HiSST: 2nd International Conference on High-Speed Vehicle Science Technology

11–15 September 2022, Bruges, Belgium

Design of the Transpiration Cooled Fin Experiment FinEx II on HIFLIER1

Giuseppe D. Di Martino[1], Hannah Böhrk[2], Schäfer Joelle[3], Clemens Müller[4], Jonas Peichl[5], Fabian Hufgard[6], Christian Dürnhofer[7], Stefan Löhle[8]

Abstract

For hypersonic flight vehicles, sharp leading edges are integral part of the structure, such as air intakes, wing leading edges and stabilizer fins. However, due to the short standoff distance of the forming shock waves during hypersonic flight, these structures typically face severe thermal loads. In the present paper, transpiration cooling in combination with the application of ceramic matrix composites structures is investigated as a possible approach for novel hypersonic flight thermal protection for sharp leading edges. For this purpose, in the framework of the HIFLiER 1 flight research experiment, the DLR Institute of Structures and Design, in collaboration with the Institute of Space Systems of the University of Stuttgart, is responsible for the design and construction of an experimental module of the sounding rocket. The module will house four fins, whose leading edge is made of an inhouse-developed porous C/C-SiC material, which would allow the transpiration cooling application.

Keywords: *Transpiration Cooling, Ceramic Matrix Composites, Thermal Protection System, Hypersonic Flight*

1. Introduction

The development of hypersonic flight vehicles presents important challenges for what concerns the thermal protection of the external structures, which are exposed to the aerodynamic flow and the corresponding harsh thermal loads due to the forming highly-energetic shock waves [1]. These thermal loads become even more critical in the cases of sharp edges, like for example for wing leading edges, stabilizer fins and air intakes [2].

Typically, these requirements lead to the application of lightweight ceramic matrix composites (CMC), such as carbon fibre reinforced silicon carbide (C/C-SiC), for thermal protection systems, as they are able to withstand high temperatures [3]. In this framework, the Institute of Structure and Design of the German Aerospace Centre (DLR-BT) has played a fundamental role in the recent years for the

[1] *Research scientist, DLR Institute of Structures and Design, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, Giuseppe.DiMartino@dlr.de*

[2] *Duale Hochschule Baden-Württemberg Stuttgart, Jaegerstrasse 58, 70174 Stuttgart, Germany, previously: DLR Institute of Structures and Design, hannah.boehrk@dhbw-stuttgart.de*

[3] *Student research assistant, DLR Institute of Structures and Design, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, Joelle.Schaefer@dlr.de*

[4] *M.Sc. Student, DLR Institute of Structures and Design, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, Clemens.Mueller@dlr.de*

[5] *Research scientist, DLR Institute of Structures and Design, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, Jonas.Peichl@dlr.de*

[6] *PhD student, High Enthalpy Flow Diagnostics Group (HEFDiG), Institute of Space Systems, Pfaffenwaldring 29, 70569 Stuttgart, Germany, hufgard@irs.uni-stuttgart.de*

[7] *PhD student, High Enthalpy Flow Diagnostics Group (HEFDiG), Institute of Space Systems, Pfaffenwaldring 29, 70569 Stuttgart, Germany, cduernhofer@irs.uni-stuttgart.de*

[8] *Research scientist, Group leader HEFDiG, Institute of Space Systems, Pfaffenwaldring 29, 70569 Stuttgart, Germany, loehle@irs.uni-stuttgart.de*

development of such materials [4], the full characterization and the integration and validation as thermal protection systems (TPS) in sounding rocket flight experiments, e.g. in SHEFEX I and II [5, 6], in KERAMIK on FOTON-M2 [7], and most recently in STORT [8, 9]. Among them, the FinEx experiment on the HiFire-5 flight experiment [10] allowed to successfully demonstrate the use of C/C-SiC material for stabilizer fin structures.

However, with increasing thermal loads, the active cooling of the structure could become necessary. Among the different techniques, the principle of transpiration cooling, schematically represented in Fig. 1, consists in forcing a coolant through a porous structure, creating an internal cooling effect by exchanging heat between the solid structure and the fluid. Furthermore, the exiting coolant mixes with the boundary layer and forms a protective cooling film, decreasing the incoming heat flux onto the wall. The high effectivity of this cooling method could be shown by e.g. Eckert and Livingood [11], and represents a highly efficient cooling method especially for thermally high loaded structures [12, 13]. However, due to the lack of suitable permeable materials, it saw so far only limited application.

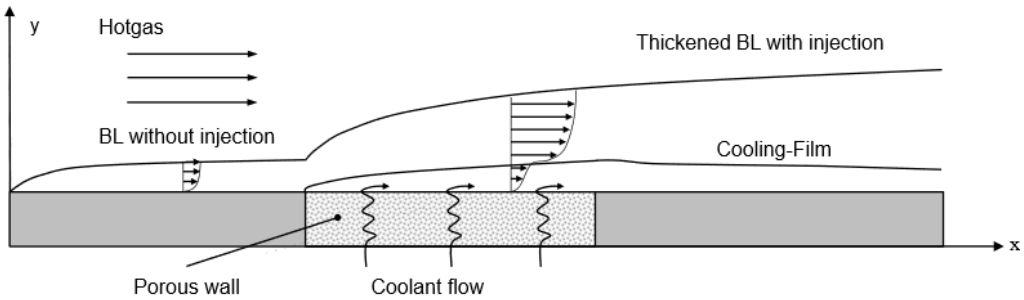


Fig. 1. Schematic description of transpiration cooling

As a possible approach for the application of the transpiration cooling technology on thermally high loaded structures for hypersonic flight, in combination with the application of CMC structures, the so-called OCTRA (Optimized Ceramic for Hypersonic Application with Transpiration Cooling) material was developed at the DLR-BT [14], which consists in a variant of the C/C-SiC CMC material with a specifically designed porosity level.

In order to verify the application of the abovementioned technologies to leading edges applications in real hypersonic flight conditions, the DLR-BT, in collaboration with the Institute of Space Systems (IRS) of the University of Stuttgart, is working to the design and construction of an experimental module (so called FinEx II) in the framework of the Hypersonic International Flight Research Experimentation (HIFLIER1), a project for a flight experiment coordinated by the US Air Force Research Laboratory (AFRL) and operated by DLR's Mobile Rocket Base (MORABA). An overview of the experiment and the design of the rocket module and the fins is presented in the present paper.

2. Material for transpiration cooling application: OCTRA40

As mentioned, the DLR-BT has developed during the years a strong expertise in the manufacturing of CMC materials suitable for high temperature applications. In particular, a special focus was dedicated to the manufacturing of high-quality C/C-SiC with the Liquid Silicon Infiltration (LSI) method [15], which involves the following steps.

- Manufacturing of the initial part made of carbon fibre reinforced polymer (CFRP).
- Pyrolysis process through which the matrix is carbonized and the part passes to the C/C status.
- In-situ joining of different parts in C/C-state for obtaining complex geometries and/or thicker components. In particular, the in-situ joining is an inhouse-developed technique [16] consisting of fixing together two different components when they are still in the porous C/C status (i.e. after pyrolysis and before siliconization) using a carbonaceous paste to enrich the gaps of the parts.
- Liquid silicon infiltration to create the C/C-SiC final component. In case of in-situ joining of parts, during this step, the low amount of paste pyrolyzes, while the capillary effect combined with the low viscosity of the molten silicon ensures a quick filling of the composite and the joint area.

The classical C/C-SiC materials, however, cannot be used for transpiration cooling, as they are practically impermeable [15]. For this reason, the recent developments were focused on the modification of the above described LSI process for the manufacturing of a variant of the C/C-SiC material with defined permeabilities, as described by Dittert et al. [14]. For this purpose, in the first step of the process, a defined portion of the carbon fibres within the baseline composite material is replaced with thermally non-stable aramid fibres. The fibres are degrading in the pyrolysis process step, leading to defined cavities inside the material, which cannot be completely filled in the final infiltration of liquid silicon. This allows for adjustable porosities in a range between 1% and 30% for the OCTRA material.

The material variant used in the upcoming study is OCTRA40, which is obtained using an aramid fibre ratio of approximately 40% in the first step, leading to a final open porosity of approximately 30%. Fig. 2 shows the microscopic structure of OCTRA40.

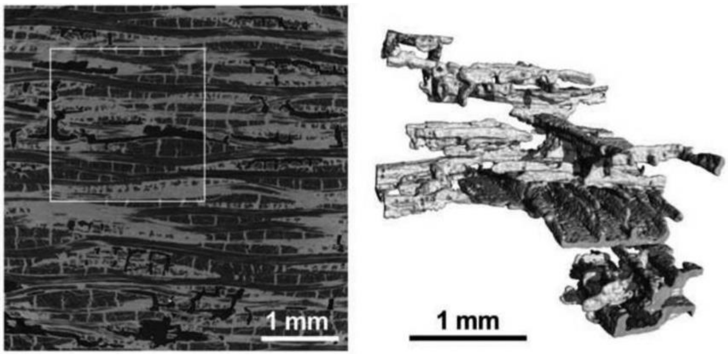


Fig. 2. X-ray CT image of OCTRA 40 [14]

The applicability of the OCTRA material for sharp leading edges of re-entry vehicles was successfully demonstrated by Dittert et al. [17]. A wedge-shaped specimen was exposed to a high enthalpy air plasma flow in an arc jet wind tunnel at IRS, showing that high cooling efficiencies could be achieved even at low coolant mass flow rates. In the present project, the aim is to validate the technology in real hypersonic flight conditions.

2.1. OCTRA40 material characterization

Since the OCTRA40 material is still in the development phase, it presents still some issues in terms of properties repeatability and some differences, although limited, can be still detected among different material batches. For this reason, a preliminary work was carried out for the characterization of the material main properties for the plate used in the manufacturing of the fins, which will be employed in the flight experiment [18].

For the target application, a fundamental role is obviously played by the coefficients representing the permeability of the material. In particular, the pressure loss of a fluid flowing through a porous material can be characterized through the Darcy-Forchheimer equation, which is formulated by Innocentini et al. [19] as

$$\frac{P_i^2 - P_o^2}{2P_o L} = \left(\frac{\mu}{K_D}\right) u_D + \left(\frac{\rho}{K_F}\right) u_D^2 \qquad (1)$$

The Darcy and Forchheimer coefficients K_D and K_F are material specific permeability coefficients. The values for the OCTRA40 material used for the upcoming experiments were determined at the AORTA (Advanced Outflow Research Facility for Transpiration Application) test bench [20] using representative cylindrical material samples with a diameter of 8 mm and a height of 12 mm. Steady state pressure measurements were conducted using different mass flow rates of nitrogen at ambient temperature to obtain the pressure loss-mass flow curve. K_D and K_F are then obtained by fitting Eq. (1) to the experimentally obtained curve using a "least squares" algorithm.

As the material is practically impermeable orthogonally to the fibre plies, the permeability coefficients were only determined in the direction parallel to the fibre plies. The resulting values for K_D and K_F are given in Table 1.

Table 1. Permeability coefficients for OCTRA40

Darcy coefficient K_D, m^2	1.62 x 10^{-12}
Forchheimer coefficient K_F, m	4.5 x 10^{-7}

The thermophysical properties of the OCTRA40 material at ambient temperature are given in Table 2, which were determined using a differential scanning calorimeter HotDisk TPS 3500. To account for the anisotropic structure of the material, the thermal conductivity was determined in the direction orthogonal to the fibre plies, as well as parallel to the fibre plies.

Table 2. Thermophysical Properties of OCTRA40

Specific heat c_p, J/(kgK)	710.6
Thermal conductivity orthogonal to the fibres $k_\perp$, W/(mK)	12.88
Thermal conductivity parallel to the fibres $k_\parallel$, W/(mK)	17.26

3. Design overview

The general design of the rocket module dedicated to the FinEx II experiment is shown in Fig. 3.

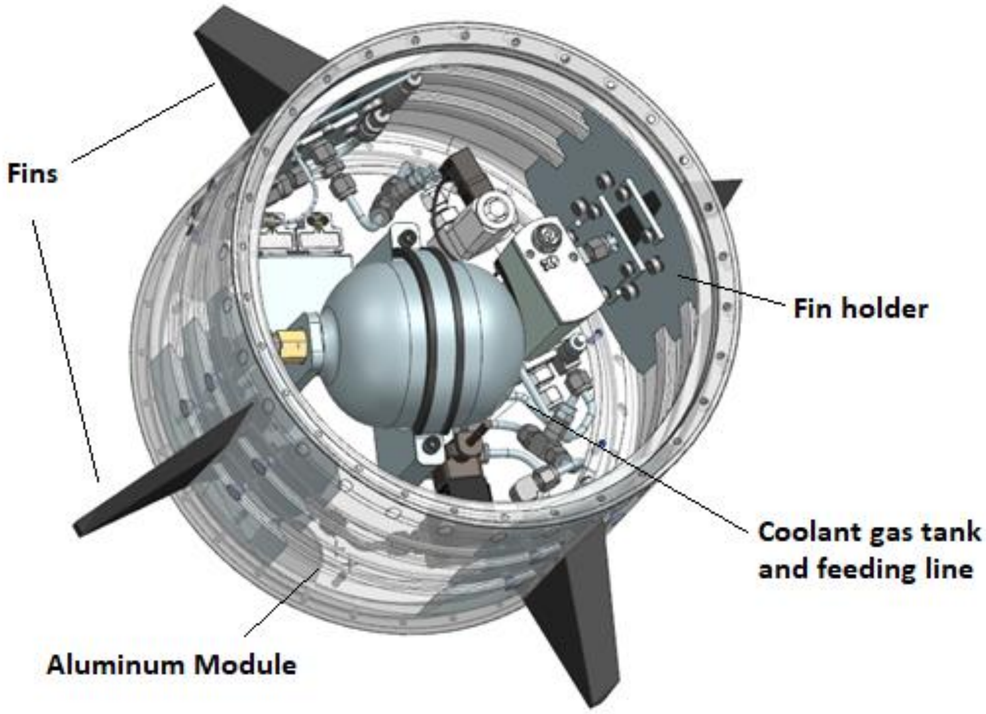


Fig. 3: FinEx II module overall design

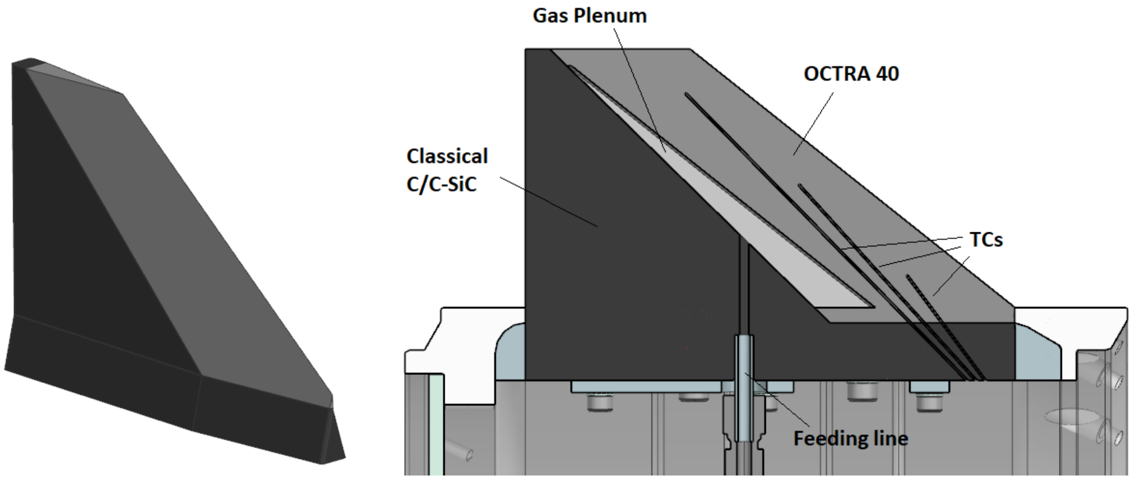
In particular, the module is equipped with four identical fins, of which one is not cooled as a reference while the other three are connected to the gas line which feeds the gaseous nitrogen for the transpiration cooling in different operating conditions, as described in Sec. 3.4.

In the following sections a detailed description of the design and manufacturing strategy of the fins and of the gas feeding line is presented. Further details can be found in [21].

3.1. Fin design

The fin design is shown in Fig. 4. The maximum height of the fin from the module external surface is around 86 mm, while the length is around 163 mm.

The fin is made of two different parts joined together. In fact, in order to concentrate the transpiration cooling in the region of the leading edge, which is expected to reach higher temperatures, only the forward part of the fin (displayed in light grey in Fig. 4) is made of the permeable OCTRA40 material, while the remaining part (in dark grey in Fig. 4) is made of classical impermeable C/C-SiC.



a) Fin isometric view **b) Cut view of the fin integrated in the module**

Fig. 4: Fin design

Inside the permeable leading edge, a plenum volume for the cooling gas is foreseen. The gaseous nitrogen is fed in the plenum through a hole in the C/C-SiC component in which a 6 mm stainless steel tube is soldered, which assure also the sealing at the operating pressure. Three holes are included in the OCTRA40 leading edge for the routing of type K thermocouples for temperature measurements. The position of the thermocouples was defined for optimizing the inverse estimation of the wall heat flux, according to the methodology described in Sec. 3.4.

Finally, Fig. 5 shows the fibre orientation chosen for the CMC material of the fin, which plays a fundamental role in the fin design for the present application, especially for the part made of OCTRA 40. In fact, considering the manufacturing process of the OCTRA material described in Sec. 2, it can be expected that the main orientation of the pores resulting in the material and consequently the main direction of the cooling flow will be the same as the chosen fibre orientation.

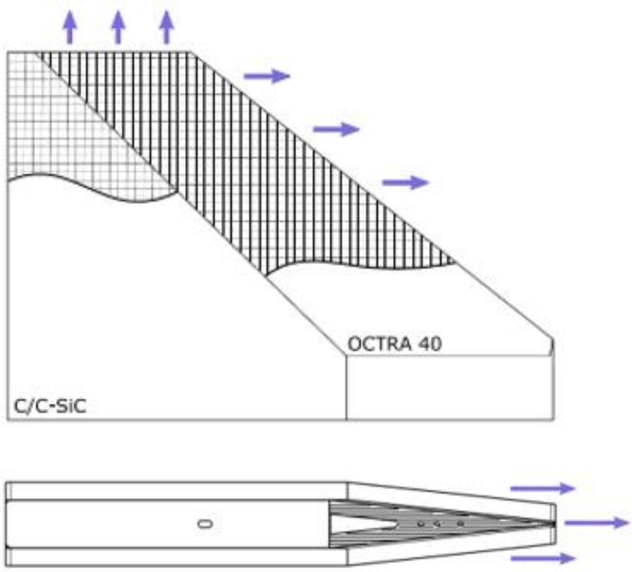


Fig. 5: Fin fibres orientation

3.2. CMC fins manufacturing process

As already mentioned, the CMC fins were manufactured with the LSI method generally described in Sec. 2.

In the present case, for the backward component of the fin a material plate is manufactured via hot pressing method and pyrolyzed to the C/C status. In parallel, for the porous leading edge a plate is manufactured also with the hot-pressing method but using fabric plies with carbon and aramid fibres, as also explained in Sec. 2. The pyrolysis of this plate generates the C/C plate with a higher porosity which is the basis material for the manufacturing of the OCTRA40 component.

The two plates in the C/C status are then cut according to the transversal profile of the fin, i.e. following the geometry shown in Fig. 4b for the two different part, and the plenum volume is milled in the leading edge part.

At this point the two individual parts are joined together, using a dedicated tool to allow the application of the needed pressure on the joining area and the correct relative alignment of the parts in the process, as shown in Fig. 6.

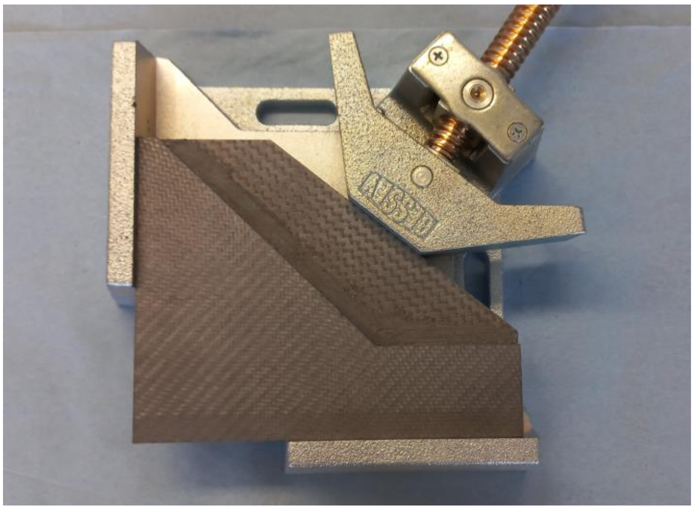


Fig. 6. Joining of OCTRA40 leading edge to the remaining classical C/C-SiC part

The obtained joined component is then siliconized, yielding the impermeable classical C/C-SiC for the back component, while the leading edge becomes OCTRA40.

The fin outer contour is finally milled, using diamond-based tools to machine the tenacious C/C-SiC material, and the holes for the gas feeding and for the thermocouples are obtained via electrical discharge machining (EDM). A picture of the final component is shown in Fig. 7.

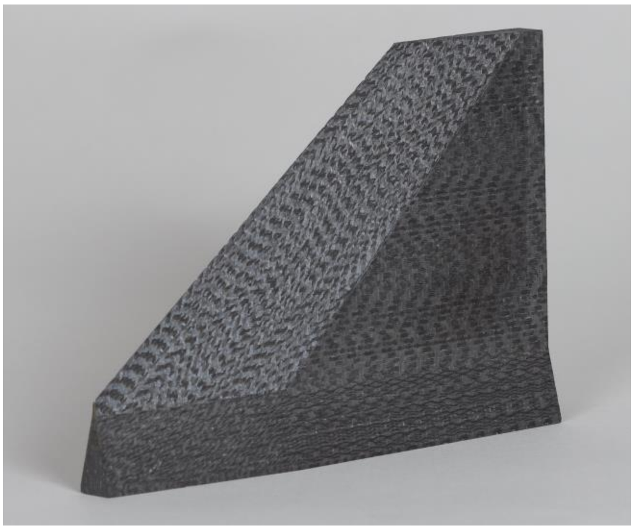
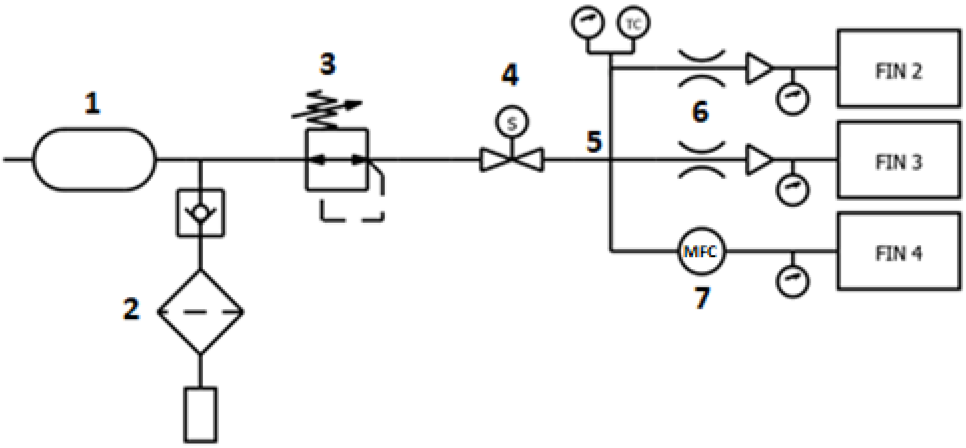


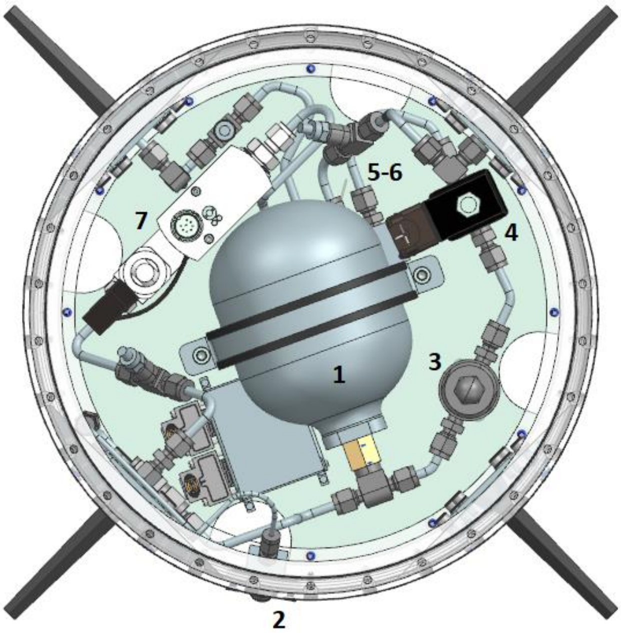
Fig. 7. Fin for FinEx II

3.3. Gas feeding system

Fig. 8a shows the schematic representation of the feeding line for the gaseous nitrogen employed as coolant gas, while Fig. 8b shows the corresponding parts in the 3D CAD model, as designed for the FinEx II experiment module.



a) Schematic representation



b) CAD model

Fig. 8. FinEx cooling gas feeding line

The gas is initially contained at an initial pressure of 240 bar in a small gas tank (ARMOTECH, 1), which has an internal volume of 800 ml. The filling of the tank is carried out before flight through the filling line (2), including a dedicated intake valve, a Swagelok® filter to avoid any contamination of the gas in the system and a check valve.

A pressure reducer (Swagelok®, 3) set to a specific position before flight reduces the gas pressure to the nominal total pressure defined for the transpiration cooling. The pressure reducer is followed by the solenoid valve (Bürkert 6013, 4), which is opened via an electric signal during the prescribed experiment windows.

After the solenoid valve the gas is split in three different lines through a dedicated component (5). At this point a combined pressure and temperature sensor (Kulite® HKL-T-312) is foreseen for measuring the gas total pressure and temperature.

For two lines a constant mass flow rate of the cooling gas is foreseen, which is obtained including along the line a Venturi nozzle (6) with a prescribed throat area operating in choked conditions (M=1 at the throat section). On the other side, a mass flow rate controller (Bronkhorst® IN-FLOW F-201AI, 7) is included in the remaining line, which is in turn connected to the electronics dedicated to control the mass flow rate of the cooling gas according to the aerothermal load acting on the corresponding fin, as it will be described in Sec. 3.4. All three lines include finally a combined pressure and temperature sensor, which essentially measures the pressure and temperature in the plenum inside the corresponding fin.

3.4. Transpiration cooling operating conditions and measurements techniques

As already mentioned, the FinEx module on the HIFLIER1 flight experiment will host four fins, each of them with different operating conditions.

A first fin is left uncooled to have reference data for assessing the effect of the transpiration cooling on the other fins.

As also anticipated in the previous section, the other three fins are connected to the gas feeding line for the transpiration cooling with different mass flow rate operating conditions, as summarized in Table 3. For all the cooled fins, the coolant mass flow will be activated in two different time windows during the flight, with a duration of 40 s each, when hypersonic conditions (with Mach numbers up to 6) are reached during the ascent and during the descent phases.

Table 3. Transpiration cooling operating mass flow rates for the different fins

Fin 1	Fin 2	Fin 3	Fin 4
No cooling	1.0 g/s	0.5 g/s	CATS method [24]

For the fins 2 and 3 a traditional approach is implemented with a constant mass flow rate of the coolant gas. The value of the mass flow rate for the fin 2 was defined based on the experience gained in the previous project SHEFEX II [6], while for the fin 3 half the value is considered to have an intermediate condition between the first two fins and to verify if the transpiration cooling is still sufficiently effective saving at the same time coolant gas mass.

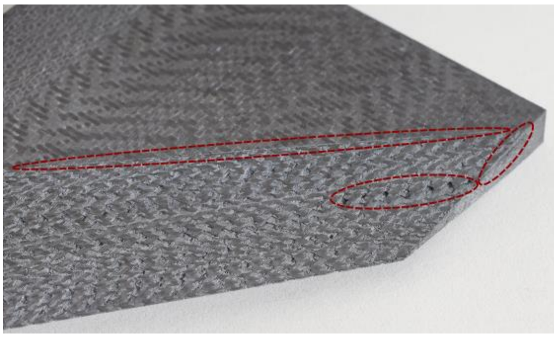
For the last fin a new approach is considered in which the mass flow rate of the cooling gas is adjusted in real time according to the instantaneous actual thermal load, in order to optimize the consumption of the coolant gas respect to the target maximum heat flux and minimize at the same time the countereffects of injecting a gas mass flow in an external boundary layer, which could result in increased drag and more turbulence in the wake. For this purpose, the Cooling Adjustment for Transpiration Systems (CATS) method, developed at the IRS, is implemented in which the heat flux at the transpiration cooled wall is determined in correlation to the real-time non-intrusive measurement of the pressure in the plenum, as investigated in previous studies [22, 23]. A detailed description of the CATS method and a first validation in a plasma wind tunnel is given in [24].

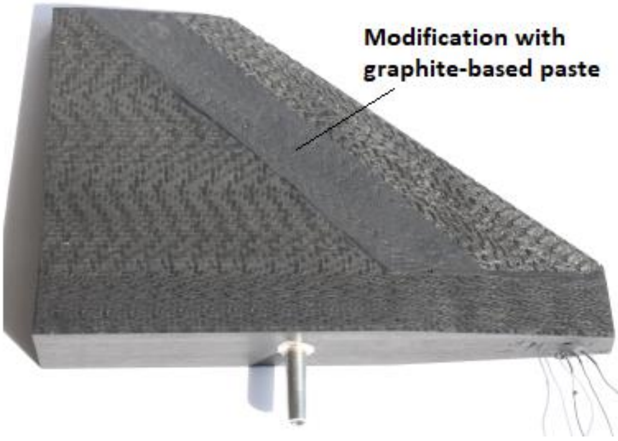
As shown in Fig. 4b, each fin is instrumented with three thermocouples which provide a first indication of the material thermal behaviour in the different operating conditions. Moreover, from the in-depth temperature measurements the effect of the transpiration cooling technology on the spatially resolved heat flux can be determined, applying the so-called Non-Integer System Identification (NISI) technique, defined and implemented at the IRS [25], for solving the inverse heat conduction problem. This approach connects a the surface heat flux and the in-depth temperature through a calibration procedure. During calibration, a known heat flux is applied by a diode laser and the temperature response is recorded. This calibration procedure allows the application to any material without any a-priori knowledge of thermophysical properties, except the absorptivity at the laser wave length, and of the sensor location.

4. Preliminary investigation in arc-jet facility

For a preliminary investigation and validation of the experiment concept, from the fin design to the application of the transpiration cooling technology and the estimation of the spatially resolved heat flux with the NISI technique, an experimental campaign was carried out in the plasma wind tunnel PWK4 facility at the IRS [18].

However, it is worth specifying that, the OCTRA40 material used for this first fin presented mild defects, yielding during the machining to a slight delamination in the left upper region of the fin, as shown in Fig. 9a. Since this would cause a higher outflow of the coolant gas in the delamination region, the fin was modified sealing part of the leading edge pores with a graphite-based paste, as shown in Fig. 9b.





a) Delamination in the OCTRA40 **b) Fin after modification with graphite-based paste**

Fig. 9. Fin for test in PWK

The fin in this configuration was anyway tested in the plasma flow, giving significant results. The setup of the test is shown in Fig. 10, while Table 4 summarizes the operating condition of the PWK facility during the experiments. Following an incremental logic, the fin was tested at two different distances from the inlet of the plasma flow, i.e. at $x = 385\ \mathrm{mm}$ and at $x = 235\ \mathrm{mm}$. At each position, the fin was tested in three operating conditions for the transpiration cooling, i.e. with a mass flow rate of the cooling gas of 0 (uncooled condition), 0.25 g/s and 0.5 g/s respectively. For each of the six resulting test conditions the fin was kept in the flow for 10 seconds. Fig. 11 shows a picture of the fin in the plasma flow at $x = 235\ \mathrm{mm}$.

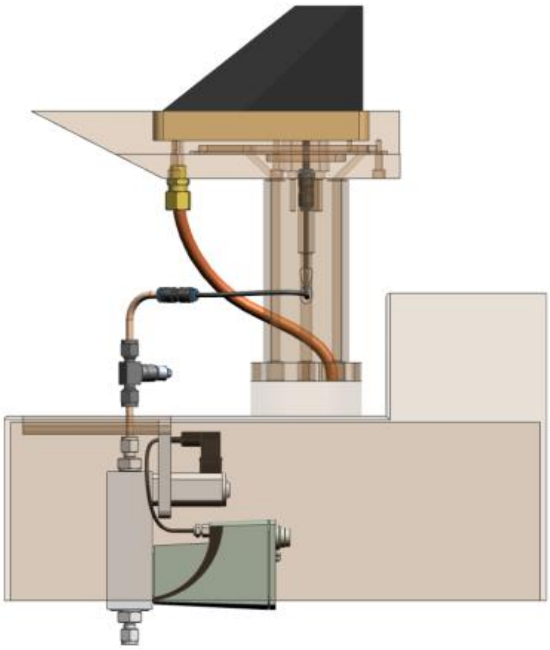


Fig. 10. PWK4 fin test setup

Table 4. Operating condition of PWK facility during the tests

Gas total mass flow rate, g/s	Current at the electric arc, A	Voltage at the electric arc, V	Test chamber pressure, Pa
6,5	600	93	35

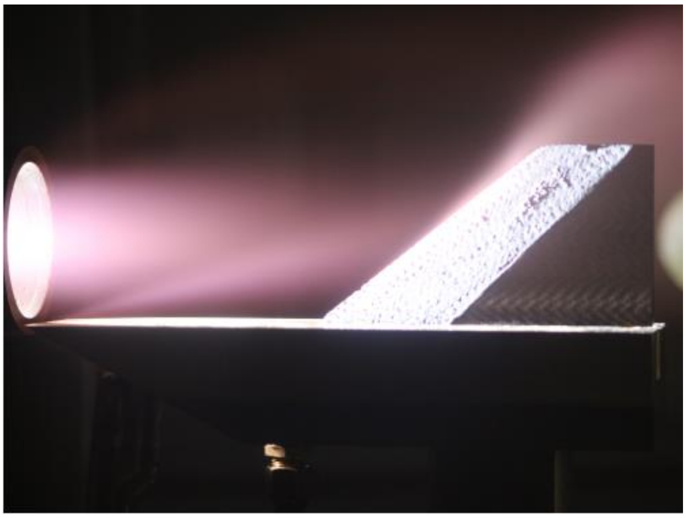
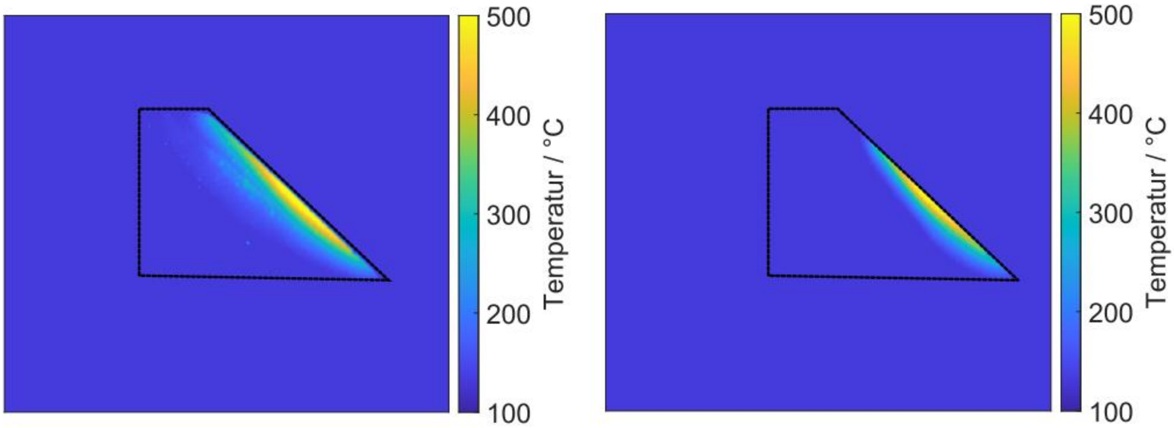


Fig. 11. Picture of the fin in the plasma flow at x=235 mm

An overview of the test results is reported in [18] and a further detailed description will be fully presented in a following paper. Here we just report as an example the comparison of the temperature distribution on the fin as detected by a thermographic camera, during the tests at $x = 235$ mm, in the case of no cooling and with transpiration cooling with 0.5 g/s of coolant, as shown in Fig. 12.



a) Uncooled **b) Coolant mass flow rate 0.5 g/s**

Fig. 12. Thermographic camera temperature distribution on the fin during tests at x=235 mm

In particular, it can be noticed that the case with transpiration cooling is characterized by generally lower temperatures. The only exception is given by the impingement of the shock wave generated at the holder, which can be also observed from Fig. 11, which causes relatively high temperatures in both cases. On the other side, also in this case the phenomenon affects a smaller region in the case with transpiration cooling. Moreover, this phenomenon is not expected to happen in flight.

5. Conclusions

in the framework of the HIFLIER1 flight experiment coordinated by the US Air Force Research Laboratory, the DLR-BT is developing, in collaboration with the IRS, a module of the sounding rocket for testing the application of the transpiration cooling technology to sharp edges in hypersonic flight conditions.

In particular, for this application the transpiration cooling technology is combined with the use of CMC materials thanks to a porous variant of the C/C-SiC material developed at the DLR-BT, named OCTRA40, which is employed for the leading edge of the test fins.

An overview of the design of the module, the fins and the coolant gas feeding line is given. In particular, the module is instrumented with four identical fins, of which one will remain uncooled as reference, while the other three will be transpiration cooled with different operating conditions. For one of the fins the CATS technique, developed at IRS, for an optimized control of the coolant mass flow rate according to the actual instantaneous thermal load will be implemented and tested. The effect of the transpiration cooling will be assessed by the in-depth measurements of the leading edge material temperature, which in turn will also be used for determining the spatially resolved heat flux acting on the surface by means of the so-called NISI method.

Finally, the preliminary activities for the validation of the experiment concept with tests in a plasma wind tunnel are described and some preliminary results are shown which proves the beneficial effect of the transpiration cooling.

Acknowledgments

The present work was carried out in the framework of the HIFLIER1 flight experiment project, primarily funded and coordinated by the US Air Force Research Laboratory (AFRL) und operated by DLR Mobile Rocket Base (MORABA).

References

1. Savino, R., Criscuolo, L., Di Martino, G.D., Mungiguerra, S.: Aero-thermo-chemical characterization of ultra-high-temperature ceramics for aerospace applications. J. Europ. Ceram. Soc. 38 (8), 2937-2953 (2018). https://doi.org/10.1016/j.jeurceramsoc.2017.12.043
2. Gülhan, A., Neeb, D., Thiele, T., Siebe, F.: Aerothermal Postflight Analysis of the Sharp Edge Flight Experiment-II. J. Spacecraft Rockets 53 (1), 153-177 (2016). https://doi.org/10.2514/1.A33275
3. Natali, M., Kenny, J.M., Torre, L.: Science and technology of polymeric ablative materials for thermal protection systems and propulsion devices: A review. Progress Mater. Sci. 84, 192-275 (2016). https://doi.org/10.1016/j.pmatsci.2016.08.003
4. Hald, H., Weihs, H.: Safety Aspects of CMC Materials and Hot Structures. Proceedings of Joint ESA-NASA Space-Flight Safety Conference, ESA SP-486 (2002).
5. Weihs, H., Longo, J., Gülhan, A.: Sharp Edge Flight Experiment SHEFEX. Fourth European Workshop on Thermal Protection Systems and Hot Structures Conference Proceedings, ESA SP-521 (2002).
6. Weihs, H., Longo, J., Turner, J.: The Sharp Edge Flight Experiment SHEFEX II, a Mission Overview and Status. 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, AIAA 2008-2542 (2008). https://doi.org/10.2514/6.2008-2542
7. Reimer, T.: The KERAMIK Thermal Protection System Experiment on the FOTON-M2 Mission. 5th European Workshop on Thermal Protection Systems and Hot Structures, ESA (2006).
8. Gülhan, A., Hargarten, D., Klingenberg, F., Siebe, F., Di Martino, G., Reimer, T.: Main Results of the Hypersonic Flight Experiment STORT. 2nd International Conference on High-Speed Vehicle Science Technology (2022).
9. Di Martino, G.D., Reimer, T., Dauth, L., Baier, L.: Structure Design of a Sounding Rocket Fairing with a Segmented Filament Winding-Ceramic Matrix Composite Thermal Protection System. 2nd International Conference on High-Speed Vehicle Science Technology (2022).
10. Böhrk, H., Löhle, S., Fuchs, U., Elsäßer, H., Weihs, H.: FinEx – Fin Experiment on HIFiRE-5. 7th Symposium on Aerothermodynamics for Space Vehicles (2011).

11. Eckert, E.R.G., Livingood, J.N.B.: Comparison of Effectiveness of Convection-, Transpiration- and Film-Cooling Methods with Air as coolant. Technical Note 3010. National Advisory Commitee for Aeronautics. 1953
12. Kays, W. M.: Heat transfer to the transpired turbulent boundary layer. Int. J. Heat and Mass Transf., 15 (5), 1023–1044 (1972). https://doi.org/10.1016/0017-9310(72)90237-2
13. Glass, D. E., Dilley, A. D., Kelly, H. N.: Numerical analysis of convection/transpiration cooling. J. Spacecrafts and Rockets, 38 (1), 15–20 (2001). https://doi.org/10.2514/2.3666
14. Dittert, C., Kütemeyer, M.: Octra - Optimized Ceramic for Hypersonic Application with Transpiration Cooling. Ceram. Transactions, 263, 389-399 (2017). https://doi.org/10.1002/9781119407270.ch37
15. Heidenreich, B.: C/SiC and C/C-SiC Composites. In: Bansal, N.P., Lamon, J. (eds.) Ceramic Matrix Composites: Materials, Modeling and Technology, pp. 147–216. Wiley-Blackwell, 2014.
16. Kochendorfer, R., Lutzenburger, N., Weihs, H.: Joining Techniques for Fibre Ceramic Structures. Adv. Composites Letters 13 (1) (2004). https://doi.org/10.1177/096369350401300106
17. Dittert, C., Böhrk, H., Löhle, S.: A Transpiration Cooled Wedge with adapted Permeability. 1st International Conference on High-Speed Vehicle Science Technology (2018).
18. Müller, C.: Investigation of the thermal behavior of a transpiration-cooled ceramic fin for HIFLIER1 with inverse heat conduction methods. Master's thesis, Institute of Space Systems, University of Stuttgart, IRS-22-S-035 (2022).
19. Innocentini, M.D.M., Nascimento L.A., Pandolfelli, V.C.: The pressure-decay technique for air permeability evalulation of dense refactory ceramics. Cerment and Concrete Research 34, 293-298 (2004). https://doi.org/10.1016/j.cemconres.2003.08.006
20. Selzer, M., Schweikert, S., Hald, H., Von Wolfersdorf, J.: Throughflow characteristics of C/C. In: Sonderforschungsbereich/Transregio 40 Annual Report (2014).
21. Schäfer, J.: Design of a Transpiration Cooled Flight Experiment on the Hypersonic Flight Mission HIFLIER1. Bachelor's thesis, Institute of Space Systems, University of Stuttgart, IRS-21-S-047 (2021).
22. Loehle, S., Schweikert, S., von Wolfersdorf, J.: Method for heat flux determination of a transpiration cooled wall from pressure data. J. of Thermophysics and Heat Transfer 30 (3), 567–572 (2016). https://doi.org/10.2514/1.T4815
23. Hufgard, F., Loehle, S., McGilvray, M., Hermann, T., Schweikert, S., von Wolfersdorf, J., Steelant, J., Fasoulas, S.: Plenum pressure behavior in transiently heat loaded transpiration cooling system. J. of Thermophysics and Heat Transfer 35 (2), 256–267 (2021). https://doi.org/10.2514/1.T6089
24. Hufgard, F., Dürnhofer, C., Loehle, S., Schweikert, S., Müller, C., Di Martino, G., Böhrk, H., Steelant, J., Fasoulas, S.: Adjusting Transpiration Cooling to Real Time Surface Heat Flux Estimation. 2nd International Conference on High-Speed Vehicle Science Technology (2022).
25. Dürnhofer, C., Hufgard, F., Fasoulas, S., Loehle, S.: Investigation of Spatially Resolved Heat Flux Determination from In-Depth Temperature Data. 2nd International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions & Engineering (FAR) (2022).