mechanical characterization

Mechanical tests have been realized at ambient temperature and in hot conditions. Temperature increases the mechanical properties of the obtained C/SiC skins[19]. Burst test of PSS2 panels were conducted in cold and hot conditions with the same results. Specific testing has been realized at EADS-CRC in Suresnes. Test investigates tensure, compression and shear of samples of PTAH skins as well as complete sandwiches (Figure 3).

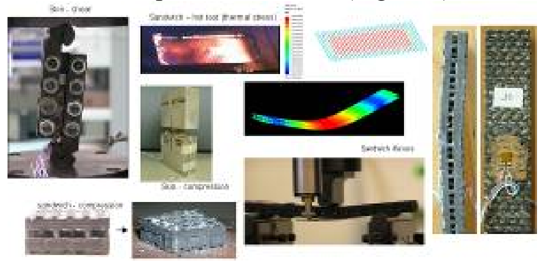

Figure 3 : mechanical characterization

Directly from these test, as well as in connection with different Finite Element Method computations, this work allows to refine the material characteristics (moduli, …) and first level engineering limits (simple failure criteria for skins and yarns).

PREVIOUS DEMONSTRATIONS

Demonstration of 2D duct manufacturing capability

Several samples, components or ducts were studied and manufactured, before the hot test of a cooled duct subscale demonstrator "PSD" done in 2005 in cold conditions and, in January 2006, in hot conditions.
The complete preform is obtained on a special tooling, then transfered to the densification ovens. Additional sealing and final proof test are then realized (Figure 4).
Between each critical step, Non Destructive Investigation is conducted, by using X-rays or neutron tomography.
Final proof test is possible thanks to the stainless steel frames and tubes compatible with the test facility.

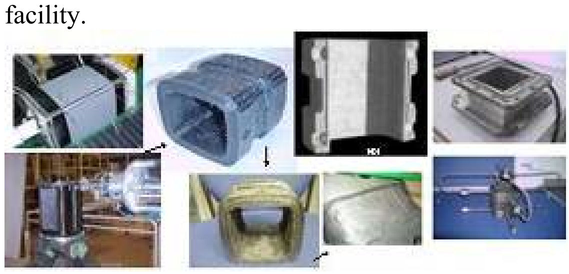

Figure 4 : manufacturing steps of PSD assembly

Successull hot testing of PSD in scramjet environment

In 2005, it was possible to test –in cold conditions- the pressure effect on the external skin of PSD ducts. A laser extensometer of EADS-CRC is used to measure the max displacement of the central part of one external skin, that can be compared with the pre-computed one under the same pressure, with good agreement.
After these mechanical non destructive mechanical characterization, the PSD1 duct has been sent at the end of 2005 to ONERA Palaiseau test center in order to be tested in hot conditions.
The characteristics of the test series held in ATD5 test cell on an existing supersonic combustion chamber were the following:

- Flight conditions : Mach 7.5
- Supersonic combustion air/H2
- Transient behaviour.
- Air as coolant (no other coolant was usable).

Incoming mass flow, coolant air pressures and temperatures were measured as well as Tback (external wall) by Thermocouples and IR camera.
Displacement laser sensor provided by EADS-CRC was used.

The PSD1 was tested in hot conditions during the whole planned test program, which included a step by step approach and severe 3D effects on cooling between the 4 faces (each PSD side communicates internally with its neighbours through the corner, and each has its own input and output). 12 hot runs were performed.
It was as far as known the first successfull scramjet hot test of a monobloc cooled C/SiC duct.

After test and analysis of such subscale ducts, larger structures are planned to be manufactured and tested, for example within the hypersonic METHYLE test facility in Bourges[16],[17].

Scaling capability

One of the tricky questions of CMC composite structures, especially due to the densification processes in controlled ovens, is the scaling. Once you have made samples, then panels or subscale ducts of 10 cm, the capability of manufacturing actual structures of 50 cm or more.
One PSW demonstration panel of 500 mm of length was then manufactured with the same process.

The Non Destructive Investigation as well as the metallographic investigation of follow-samples confirm the quality of the PTAH-SOCAR structure after all the manufacturing process. It includes the thick parts where the input coolant pipes will be screwed.

High coolant pressure capability

Up to know, pressure test were made in hot or cold conditions with 'moderate values' in the coolant channel (demonstration of no damage for coolant pressure up to 90 bar). For possible use with LH2 for instance, it could be important to be able to sustain pressure above 100 bar.
At this level, the main problem was to be able to avoid leakage in the assembly used to test the PTAH-SOCAR structure. A new device was manufactured in order to achieve this demonstration, in ambient temperature and with oil as pressure fluid.
It was not possible to pressurized more than 193 bar the PTAH-SOCAR Sample panel developed with the current status (used also for the PSR as well as the PSW scaling panel). At this level of coolant channel pressure, the PSS panel was not damaged.
The technology has been demonstrated to be able to sustain an internal coolant pressure of the class of 200 bar.

Cylindrical high pressure ducts

The figure below shows how the PTAH technology is used for manufacturing such axisymetrical cooled structures, for subscale chamber testing, for heat exchangers. With this technology , minimum internal diameter is close to 40 mm.

Figure 5 : manufacturing of PTAH axisymetrical duct

This technology used on different systems was especially used for the PSR testing within the scope of the ATLLAS program testing.

The PTAH manufacturing technique can also be used on bigger size rocket engines or nozzles.
Manufacturing capability of such a preform of PTAH structure has been checked.

This PTAH nozzle extension design has been refinemed, taking benefit of the new technological characterizations of PTAH structures, especially PSR hot testing.

Some new examples will be given in the full lenght paper.

NEW TEST OF PTAH SOCAR COOLED STRUCTURES FOR A DIVERSITY OF APPLICATIONS

To prepare these further demonstration, as well as to investigate PTAH application to actual systems such as DMR, models and technology results are available, for cooling (thermics and permeability) and for mechanics.

Many applications of PTAH-SOCAR cooled structures are under investigation (Dual-Mode Ramjet, Liquid Rocket Engines, detonation- based engines, fuel cells, heat exchangers, micro combustion , transpiration cooling, …).

Some cooled axisymetrical PTAH structures (called PSR) have been manufactured and are tested, particularly in oxygen/kerosene high pressure environment, within the ATLLAS project[18].

LRE application

Preliminary investigations have been done of the possibilities and interest of using the PTAH technology for axisymetric Liquid Rocket Engines and presented in Joint propulsion conference[19] in 2004.
Manufacturing process adaptation (see Figure 5), mechanical strength estimation have shown possible interest. It seems quite easy to manufacture the cooled part of the engine, the uncooled part of the nozzle in the same process with CMC material. Anti-leakage treatment can be limited to external skins and combustor part, leading to transpiration positive effect at the throat region.
After some preliminary studies, a project of subscale LRE nozzle extension had been drawn.

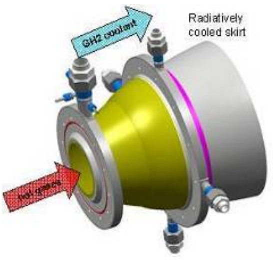

Figure 6 : project of subscale PTAH LRE nozzle extension

This common definition phase has included PTAH cooling circuit computations with existing models. Results with the NANCY code[15] are detailed in previous publications, with H2/O2 combustion at Mixture ratio =6 and combustion pressure of 100 bar and GH2 cooling. Following computations were performed with other tools and described in [4].

The paper will give some current information on this topic, but most of the corresponding techno step will be given by PSR small-scale high-pressure testing.

Test of simple PSR ducts in LRE environment

Manufaturing and test of such LRE nozzle extensions are planned in the years to come.
In the mid-time, within the scope of the ATLLAS program[18], some small diameter PTAH structures were extensively tested in a kerosene-oxygen rocket combustion chamber under various conditions.

The figure below shows one CAD assembly of PTAH 37 mm diameter PSR cooled duct to be tested at Munich Technical University under LRE environment.

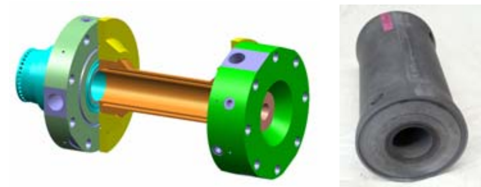

Figure 7 : Assembly of PSR duct for TUM testing

The PSR cooled duct (in orange in Figure 7) is equipped with integrated small shoulders and assembled into a water-cooled modular LRE facility.
In the TUM facility, a wide range of Mixture Ratio as well as coolant mass flow can be investigated with a combustion chamber pressure up to 100 bar). PSR test series are planned up to 2009, in a step by step approach comparable to the PSS one. No preheating of the coolant is planned for the test at TUM.

Thermal and preliminary mechanical computations were performed with different approaches, before, during and after the test campaigns.

These test series allowed to investigate the PTAH materials compatibility in high pressure LRE environment, with hydrocarbon, water, CO_2 and oxygen medium[20].

The paper will present some of the results obtained as well as the comparison with different thermal simulations.

duct		TEST	input data (measured)			NANCY computations	
			PF2a (bar)	TF2a (K)	coolant mass flow	% DT coolant / measurements	Twall [K]
PSR0	Pcc= 9 bar and MR=2.3	**AEC-T10-07**	42	277	ref	-20%	1763
PSR1		**AEC-T10-17**	38,5	285,6	ref	-8%	1663
PSR0		**AEC-T10-06**	58,3	279,9	ref + 50 %	-21%	1591
		h gaz 1 +20%	*58,3*	*279,9*	*ref + 50 %*	*-13%*	*1818*
PSR1		**AEC-T10-11**	44,1	274,1	ref + 50 %	-12%	1589
PSR0	Pcc= 18 bar and MR=1,8	**AEC-T11-01**	61,4	276,5	ref + 65%	-23%	1767
PSR1		**AEC-T11-11**	49,8	277,3	ref + 65%	-19%	1766

Figure 8 : example of GN2 cooled PSR experimental and numerical results

The full length paper wil also headline the planned future activities, for example to sustain this environment during very long duration (application to a possible future high speed civialian aircraft).

Test of integration of external stiffeners to the cooled strucutre

The hot gas pressure and the aeropropulsive efforts need to use a back structure, especially in case of non axysetrical shapes. The principle was demonstrated in the early part of the PTAH SOCAR project. After the multi-year technology evolution, this part of the work was revisited in 2010 with the manufacturing of different samples : a PTAH-SOCAR cooled panel with a stifferner associated in an integrated way at preform state.

Figure 9 : PTAH SOCAR panel with integrated stiffener at preform state - detail

Mechanical test of these panels are planned in the months to come.

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