A specific TPS for an innovative actively cooled combustor

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Abstract

Design, fabrication and validation of Thermal Protection Systems (TPS) is a key process when designing an airbreathing hypersonic flight vehicle. It requires tools with high-predictive capacity to dimension and optimize the TPS, a detailed knowledge of the materials properties and their forming techniques and ground-based test rigs to replicate thermal loads that the vehicle will experience during its flight.
Recently ONERA and ArianeGroup have combined their know-how, tools and experiences to build a specific TPS used in an innovative actively cooled combustor. The design of the combustor has been based on past experience and its optimization was achieved with the aid of the CFD software CEDRE. As a part of the combustor is actively cooled with the effusion cooling technique, a dedicated model, which has been developed and implemented in the CFD code in a preliminary phase, has been used.
Parts of the combustor were manufactured with a CMC material: they were designed from 3D carbon textures and densified via gaseous deposits. These components enable complex geometries (such as tapped holes, for example) as well as large sizes (over 1m on this application). The resulting C/SiC materials possess thermomechanical properties and resistance to oxidizing atmospheres allowing them to withstand several thousand seconds on airbreathing propulsion applications. The low density (around 2) of CMC parts makes it possible to achieve particularly unique performances. Finally, long-duration direct-connected tests have been performed in various flight-like conditions to demonstrate the effectiveness and the robustness of this new combustor. This successful proof of concept has provided results that will enable enhancement of the entire numerical and experimental approach, integrating lessons learned, and enable future improvements of the TPS.

Keywords: *TPS, actively cooled combustor, Ceramic Matrix Materials*

Nomenclature

Latin
k – Turbulent kinetic energy
T – Temperature
Tpi – Thermocouple
x, y, z – Coordinates

Greek
ω – Pseudo-dissipation
Superscripts
* – adimensionalized

1. Introduction

Since the 1950s, ONERA has been conducting studies and research on supersonic and hypersonic airbreathing propulsion systems, and especially on subsonic and supersonic combustion ramjets. Early in the 1960s, flight tests have been conducted with experimental high-speed airbreathing vehicles. At that time, the kerosene-fueled STATALTEX missile reached Mach 5 at altitudes above 30 km [1]. The program ESOPE, initiated in 1966, led to ground-based test demonstrations of a Mach 6 scramjet engine

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in the late 1960s [2]. Since these pioneering tests, several projects have been conducted in France to develop subsonic and supersonic combustion ramjets [3]. These developments were closely tied to associated theoretical studies and to the development of ground-based test facilities, experimental combustors and numerical tools, as CFD codes, with the aim of understanding the basic physical phenomena, identifying and addressing the main technical challenges, and finding innovative solutions to develop expandable or reusable subsonic or supersonic combustion ramjet engines.

ArianeGroup, as part as Europe's primes industrials actors for both rocket propulsion and hypersonic reentry vehicles, plays a central role in advancing high-temperature materials for next-generation systems. In launcher propulsion, ArianeGroup is responsible for the development of cryogenic engines and solid boosters where nozzle extensions and thrust chambers face extreme thermal and mechanical loads. In parallel, the company is part of the European efforts on civil hypersonic demonstrators and space reentry vehicles, where Thermal Protection Systems (TPS) must be thermally efficient, lightweight, and reusable. At the same time, ArianeGroup also contributes to defense-related atmospheric reentry systems, which experience far higher thermal fluxes and mechanical stresses. This broad portfolio has given ArianeGroup unique expertise in tailoring material systems to distinct mission environments, balancing reusability, mass efficiency, and robustness depending on the operational domain. Within this spectrum of solutions, C/SiC-based TPS has emerged as a key enabler for civil launchers and hypersonic platforms, offering superior oxidation resistance and structural integrity compared to traditional ablative composites that erode in flight. Unlike metallic hot structures, which suffer from high density and limited temperature capability, C/SiC components provide a much higher specific strength at temperatures beyond 1400°C, while maintaining toughness through fiber reinforcement.

When designing a new high-speed airbreathing engine, identifying the material and the structural solution which might sustain the mechanical and heating loads during its mission, as well as the "non-operational" loads during the non-operational phases of its mission [4], is either the primary or one of the most pressing technical challenge to be overcome. Various solutions may be discussed, dependent on the mission and its duration, the anticipated mechanical, thermal and thermomechanical loads, the geometric complexities, and whether the application has to be reusable or not.

Ablative materials offer a reliable passive method for thermal protection, and are one of the most widely used solutions in high-temperature environments such as those encountered in liquid and solid rocket engines and nozzles. Active cooling methods, such as regenerative-cooling, transpiration-cooling, effusion-cooling and film-cooling, are also possible, and of special interest especially in several thermal environments, as in subsonic and supersonic combustion ramjets [5;6]. The experimental flight test demonstrator X-51A waverider reached Mach 5.1 in 2013, using a regenerative-cooling technique to protect the engine [7]. A ceramic based transpiration-cooled TPS was flown on outer surfaces of the experimental vehicle SHEFEX-II [8].

In a recent joint study, ONERA and ArianeGroup have combined their know-how to define, build, and test a new ramjet combustion chamber protected with an effusion cooling technique. The concept is not novel, having been introduced several years ago [9;10]: see Fig 1. Nevertheless, the originality of this study stems from its application of state-of-the-art tools and materials, to assess the possible expansion of the concept's potential.

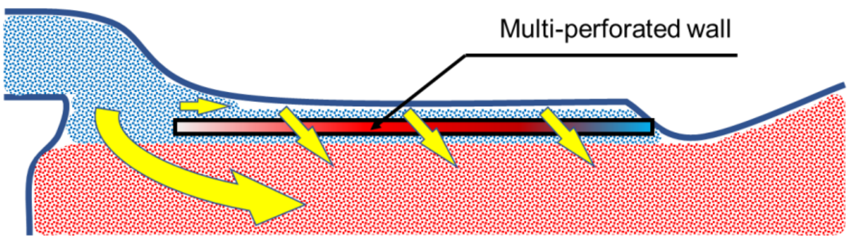


Fig 1. Principle of the effusion-cooling technique applied to a subsonic ramjet engine, adapted from [9].

This article primarily focuses on the tools, materials and specific solutions that have been developed to build the engine, rather than an in-depth examination of the engine itself. The engine and its TPS have been fully dimensioned using numerical tools, leveraging computational capabilities to optimize the overall design. Hence, in a first part, the CFD code and the specific model developed to predict the effect of the effusion cooling technique are described, as well as validation studies that were performed. The second part of this article focuses on the thermostructural material, including its manufacturing process and tailored forming techniques. Following the numerical dimensioning of the engine and the material selection, Section 3 presents the fabrication and the practical testing of the engine, highlighting the methodological framework that guided these tests, whose results are still under analysis.

2. Development and validation of the CFD code CEDRE

A distinctive aspect of this study lies in the fact that the engine has been fully designed and improved with numerical tools, and especially with the Computational Fluid Dynamics (CFD) code CEDRE, highlighting the increasing reliance on numerical methods in the development of new ramjet engines.

2.1. CEDRE

CEDRE [11] is a multi-physics platform, developed by ONERA, working on general unstructured meshes intended to both advance research and process industrial applications in the fields of energetics and propulsion. The code itself consists of several solvers dedicated to physical subsystems: fluid calculation, Lagrangian and Eulerian solver for dispersed or diluted particles, heat conduction in solid walls, thermal radiation, stochastic reaction models, liquid films, etc.

CEDRE is under continuous development and is intensively used to perform simulations of subsonic and supersonic, turbulent and reactive flows in airbreathing engines. Most of the calculations aim at:

- validating the implemented methods: see, for example, recent studies concerning models for gliding arc discharges in supersonic flow [12], simulations of a rotating detonation [13] and unsteady simulation of rough-wall turbulent supersonic flows [14],
- providing complementary insights to improve the understanding of engine tests and the analysis of the associated data: see, for example, recent publications concerning simulations of a reactive supersonic jet [15], the acoustic field of a subsonic combustion ramjet [16], or the simulation of a simplified scramjet combustor [17],
- and guiding the definition and the optimization of new combustors: see, for example, the study of a fluidic oscillator to fuel a supersonic flow [18] or the use of DC gliding arcs to enhance the operating conditions of a supersonic combustor [19].

2.2. Specific Model used for effusion cooling

The effusion-cooling effect (see Fig 2) is generated by multiperforating wall surfaces with high densities of holes, facilitating the injection of a coolant fluid at a temperature sufficiently low to provide a thermal protection to the wall. Fluids as air, nitrogen or fuels may be used for this cooling technique. Such solution is commonly used in aeronautical gas turbines, to protect the walls of the combustor.

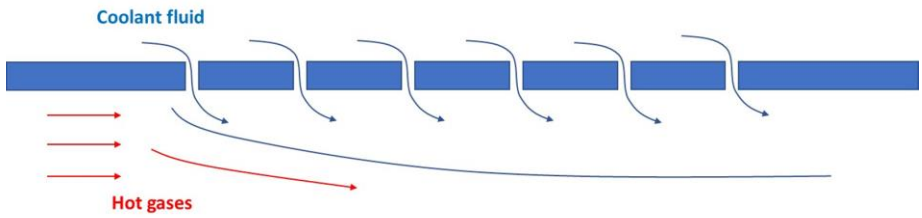


Fig 2. Principle of the effusion-cooling technique.

Numerical simulations can accurately capture and predict the flow dynamics and the thermal behavior of a wall with an isolated or a small number of holes [20;21]. However, scaling up to simulate an entire combustion chamber, featuring multiperforated walls with hundreds to thousands of holes poses significant computational challenges, and is, up to now, too expensive.

A compromise between accuracy and computational cost has then been sought, leading to the development of an alternative global approach [22]. A specific boundary condition has been devised, coupling an analytical thermal model for the plate to the full 3D CFD of the flow outside of the holes.

This model, which has already been applied with success (in respect to the level of simplification) to a full coverage film-cooled chamber [22], has been used in the present study.

The discharge coefficient of the holes is one of the key parameters among the various ones needed to solve the fluid mass flow, momentum and temperature through the plate and the solid temperature on both sides of the plate. Specific tests have been performed to evaluate this coefficient on multiperforated samples which replicate as much as possible the characteristics of the actual combustion chamber multiperforated walls.

In a different framework, an experimental set-up has been developed at ONERA, to build detailed databases of the flow encountered around multiperforated plates: see, for example, [23]. Recent data have been used to assess the validity of the effusion-cooling model in CEDRE: the calculations are detailed in the next sub-section.

2.3. Illustration of an experimental case used for CFD validation of effusion-cooling

In order to assess the numerical models used for the effusion-cooling of the full-scale combustion chamber, data obtained on a specific ONERA experiment have been used. The set-up is illustrated on the Fig 3a. This facility is made of two independent flows, separated by a multi-perforated test sample.

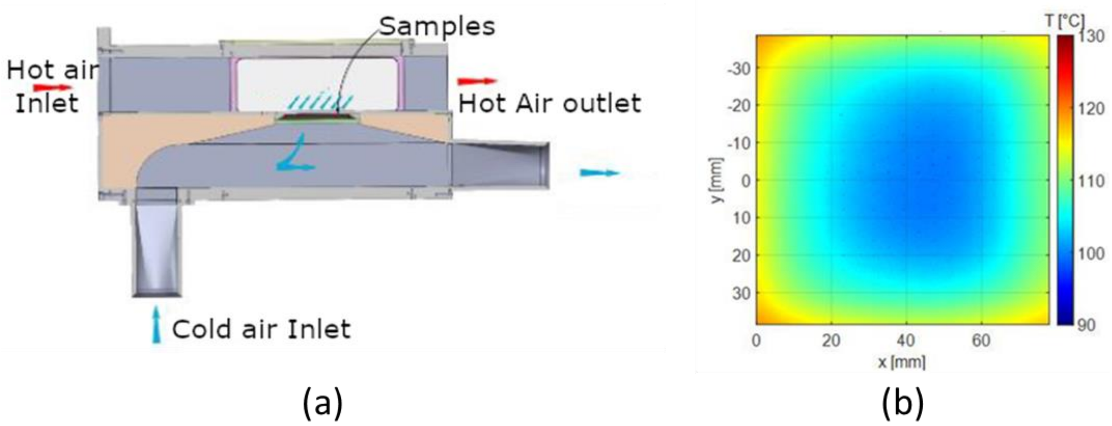


Fig 3. (a) Geometry of the multiperforated plate experiment, (b) Measured temperature field over the multi-perforated sample

The facility is instrumented via thermocouples and features larges optical accesses enabling infrared thermometry of the samples. In this study, a multi-perforated sample have been tested with a 400 K primary hot air flow cooled with a 318 K secondary air flow. The temperature field obtained on the sample thanks to thermography measurements is displayed on Fig 3b.

Reynolds-averaged Navier-Stokes (RANS) numerical simulations have been performed with CEDRE, within the framework of Menter's $k - \omega$ shear stress transport (SST) turbulence model [24]. The Reynolds fluxes of mass and energy deduced from the turbulent diffusivity approximation by introducing turbulent Schmidt and Prandtl numbers, which are set to a conventional value of 0.9 [25]. The boundaries of the sample are modeled as a multiperforated boundary, where the properties of the material are used to compute the heat and mass exchanges between the two sides of the plate.

As it can be seen on the temperature field, the thermal boundaries of the sample play a significant role on the temperature distribution. In order to refine the simulation, in a second step, heat conduction has been computed within the sample, neglecting the holes, thanks to the ACACIA solver of CEDRE.

As can be observed in Fig 4, this modeling strategy manage to reproduce both the temperature contour shape and level.

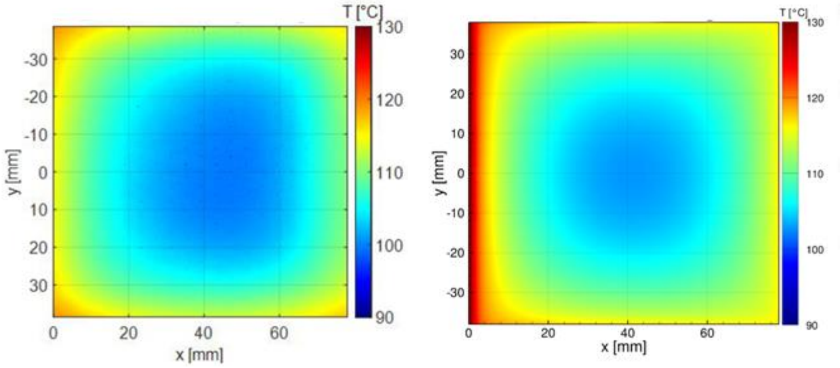


Fig 4. Comparison of the wall temperature measured in the experiments (left) and computed values (right).

3. C/SiC Technologies: Overview, production and performance

3.1. Material Overview

Ceramic matrix composites (CMC) reinforce a brittle ceramic with strong fibers and interfacial layers, yielding materials that retain high strength and toughness at temperatures far above metal limits. Carbon Fiber-Reinforced Silicon (C/SiC) CMCs specifically consist of carbon fiber tows embedded in a silicon-carbide matrix. Compared to more established C/C (carbon-carbon) composites, C/SiC can operate at higher temperatures in oxidizing environments (thanks to the SiC matrix forming a protective silica scale), yet is lighter and often less expensive than SiC/SiC (all-SiC) composites. Key advantages of C/SiC include high specific strength and stiffness combined with high fracture toughness, owing to the fiber-reinforced microstructure. These properties make C/SiC promising for extremely hot gas environments demanding materials that can survive with or without active cooling or excessive insulation.

Microstructure of C/SiC:

A typical C/SiC uses 2D woven or 3D braided carbon fiber preforms with a thin carbon-rich interphase around each fiber bundle to deflect cracks. After forming the fiber preform, ceramic matrix infiltration creates the SiC matrix.

Properties:

- C/SiC inherits ceramic-high stiffness and melting point from SiC, and low density plus damage tolerance from carbon fibers.
- Specific strength (strength per weight) remains high at elevated temperature (e.g. >1000°C) compared to metal alloys.
- Its thermal conductivity is moderate (~5–25 W/m·K, between that of graphitized C/C and SiC/SiC), which helps spread heat loads and reduce thermal gradients.
- Coefficients of thermal expansion (CTE) are intermediate ($\sim 2\text{–}4\times10^{-6}$ /K) and matched (fiber vs matrix) enough to limit microcracking.
- Toughness is much higher than monolithic SiC – the fiber pull-out mechanism allows plastic-like behavior under thermal shock or impact.
- However, the SiC matrix will oxidize in air; in practice a thin oxide scale forms, which initially protects the SiC surface by sacrificial melting and evaporation of SiO_2. (This "passive oxidation" limits temperature; above ~1600°C the SiO_2 may evaporate rapidly.) If needed, environmental barrier coatings or sacrificial coatings can extend oxidation life.

Comparison to C/C:

Carbon/carbon (C/C) composites, which use carbon fibers in a carbon matrix, exhibit the highest melting point, reaching up to 3600°C for graphite, and can endure higher peak temperatures in inert conditions.

However, in non-inert conditions, they are susceptible to oxidation, which can limit their use in certain high-temperature environments.

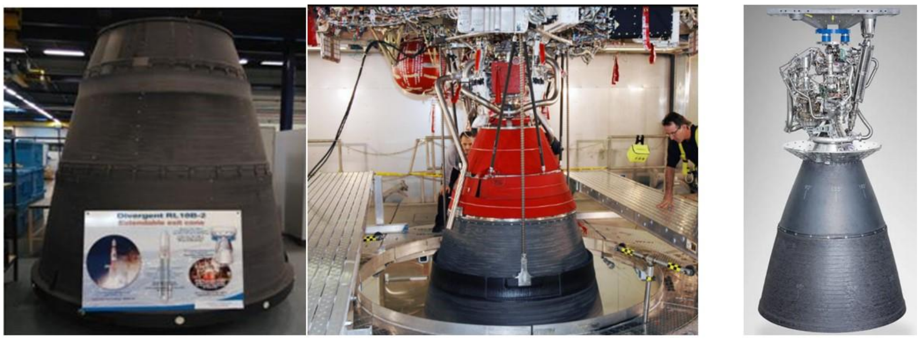
C/SiC composites, which combine carbon fibers with a SiC matrix, provide a balanced solution. The C/SiC material, with its SiC matrix, is inherently oxidation-resistant (forming SiO_2) and can withstand repeated exposures to temperatures ranging from 1400 to 1600°C in hot oxidizing gas environments.

3.2. C/SiC for High-Performance Aerospace Applications at ArianeGroup

The primary propulsion use of C/SiC is in nozzle and chamber components exposed to combustion gases. The advantages are clear: C/SiC nozzles can operate at higher hot-gas temperatures without active cooling, enabling higher expansion ratios or chamber pressures. For example, replacing a steel tube with C/SiC could eliminate cooling channels and reduce weight.

In practice, liquid engines use C/SiC mainly in extensions and divergent cones where temperatures peak. Throat reinforcements or liners can also employ C/SiC to raise the maximum chamber temperature. Research is underway on combining C/SiC with ultra-high-temperature ceramic (e.g. HfC, ZrC) in the matrix for even higher heat fluxes.

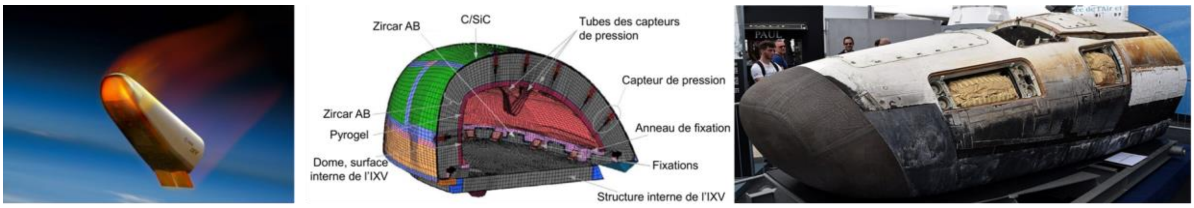
ArianeGroup contributes to the carbon-carbon (PAN-based) nozzle extension for NASA’s RL10 engine on the Interim Cryogenic Propulsion Stage (ICPS) of Artemis (see Fig 5a). In Europe, ArianeGroup development of next-generation reusable boosters (Themis, Maia) includes studies of C/SiC and UHTCMCs for combustion chambers.



(a) RL10 (b) VINCI

Fig 5. Illustrations of two CMC-based nozzles: (a) the RL10 engine, (b) the VINCI engine.

C/SiC is also attractive for hypersonic vehicle leading edges and nosecones, which see both aerodynamic heating and plasma. C/C has traditionally been used but may requires oxidation protection. C/SiC’s built-in oxide layer provides passive protection at moderate Mach numbers. The French V-MAX hypersonic glider (ArianeGroup, DGA) and ESA’s IXV spaceplane [26;27] both employ ArianeGroup advanced TPS – C/C or C/SiC panels or tiles. The C/SiC material’s toughness and consistent ablation behavior (compared to C/C ceramic or carbon phenolics) is an advantage for flight-by-flight reusability.



(a) Artist view of the IXV (b) Nose assembly (c) Post-flight view of the experimental vehicle

Fig 6. Experimental IXV vehicle: (a) artist view, (b) nose assembly and (c) post-flight view of the experimental vehicle.

C/SiC composites are employed in critical rocket propulsion applications where minimizing ablation is essential. For instance, in Divert and Attitude Control Systems (DACS) for kill vehicles (see Fig 7), where low ablation is crucial for maintaining precision and reliability. Another notable application is Thrust Vector Control (TVC) like jet vanes, where the reduction of ablation enhances the system's performance and longevity under extreme operational conditions.

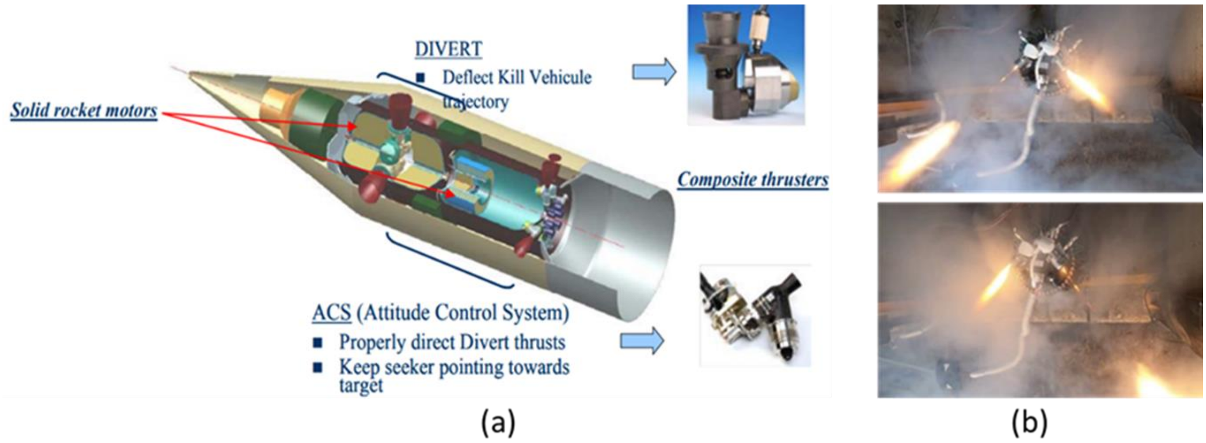


Fig 7. (a) Kill Vehicule and example of DACS integration, (b) views of a long duration duty cycle with proportional EMA (high frequency actuation)

C/SiC's benefits are also being applied to airbreathing engines such as M88 exhaust panels or ramjet/scramjet chamber and injector.

Fig 8. Illustration of a CMC-based exhaust panel (a) of the M88 engine (b).

3.3. Chemical Vapor Infiltration (CVI) Route for C/SiC Production

One of the most mature processes for producing high-quality C/SiC composites is chemical vapor infiltration (CVI), which allows the formation of dense, uniform SiC matrices with controlled porosity. This process is sketched on Fig 9.

Carbon Fibers Preform Fabrication

The process begins with the fabrication of a carbon fiber preform, which may be 2D woven laminates or 3D needled architectures. Three-dimensional (3D) needling enhances through-thickness strength and damage tolerance, while also enabling the production of complex-shaped preforms such as curved nozzle extensions, complexes combustion chamber or thruster body.

PyC Interface Infiltration

The first infiltration step deposits a thin layer of pyrolytic carbon (PyC) onto the fibers, via CVI at intermediate temperatures, to serve as a compliant interphase that promotes crack deflection and fiber pullout. After the initial PyC deposition, the preform is subjected to machining to lower the characteristic length scale for SiC gaseous precursors diffusion. Control of this interphase is critical: too thick and fibers debond too easily; too thin and cracks cut through fibers.

Matrix Infiltration

The preform is then infiltrated with silicon carbide using gaseous precursors in a hot-wall CVI furnace under low pressure and high temperature. This step deposits SiC within the pore network of the preform, gradually densifying the material. Because CVI is diffusion-limited, a single cycle rarely achieves full density; instead, the process alternates between SiC deposition and intermediate machining to relieve surface densification and reopen access paths for gas penetration.

Quality and oxidation resistance

Throughout the CVI process, stringent quality control is required. Process control is especially critical since CVI is highly sensitive to parameters such as gas flow distribution, furnace temperature uniformity, and precursor composition. These quality controls allow achieving fiber protection against oxidation. In fact, any open pore network that connects the surface to the carbon fibers constitutes a critical risk in service, since high-temperature oxidizing gases can directly consume the carbon. Therefore, the CVI process is tailored to (1) minimize interconnected porosity, (2) ensure high uniformity of matrix infiltration around fiber bundles, and (3) deliberately leave a continuous outer "sealcoat" of pure SiC on the final machined surface. This sealcoat acts as the first barrier against oxidizing exhaust gases, forming a protective silica (SiO_2) scale in service and preventing oxygen ingress. Final finishing operations must therefore balance dimensional precision with maintaining sufficient sealcoat thickness.

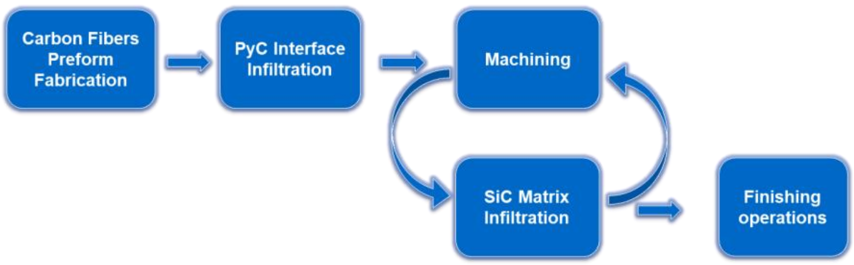


Fig 9. Schematic of C/SiC production via CVI

3.4. Performance and Testing

The development of C/SiC materials for aerospace applications follow a structured progression:

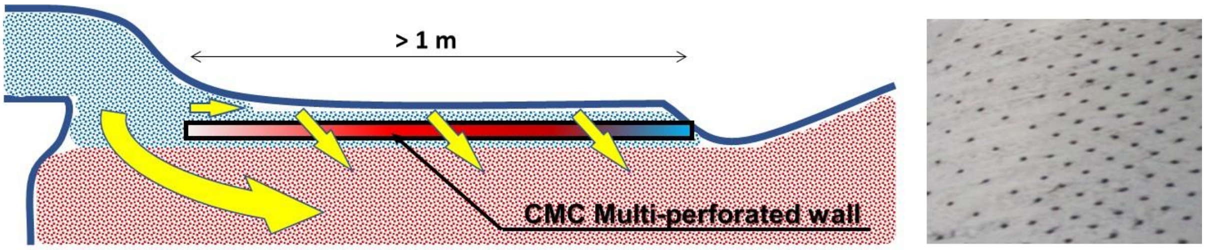
- Starting with laboratory-scale testing to assess fundamental properties and behavior through small-scale mechanical and thermal tests. This initial phase establishes baseline material properties and identifies potential issues or areas for improvement.
- The next stage involves technological representative testing, where the material's performance is evaluated under specific conditions, such as oxidation and porosity, through samples that validate material performance on specific conditions and refine manufacturing processes.
- Following this, the scale-up to reduced scale focuses on assessing manufacturability, producing reduced-scale components, and performing sub-scale tests to validate material performance on specific conditions and identify scale-up issues.
- Finally, full-scale implementation involves producing full-scale components using validated manufacturing processes and performing comprehensive tests to validate the representative parts (materials and design). This final stage, corresponding to Technology Readiness Levels 5 to 6 (TRL5 – TRL6), ensures the material's suitability and the component's reliability for the intended application.

C/SiC materials are among those whose performance is highly dependent on the specific application. Therefore, the complete validation of all criteria that the material must meet is only possible through fully representative hot-fire tests. Consequently, ArianeGroup has developed substantial means to conduct these full-scale tests, such as plasma torch facilities for atmospheric re-entry applications and specialized test stands for liquid propellant engines.

ONERA possesses and continues to develop multi-scale and multi-physics testing capabilities to support the maturation of C/SiC materials. In particular, the ONERA Palaiseau facilities feature test rigs that are highly representative in terms of flow rate, pressure, and power. Among other applications, these facilities allow testing airbreathing engines and combustion chambers made of C/SiC for high-performance applications.

4. Engine fabrication and tests

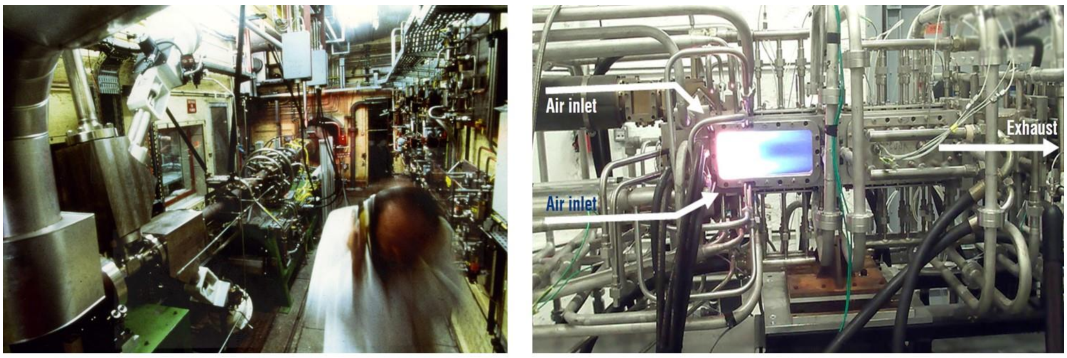
Thanks to the aforementioned state-of-the-art tools and materials, a new ramjet engine, protected by effusion-cooling, has been defined, built, and tested. This engine was constructed based on the principle schematic in Fig 10a. The assembly of C/SiC parts, that makes the core of the combustor, exceeds 1 meter long. A detailed view of a perforated C/SiC part is displayed on the Fig 10b. The composite parts were made and assembled in ArianeGroup factories, then brought to ONERA facilities in Palaiseau.



(a) (b)

Fig 10. (a) Principle of the engine. (b) Detailed view of a portion of a multiperforated C/SiC part.

Direct-connected tests have been performed on the ramjet test rigs at ONERA Palaiseau. These facilities (see Fig 11) are routinely used to perform high-speed airbreathing combustor tests in supersonic and hypersonic flight-like conditions, between Mach 2 and Mach 7.5 [28]. In these facilities, typical air stagnation temperature levels range from 600 K to 2400 K and air mass flow rates levels from roughly 1 $kg.s^{-1}$ to 40 $kg.s^{-1}$. Pre-burners, mainly fueled with hydrogen, are used to increase the incoming air temperature. Gaseous as well as liquid fuels may be used during these tests. An air ejector may be used for some tests for high-altitude simulation. A typical direct-connected test rig, with its different stages, is displayed on Fig 12.



(a) (b)

Fig 11. Illustrations of the ONERA test rigs at Palaiseau: (a) the ATD5 test cell dedicated to direct-connected tests in high-Mach flight conditions, (b) test of a typical subsonic combustion ramjet engine in the ATD8 test cell.

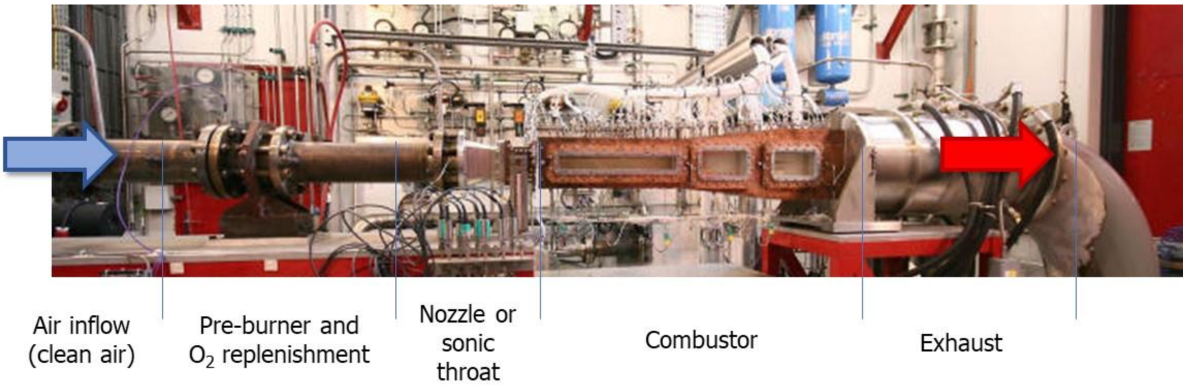


Fig 12. The different stages of a typical direct-connected test rig used for ramjet combustor studies at ONERA Palaiseau.

Regarding the tests on the new engine, a hydrogen-fueled air pre-heater, with oxygen replenishment, has been used to increase the upcoming air temperature. Various air mass flow rates and stagnation temperatures have been implemented during the test campaign. Nonetheless, the maximum stagnation temperature has been limited by the maximum allowable temperature for the metallic parts of the test rig used during this campaign, roughly 1100 K, which corresponds to a flight Mach number ranging between 4 and 5. Downstream the combustor, an air ejector was used to lower the downstream pressure. A liquid hydrocarbon fuel was used for the engine.

Pressure taps and thermocouples have been integrated all along the combustor. The evolution of the temperature on the C/SiC parts was monitored thanks to dedicated thermocouples. Unfortunately, the harnessing of these thermocouples proved to be difficult: some of them were detached during the tests.

Each test lasted several dozens of second once the engine was ignited, to reach the stationary thermal state of the combustor walls. For all the conditions that have been tested, the maximum allowable temperature for the TPS walls has never been reached, demonstrating that, for those conditions, the system performs as effectively as designed. The dimensionless temperature evolutions recorded by the various thermocouples positioned on the C/SiC walls for a Mach > 4 flight-like condition is shown in Fig 13. Values predicted by CFD calculations once the thermal state has been reached, as well as the maximum dimensionless allowable temperature for the TPS walls are also displayed on Fig 13. The measured temperatures remain below the maximum allowable values, and the numerical predictions are fully consistent with the experimentally observed data. One can also note that, for this test case, a significant margin exists with respect to the allowable limit.

After each test run, the engine was carefully checked, to confirm its continuous and trouble-free operation. Up to now, the engine accumulated more than 1000 seconds of total ignited run time. After several ignitions and blow-off cycles, the combustion chamber shows no signs of damage and can still be used for other exploratory test campaigns, particularly to further investigate its operational limits.

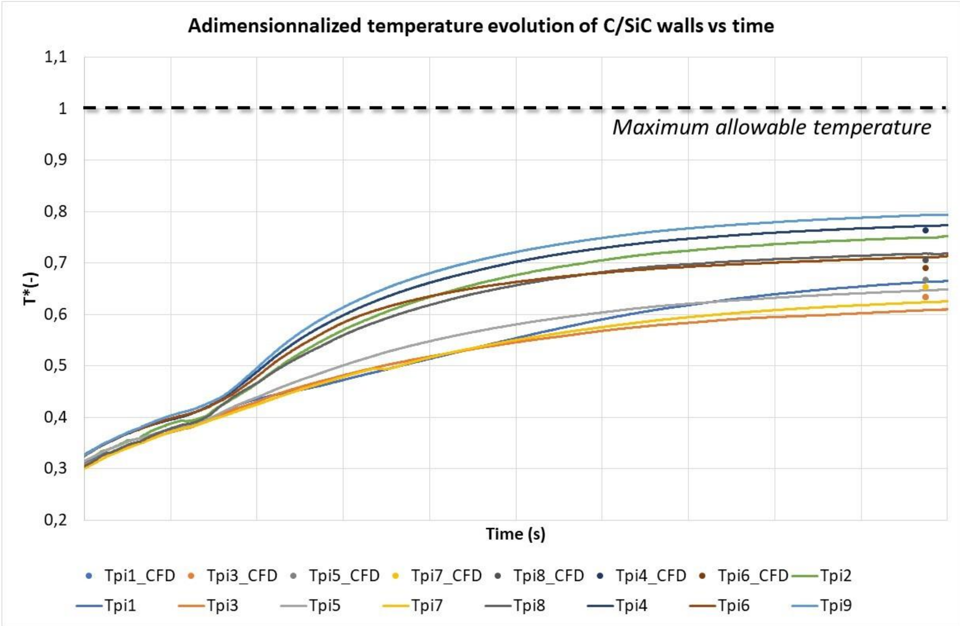


Fig 13. Dimensionless temperature T* evolutions on the C/SiC part during the tests compared with the CFD predicted values.

5. Conclusions

An actively-cooled combustor has been recently designed and tested. Although the effusion-cooling technique used for the TPS is not novel, state-of-the-art tools and materials have been used to assess the possible expansion of the concept's potential.

The CFD code and the materials that have been used to build the engine have been described in this article. Tests have been performed in various supersonic flight-like conditions. Even if the results are still under analysis, the tests have shown that the engine and the TPS performed as effectively as designed.

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