



Outflow characterization of a transpiration cooled fin

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Abstract

Transpiration cooling is a very promising active method for thermal management of critical components for hypersonic flight. On the other side, its efficiency is affected by the characteristic of the cooling gas outflow from the porous material. This paper presents a study on the outflow characteristics of a sharp-edged, transpiration cooled fin as flown as part of the FinEx experiment of the HIFLIER1 sounding rocket. The permeable ceramic matrix composite material used for the transpiration cooled leading edge shows in general a outflow pattern dominated by single jets, distributed relatively homogeneous over the surface, disrupted by significant strong jets induced by small inhomogeneities. The general strongly anisotropic outflow characteristics were also investigated. The findings of the outflow characterization led to valuable insights for the design of future sharp-edged transpiration cooled structures.

Keywords Transpiration cooling · Experimental methods · Thermal protection systems · Ceramic matrix composites

1 Introduction

The thermal protection of the external structures represents one of the most challenging requirements for the development of hypersonic flight vehicles, since they are exposed to the harsh thermal loads determined by the forming of highly energetic shock waves, especially at sharp-edged structures [1, 2]. Typically, these requirements lead to the application of lightweight ceramic matrix composites (CMC), such as carbon fiber-reinforced silicon carbide (C/C-SiC), for thermal protection systems (TPS), as they are able to withstand high temperatures [3]. In this framework, the Institute of Structures and Design of the German Aerospace Center (DLR-BT) has developed a unique expertise for the development of such materials, its full characterization as well as the integration and validation as a TPS for hyper-

sonic sounding rocket flight experiments, successfully flown for example in SHEFEX programs [4, 5] and most recently in STORT [6]. Moreover, the usage of this material for stabilizer fin structures could be successfully demonstrated in the FinEx experiment on the HiFire-5 flight experiment [7]. However, in order to overcome the load limits, in the cases in which the heat fluxes become even more critical, active cooling of the structure could become necessary, e.g., for flight at high Mach numbers or for longer flight duration. In this framework, one of the possibilities is represented by the usage of transpiration cooling, which works by feeding a coolant fluid through a porous wall into the hot gas region, with the double effect of directly cooling the wall itself and mixing into the boundary layer resulting in a lower convective heat flux on the structure [8, 9]. Such a technology showed first high potential for application in combustion chambers and gas turbines [10]. In the last 15 years, the interest on its application also for vehicle thermal management in hypersonic regime has been growing [11, 12]. In order to combine the application of CMC structures with the transpiration cooling technology, suitable CMC materials have to be used. For past fundamental investigations on transpiration cooling using CMC materials, Carbon fiber-reinforced Carbon (C/C) was used, e.g., in [13, 14], while other research groups focused on developing a new class of porous Ultra-high-Temperature Ceramic Matrix Composite (UHTCMC) materials [15, 16]. In this framework, the

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low oxidation resistance of C/C led at DLR-BT to the development of the so-called OCTRA (Optimized Ceramic for Transpiration Cooling Application) material [17], which consists in a variant of the C/C-SiC CMC material with defined porosity level designed specifically for transpiration cooling applications.

Such material has been already investigated in the past with ground testing, both for application on sharp leading-edge design [18] as well as for combustion chamber cooling [19]. Moreover, more recently, the application of the OCTRA material for sharp-edged structures under hypersonic conditions has been validated also in-flight through the so-called FinEx experimental module successfully flown on the HIFLIER (Hypersonic International Flight Research Experimentation) sounding rocket. In this case, a module of the rocket included four fins, whose sharp leading edge was made of the porous OCTRA material, with two of them being transpiration cooled and the two others acting as uncooled reference. For details on the design of the flight experiment and the respective results from the flight campaign, the authors refer to [20, 21].

While the flight experiment was of fundamental importance to test the technology under realistic operating conditions, for a deeper understanding of the involved phenomena, there is still the need to complement the flight data with characterizations in controlled laboratory environments. In particular, one question of interest is how the cooling gas outflow is distributed on the porous material and how this could affect the cooling efficiency. In fact, transpiration cooling relies on a relatively homogeneous outflow of the coolant, as inhomogeneities like pore blockages lead to hot spots, as shown, e.g., by Liu et al. [22]. These hot spots could potentially compromise the structural integrity of the thermal protection system. As the materials used for transpiration cooling are not perfectly homogeneous and real-world designs might have large blockages like fasteners and sensors integrated in the structure, the knowledge of the outflow pattern can serve as a boundary conditions for the prediction of the temperature of the transpirational cooled structure through computational fluid dynamics simulations [23]. König et al [24] found for the cooled wall temperature a good agreement between experimental data and numerical simulations when using a non-uniform mass flow boundary condition derived from outflow pattern measurements.

The characterization of the outflow distribution on porous components suitable for transpiration cooling has been carried out in past works mainly either on simple material probes with expectedly homogeneous outflow [24–26], or on components with simplified geometry [27, 28]. In the present work, the outflow characterization is done on the sharp-edged fin prototype as the one used on the FinEx transpiration cool-

ing experiment on the HIFLIER sounding rocket. In this case, specific design choices needed to be done corresponding to the challenges of the use case, which led to a complex geometry and suitable material choices. In particular, the design objective was to obtain a cooling gas outflow parallel to the nominal flow direction, on the contrary of other applications in which an outflow perpendicular to the component surface is desired, and to concentrate the cooling on the leading-edge area, where the highest aerothermal loads are expected. On the other side, geometrical and manufacturing constraints had to be taken into consideration. For these reasons, the activities presented in the paper represent a unique example on the correlation of specific application-oriented design choices to the actual resulting outflow.

For the characterization of the outflow pattern, several methodologies can be used. For example, miniature-hot wire anemometry can be employed to characterize the outflow pattern of transpiration cooled samples, in order to determine the local outflow velocity [25, 27]. In particular, this technique offers a higher sensitivity and negligible interference yielding consequently highly accurate results. On the other hand, the space resolution is limited in this case by the wire length (typically 1–2 mm). Moreover, the calibration of such a device is strongly dependent on the flow conditions and is usually done for a homogenous flow [29]. Moreover, the technique is insensitive to velocity direction changes, making the application of such a methodology quite unpractical for the present work. Other laser-based visualization techniques like Laser Doppler Velocimetry (LDV) or Particle Image Velocimetry (PIV) [30] could theoretically provide very accurate and detailed results. On the other hand, they are relatively complex and expensive. Moreover, the need to use seeding particles creates the risk of blocking the pores and affecting the outflow distribution. In the present paper, the classical Pitot tube methodology is employed. Such technique has been implemented by the authors in the AORTA (Advanced Outflow Research facility for Transpiration Applications) test bench developed at DLR-BT and has been extensively used for characterizing different permeable materials [24, 28, 31, 32]. In comparison with the methodologies described above, it must be mentioned that the Pitot probe-based measurement generates relatively higher inaccuracies on the quantitative results, because of the tube interference effects on the flow, as it will be discussed also in the following. On the other hand, it provides a reliable assessment of the qualitative flow distribution with a high space resolution, also in case of strongly concentrated jets. Moreover, the measurement setup allowed to carry out different measurements by changing the relative orientation of the Pitot tube with respect to the component surface, giving an interesting insight on the outflow main direction.

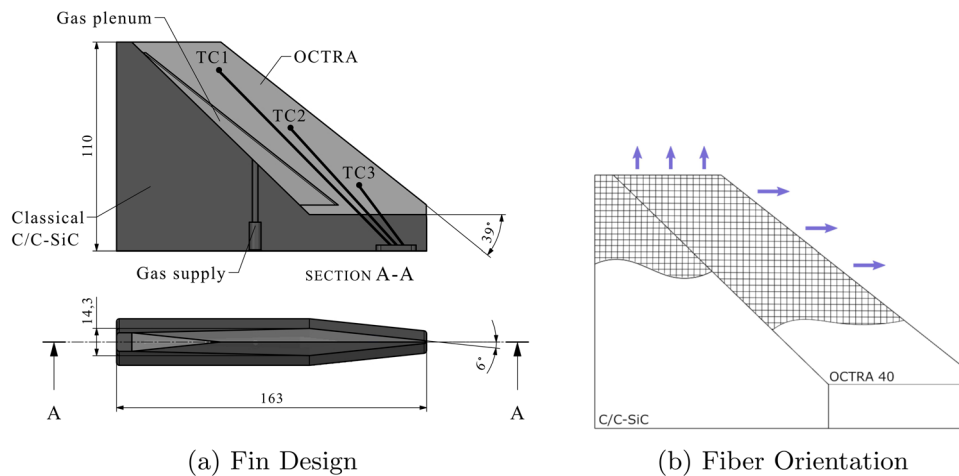


Fig. 1 Description of the investigated Fin

2 Experimental setup

In the following, a brief description of the investigated fin is given, which has the same design as the fins flown on the HIFLIER flight experiment. Furthermore, the experimental test bench for permeability and outflow investigations is described.

2.1 Description of investigated fin

The fin used for the presented experiment is made of the so-called OCTRA material, which is a permeable version of the typically used C/C-SiC material. While classical C/C-SiC material produced via liquid silicon infiltration is almost impermeable, OCTRA is obtained by including a predefined amount of aramid fibers in the carbon-fiber-reinforced plastic (CFRP) preform. The aramid fibers thermally degrade during pyrolysis generating larger pores which are not completely filled during the silicon infiltration. In this way, the permeability level can be defined based on the amount of aramid fibers included in the CFRP preform. More info on the OCTRA material, the manufacturing process, and the characterization of the main material properties can be found in [17].

Figure 1 shows the overall design of the CMC fin. During hypersonic flight, the highest aerothermal loads and consequently temperatures are expected at the leading edge. In order to concentrate the cooling in this region, only the forward part of the fin is made of the permeable OCTRA material (displayed in light gray in Fig. 1a

The permeable directions in the OCTRA material are determined by the orientation of the aramid fibers in the CFRP precursor. The OCTRA leading edge used here was produced using two-dimensional mixed carbon/aramid fiber plies, resulting in the main permeability directions as indi-



Fig. 2 Picture of investigated fin

cated in Fig. 1b. In the present work, the OCTRA40 variant of the material was used, indicating a 40% vol percentage of aramid fibers in the CFRP preform leading to a porosity of around 8-9% in the final C/C-SiC state. The fin in its final state is shown in Fig. 2.

2.2 AORTA test facility

The AORTA test bench used in the following study was designed for the characterization of porous materials regarding their permeability and outflow distribution.

2.2.1 Experimental setup for overall permeability measurements

The permeability of a porous specimen can be determined by performing steady-state measurements of the pressure drop over the specimen at different mass flow rates. At the AORTA facility, permeable specimens can be perfused by gaseous nitrogen with mass flows from 0.02 g/s to 12 g/s at pressures up to 15 bar, with outflow to ambient conditions.

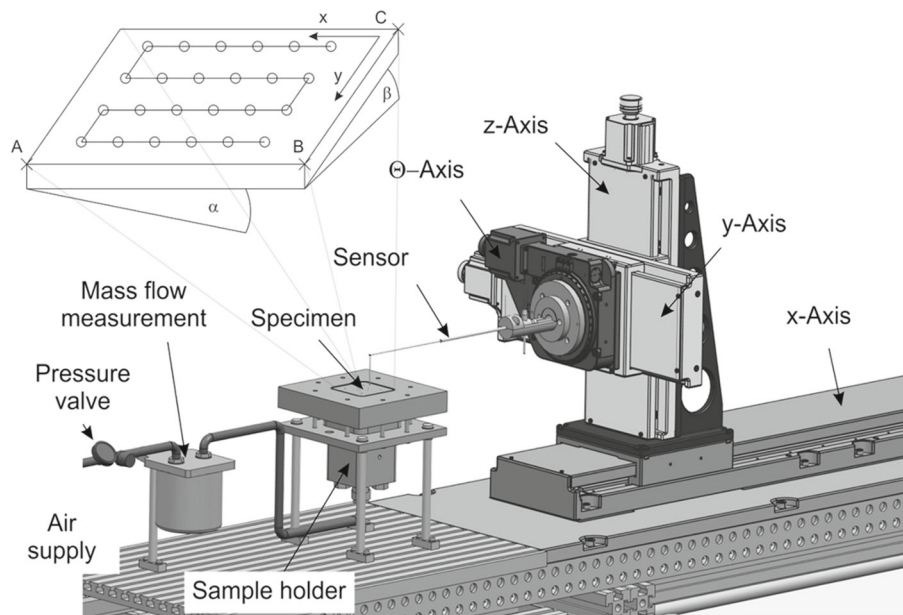


Fig. 3 Test setup and measurement procedure

The AORTA facility is made up of three parallel gas lines, which can be opened and closed by pneumatically driven valves. Each line includes a Bronkhorst CORI-FLOW mass flow controller M13, M14, and M55 respectively, each optimized for a certain range of mass flow rates. P33X-series pressure gauges for 300 bar and ambient pressure (0.8 bar–1.2 bar) with an uncertainty of 0.05% are used to measure the inlet and outflow pressures at steady-state conditions for different values of the cooling gas mass flow rate. Furthermore, type-K thermocouples (uncertainty ± 1 K) are used to measure the respective inlet and outflow temperatures.

The permeability of a porous medium is usually expressed by the Darcy–Forchheimer equation, which in the formulation by Innocentini et al. [33] describes the pressure loss of a compressible fluid through a porous medium as

$$\frac{p_{in}^2 - p_{out}^2}{2p_{out}L_c} = \left(\frac{\mu_{out}}{K_D}\right)u_D + \left(\frac{\rho_{out}}{K_F}\right)u_D^2, \quad (1)$$

where p_{in} and p_{out} are the coolant gas pressure at the inlet and outlet of the porous medium, respectively, μ_{out} and ρ_{out} are its viscosity and density at the outlet, L_c is the characteristic length of the porous medium, and K_D and K_F are the Darcy and Forchheimer coefficients. The superficial Darcy velocity u_D can be derived from the coolant mass flow rate $\dot{m}$ via the continuity equation

$$u_D = \frac{\dot{m}}{\rho_{out}A_c}, \quad (2)$$

where A_c is the outflow area. On this basis, the mass flow rates, as well as the pressures and temperatures of the flow

before entering the specimen are recorded, as well as the static ambient conditions. K_D and K_F are then obtained by fitting the measured data according to Eq. 1, using a least-squares algorithm.

2.2.2 Experimental setup for the measurement of the outflow distribution

Furthermore, at the AORTA facility (see Fig. 3), the outflow distribution of the porous material can be characterized by measuring dynamic pressures via Pitot tubes mounted on linear axes. To measure the outflow distribution, the Pitot tube is moved over the sample and stationary pressure measurements are automatically done. This allows for an automated, detailed measurement of the outflow characteristics as will be shown in the current paper.

During the measurement, a Pitot tube is moved by high precision linear units (positional accuracy $< 10 \mu m$) driven by step motors. The sensor is moved in a meander pattern over the sample and the control software automatically acquires stationary dynamic pressure values for each point as the mean value and standard deviation over 20 measurements. For the outflow measurements, a Pitot tube with an orifice diameter of 0.8 mm has been used, which is connected to a pressure transducer PTSXR from Airflow Lufttechnik GmbH with a maximum pressure of 1000 Pa. The sensor inherited uncertainty for the measurement chain amounts to 7 Pa. The mass flow is measured by a M14 Coriolis with an uncertainty below 0.5%. Figure 4 shows the representation of the setup for the characterization of the outflow at the fin leading edge with respect to the Pitot tube. In particular, the fin is held in posi-

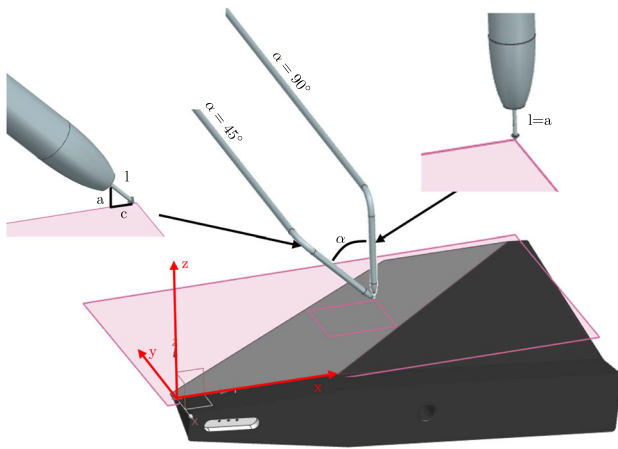


Fig. 4 Angle definition

tion by a milled sample holder, allowing the port side flank of the permeable leading edge to be aligned to the x - y -plane of the facility (with reference to Fig. 3). Note that the relative, fin centered coordinate system introduced in Fig. 4 will be used in the upcoming graphs.

The two important parameters that can be set for carrying out the outflow measurements are the distance a from the Pitot tube to the sample, measured in the z -direction, i.e., in the direction perpendicular to the measured surface plane, and the rotation angle α of the Pitot tube around the y -direction. From these two parameters, the distance l between the sample surface and the Pitot tube in the relevant direction for the measurement, i.e., in the direction of the Pitot tube itself, can be determined via simple geometrical transformation, taking into consideration also the real geometry of the tube.

In order to precisely determine the distance a , the Pitot tube is moved in increments of 0.01 mm to the sample until

a consistent electrical contact can be measured. To take into account the roughness of the sample, a small metallic plate with a thickness of 1 mm is placed on the sample for these measurements. The repeatability of this measurement is typically ± 0.01 mm. Also, with measurements of 4 points on the sample plane, the sample plane is also aligned to the x - y -plane of the sensor, with deviations in height of these points below 0.09 mm during the shown measurements.

A parametric study has been carried out performing different measurements on a limited region, highlighted in Fig. 4, for different values of α and l . To be able to compare the resulting measurement fields, the x - and z -position of the Pitot tube have to be corrected as indicated in Fig. 4. Table 1 summarizes the different cases considered.

As the possible mass flux is relatively low, due to the large outflow area, comparatively low-dynamic pressure values were expected. To account for this, $l = 2$ mm and $l = 3$ mm were chosen. With a minimum allowable distance a of 0.2 mm between Pitot tube and fin surface, this results in a smallest possible angle of α of 18.28° and 12.31° , respectively. This means that it was not possible to carry out direct measurements in the expected main outflow direction, i.e., for $\alpha = 6^\circ$, considering the fin leading-edge angle of 12° and the pore structure defined by the aramid fiber fabric, as shown in Fig. 1b. At this point, it is also worth mentioning that often the flow through a porous medium is assumed to be homogeneous and an average velocity is used to describe the porous flow. However, on a pore scale, the flow is made up for this kind of material of several fluid jets flowing out of the pores and regions with no outflow between the pores. Depending upon the size of the Pitot tube compared to the pore size and distribution, it is obvious that the measured distribution already contains some sort of averaging. Besides this averaging, additional errors are induced by the Pitot tube disturbing the flow. Thus, the absolute measured pressure values are

Table 1 Investigated test cases

Case	Angle α [deg]	Distance l [mm]	Case	Angle α [deg]	Distance l [mm]
Distance variation					
1	90	0.3	3	90	2
2	90	1	4	90	3
Angle variation					
5	18.28	2	11	12.31	3
6	30	2	12	30	3
7	45	2	13	45	3
8	60	2	14	60	3
9	75	2	15	96	3
10	96	2			
Angle variation perpendicular to flight direction					
16	18.28	2	18	90	2
17	45	2			

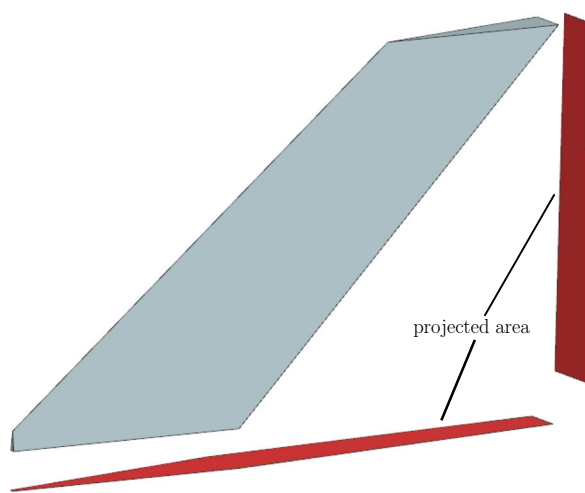


Fig. 5 Definition of projected area

distorted and should not be taken as the true values. This was already described in [31, 34]. Nonetheless, the measurements are able to differentiate between regions with flow, e.g., pores, and regions without flow and higher pressure values correlate to higher velocities and thus higher mass flow.

3 Results of fin permeability characterization

The characterization of the permeability was first performed on a cylindrical sample taken from the same OCTRA material batch from which the fins' leading edges have been manufactured, as described in [35]. Then, a measurement was taken of the investigated fin.

Steady-state pressure measurements were conducted by feeding the specified gaseous nitrogen mass flow rate in the range 0–1.5 g/s gaseous nitrogen. With reference to Fig. 5, for the calculation of K_D and K_F , the outflow area was considered as the sum of the projected areas of the porous leading-edge surface in the two expected main direction of the cooling gas outflow, as discussed in Sect. 2.1 and shown in Fig. 1b. Furthermore, a characteristic length of $L_c = 38$ mm was assumed, based on the average distance from the plenum and the leading-edge surface in the two expected main directions of the transpiration flow. The gas properties ρ and μ were calculated using the thermophysical database CoolProp [36]. The measured data points for the fin investigated in the present paper for pressure drop vs. through flow rate are given in Fig. 6 in comparison to the curve fitted using the Darcy–Forchheimer model (Eq. 1), showing a good agreement between model and measurements. It is thus shown that the Darcy–Forchheimer model fits to the given problem.

Finally, the determined Darcy and Forchheimer coefficients are given in Table 2.

Apart from deviations in permeability between different material batches, the deviation between the Darcy–Forchheimer values can be attributed to the different measurement setup—for cylindrical samples, only flow into one direction in the fiber plane is allowed, as rubber sealing prevents lateral flow. This results in an ideal through flow in the main direction of the flow, with clear definitions of A_c and L_c . In contrast, for the fin, a flow in two directions is allowed, with the assumptions described above. As already described in [37], the OCTRA material can be considered as practically impermeable for flow perpendicular to the fiber plane. Furthermore, for the fin, the mass flow range as was restricted to the operational conditions of the fin, whereas the measurement of the reference sample was taken for a much broader mass flow range. However, it can be shown that the simplified assumptions for length and area are reasonable.

An uncertainty analysis was carried out via Monte Carlo analysis [38] with 100,000 simulations, taking into account the uncertainties of the measurement equipment as given in Sect. 2.2. In Fig. 7, for K_D and K_F , the resulting histogram is shown.

The simulations yield a nearly symmetric Gaussian distribution. From that, the uncertainty value as given in Table 2 is calculated as $\pm\sigma$ of the distribution for K_D and K_F , respectively.

4 Results of outflow measurements

In the following, the results of the outflow characterization are presented. All presented outflow measurements were performed using a nitrogen mass flow rate of 2 g/s and a Pitot probe with an orifice diameter of 0.8 mm. In order to create a significant overlap between the single measurements, a step size of 0.4 mm was chosen, resulting in a measurement density of 625 Pt/cm².

All measurements have been taken at ambient conditions with $p_{amb} \approx 0.96$ bar and $T_{amb} \approx 295$ K.

4.1 Characterization of the anisotropic outflow characteristics

Due to the highly anisotropic structure of the OCTRA material as shown in Sect. 2.1, a significant directional dependency is expected, with a main outflow direction parallel to the carbon fiber plies. Therefore, a detailed investigation of the directional outflow characteristics was performed.

The measurements in the following subsection were performed taking 20x20 measurements with a step size of 0.4 mm, resulting in an 8 mm x 8 mm measurement window. The position chosen was in the center of the fin (see Fig. 4), as being as representative as possible for the general outflow behavior. The test cases chosen for the investigation

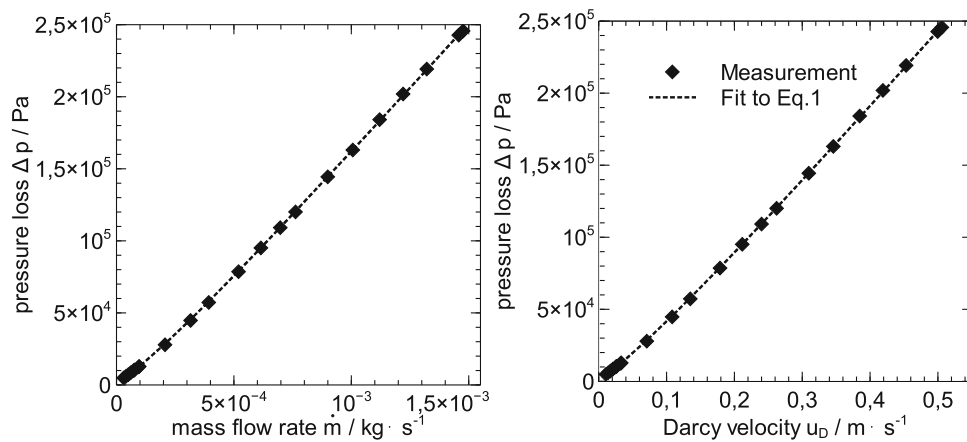


Fig. 6 Pressure loss over fin in dependency of measured mass flow rate (left) and superficial Darcy velocity (right)

Table 2 Permeability coefficients

Parameter	Symbol	Unit	Reference cylindrical [35]	Fin	Uncertainty
Darcy coefficient	K_D	m^2	$1.62 \cdot 10^{-12}$	$1.90 \cdot 10^{-12}$	$\pm 1.43 \cdot 10^{-13}$
Forchheimer coefficient	K_F	m	$4.5 \cdot 10^{-7}$	$2.72 \cdot 10^{-8}$	$\pm 1.43 \cdot 10^{-9}$

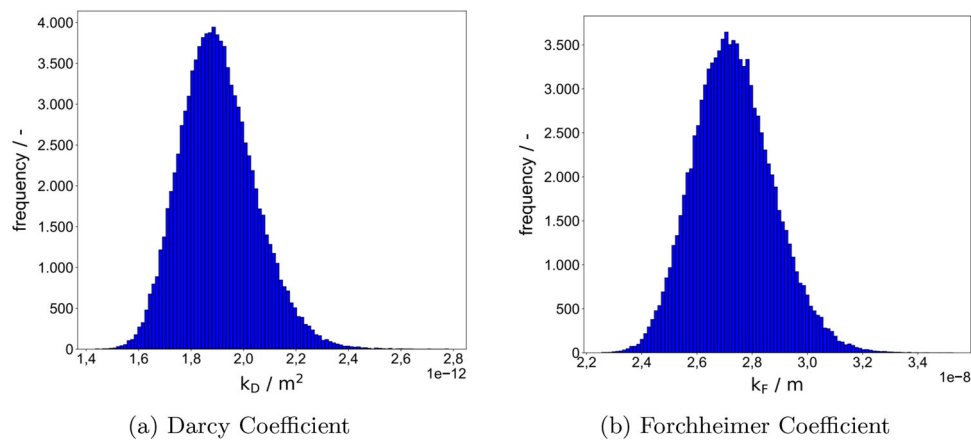


Fig. 7 Histogram of Darcy and Forchheimer coefficients for 100.000 events

are shown in Table 1. Exemplary, in Fig. 8, the outflow distribution and the corresponding standard deviations for each measurement point at a distance of $l = 0.3 \text{ mm}$ and $\alpha = 90^\circ$ are shown. The red dots in the contour plot represent a single measurement point.

By including a measurement very close to the surface, the effect of the sensor on the outflow is increased, but for materials with a jet-like outflow behavior, the mixing of the jets with each other and the ambient is minimized. Thus, this allows for a good characterization of a outflow porosity. Usually, for samples with an jet-like outflow perpendicular to the surface, this results in a positive mean dynamic pressure, with individual jets and surrounding negative dynamic pressures [31]. Figure 9 shows a histogram for

the measurement shown in Fig. 8. In contrast to experience with perpendicular outflow, for the current measurement, large parts of the sample have moderate negative pressures between -5 and -50 Pa and a large negative jet with negative pressures up to -152 Pa is visible in the center of the measurement. Negative pressures indicate a flow perpendicular to the pitot tube, thus indicating a main direction of the outflow is, as expected, not perpendicular to the surface. The mean pressure over the measurement area is nonetheless slightly positive at 0.6 Pa , caused by the measured positive jets. These indicate that some of the flow is, at least in large parts, perpendicular to the surface. This unwanted effect is most likely caused by small pores and defects in the mate-

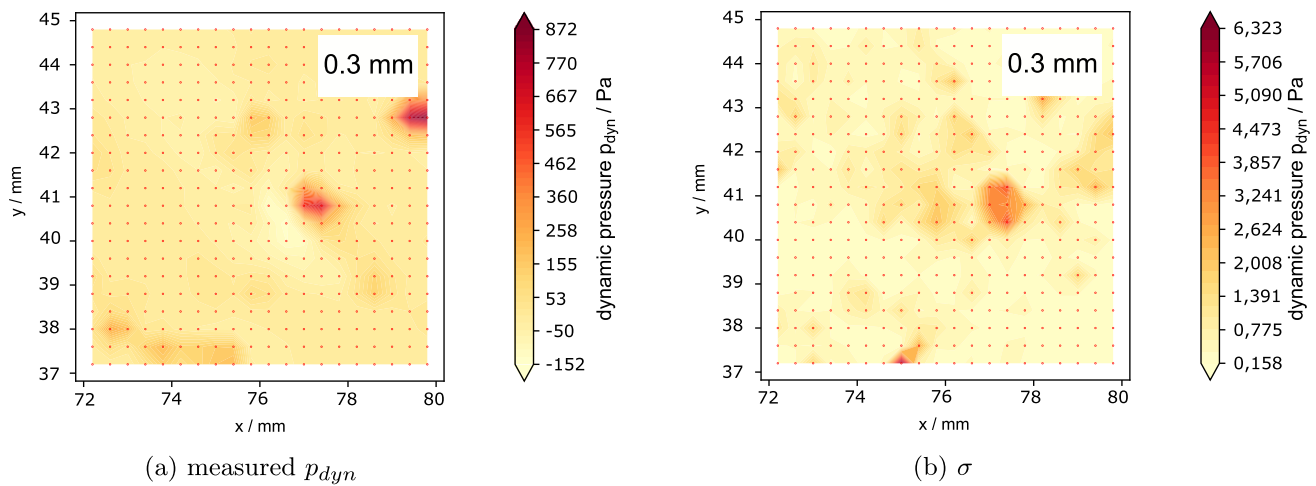


Fig. 8 Measured outflow distribution **(a)** and respective standard deviation σ **(b)**

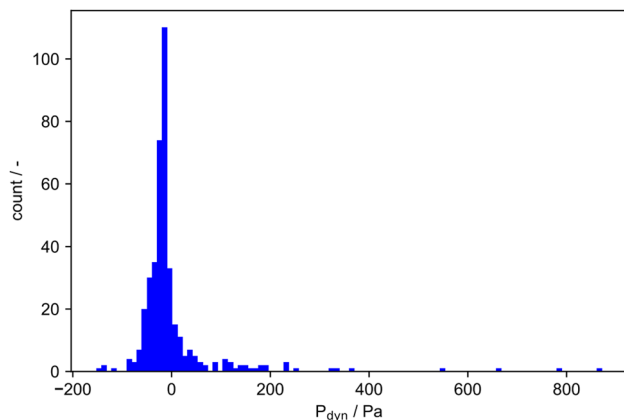


Fig. 9 Histogram of dynamic pressure for $l = 0.3 \text{ mm}$ and $\alpha = 90^\circ$

rial, deviating from the idealized assumptions explained in Sect. 2.1.

In Fig. 10, the outflow distribution of the characterized area is shown, with different distances to the fin surface. The measurements shown are taken at $l = 0.3 \text{ mm}$, 1 mm , 2 mm , and 3 mm , respectively. For these measurements, a constant $\alpha = 90^\circ$ was kept.

With a higher distance to the respective pore, maximum dynamic pressures decrease significantly. By assuming the outflow of a pore as a turbulent jet, the flow profile of a single jet widens radially, with an decrease in velocity, leading to lower dynamic pressures. This effect could be already demonstrated on perfused samples using the same facility by Selzer et al. [31].

Exemplary, an interesting behavior can be observed in the lower right corner of Fig. 10b. In Fig. 10b, two discrete jets become visible. With rising distance to the fin surface (Fig. 10c and Fig. 10d), the observed jets are widening, which is accompanied by a decrease in the measured peak dynamic

pressure. Furthermore, the position of the jet shifts slightly in direction of the leading edge (positive y -direction). This indicates that the observed jets are not perpendicular to the fin surface, but rather inclined. Also visible, the small positive jet in the center vanishes interacts with the negative jet and vanishes with rising distance.

For further investigations of the inclination of jets, more measurements were carried out considering the same measurement window but with different inclination angles relative to the fin surface.

Figure 11 shows the outflow distribution measured for the same direct distance between the fin surface and the Pitot tube $l = 2 \text{ mm}$ and different angles relative to the fin surface α . Note that the smallest angle relative to the surface was constrained to $\alpha = 18.28^\circ$. For this angular setting, as shown in Fig. 11a, a relatively high peak pressure could be measured, mostly dominated by a very strong jet, induced most probably by a very big pore or little defect in the structure. As shown in Fig. 11b and Fig. 11c, the jet is still visible; however, especially at $\alpha = 30^\circ$, the jet expands relatively strongly, which is accompanied by significantly lower measured dynamic pressures. For $\alpha = 90^\circ$, a negative pressure field was measured at the location of the jet, indicating a flow inclined to the Pitot tube.

For further considerations on the main outflow directions, the averaged pressures of the measured areas have to be considered. Figure 12a shows the average pressure values $\bar{p}_{dyn}$ of the investigated measurement window for different Pitot tube angles at $l = 2 \text{ mm}$ and $l = 3 \text{ mm}$. In contrast to the standard deviation of the sample as a measure of homogeneity of the outflow areas (see Fig. 8b), the uncertainty is here calculated using standard error propagation with calculation of the mean. The mentioned measurement chain uncertainty of 7 Pa for each pressure measurement is included. This neglects any error due to flow distortion by the pitot tube. Generally, for

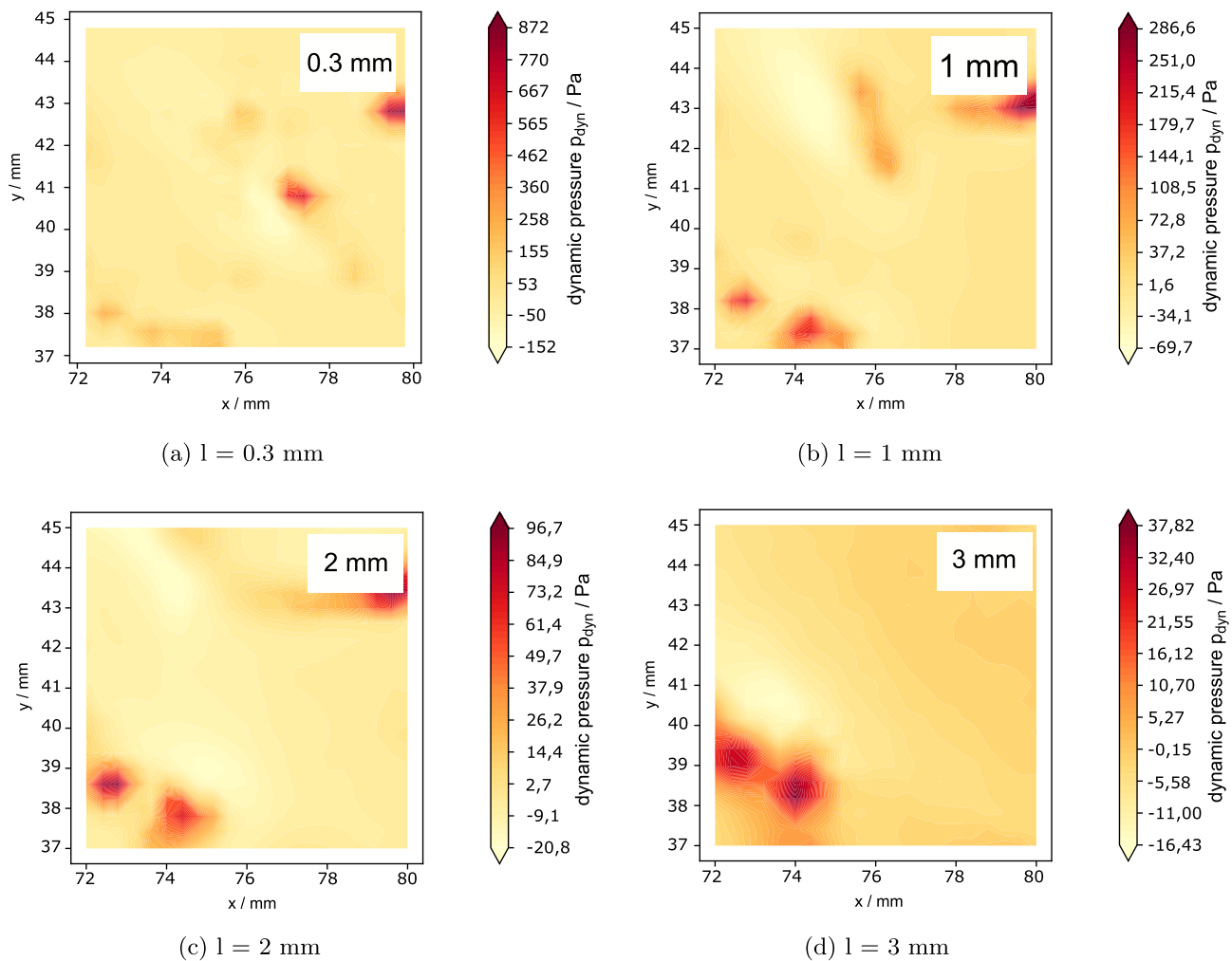


Fig. 10 Outflow distribution with different surface-probe distances

both distances investigated, the average pressure decreases with a rising angle relative to the surface α . Especially, at high α , the average dynamic pressure is negative, indicating that a strong influence of the recirculation can be observed. These results are in accordance with the findings from Dittert et al. [28] for the investigations of a porous cone made of Carbon fiber-reinforced Carbon (C/C). However, it has to be noted that the OCTRA material of the investigated fin has a more pronounced anisotropy compared to the C/C material, with a higher permeability in plane and basically no permeability out of plane, which makes it more suitable for the application on a fin leading edge. For the sake of completeness, as reported in Table 1, test ID 16-17-18, three further measurements have been carried out rotating the fin setup of 90° around the z -axis with respect to the facility (with reference to Fig. 4), in order to investigate the characteristics of the outflow also with respect to the other main direction of the pores of the OCTRA material used for the leading edge (Fig. 1b), i.e., in the direction orthogonal to the nominal

flight direction. This means also that the angle α between the Pitot tube and the investigated surface can be changed in this case, rotating the Pitot tube around the x -direction in the fin's coordinate system (Fig. 4). The measurements were taken for $l = 2$ mm and $\alpha = 18.28^\circ$, 45° and 90° and are shown in Fig. 12b. It can be noticed that for the smallest α value, the outflow in the orthogonal direction is relatively weaker, probably due to the geometrical design of the plenum and the resulting bigger distance to the external surface. This effect is rapidly averaged off by changing the measurement direction to 45° , up to 90° where the situation is practically equivalent. The agreement between these two measurements supports the assumptions of the material design described before and provides guidance for further optimization.

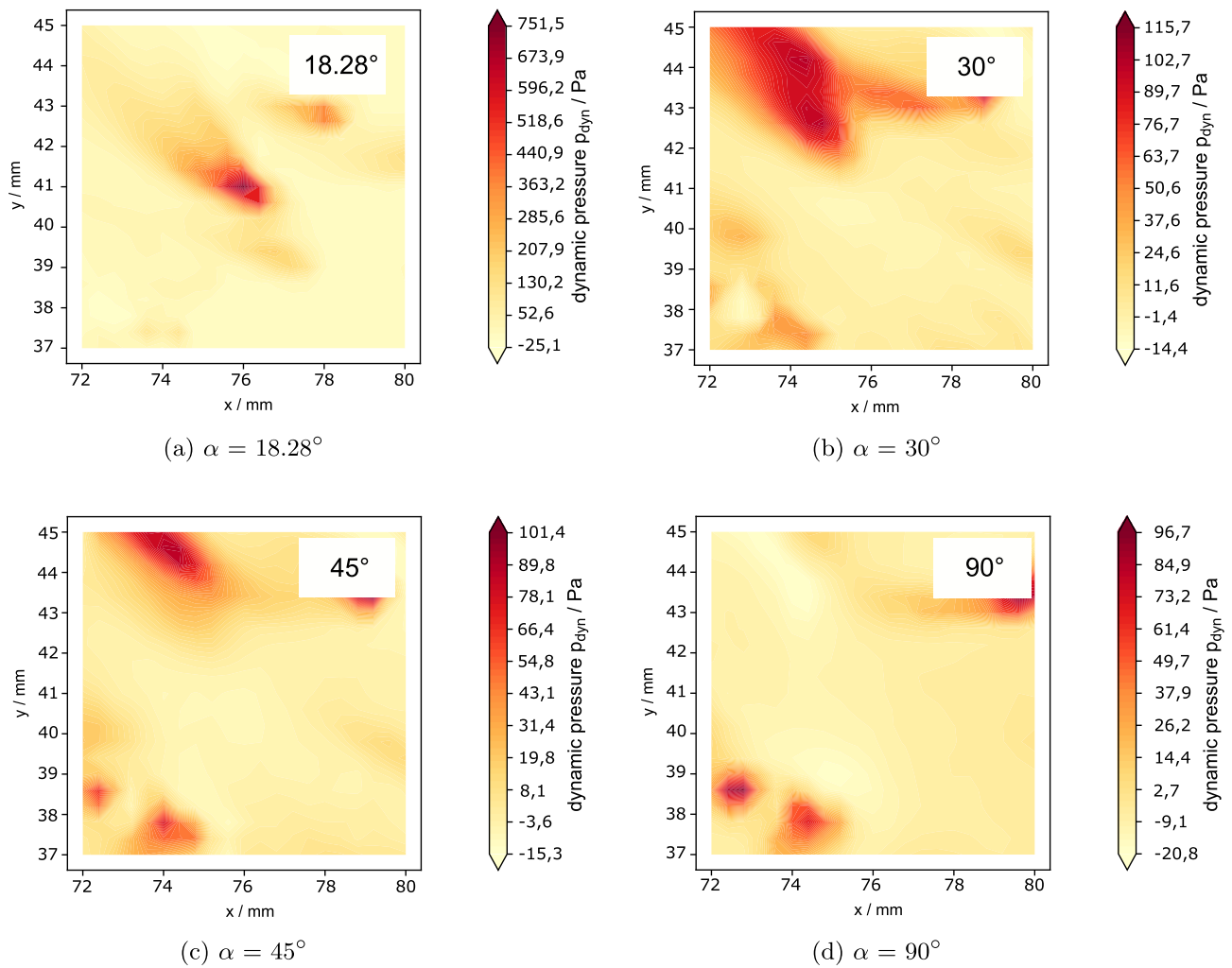


Fig. 11 Outflow distribution with different probe inclinations

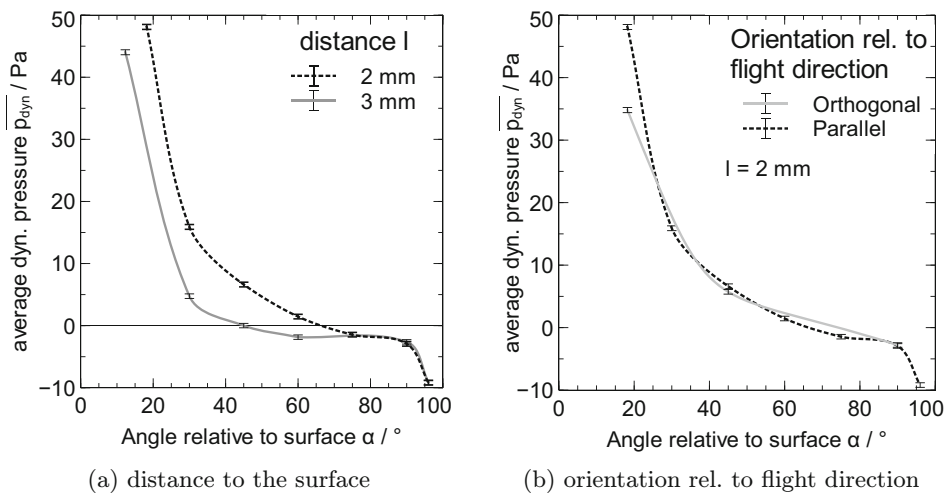


Fig. 12 Directional dependency of outflow

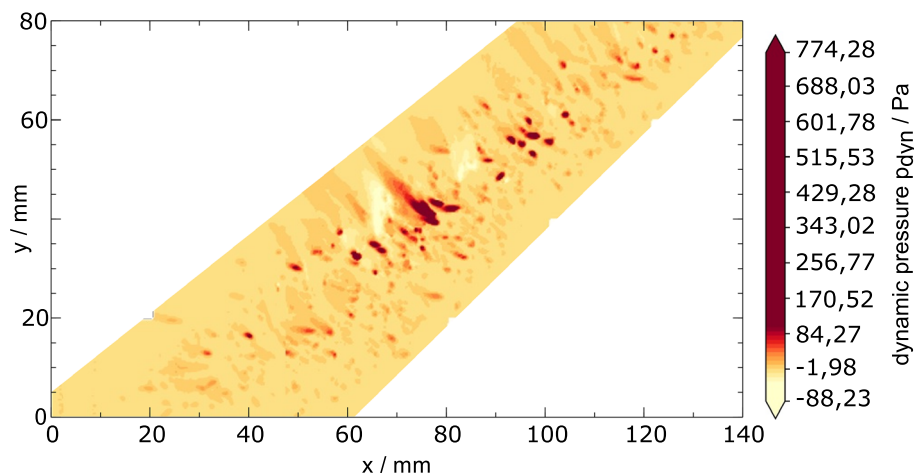


Fig. 13 Outflow distribution whole fin

4.2 Outflow characterization of full fin

The approach to guide the outflow direction into the flow direction due to the material design was presented in Sect. 4.1. An additional design goal was to guide the mass flux to the tip of the fin. Therefore, a measurement of the whole port side of the fin was performed. For this study, α was kept at 18.28° , considering again the setup shown in Fig. 4 for what concerns the relative orientation of the fin to the Pitot tube, l was kept at 2 mm.

Figure 13 displays the outflow distribution measured over the whole outflow area. Generally, it can be seen that low-dynamic pressures are measured at the leading edge of the fin and close to the interface between the permeable OCTRA part and the impermeable C/C-SiC part. The latter effect can be explained by the highly anisotropic permeation properties of the OCTRA material. This part is nearly perpendicular to the plenum, and hence, the gas has to flow nearly perpendicular to the plenum through the porous medium to exit in this area. As OCTRA is practically impermeable perpendicular to the fiber plies, no outflow could be detected in that area. The low outflow rate near the leading edge of the fin can also be explained by geometric properties of the fin. Although the leading edge is aligned to the fiber direction, as seen in Fig. 1b

However, for application in hypersonic flight, such outflow characteristics are not desired, as the highest thermal loads are apparent at the sharp leading-edge tip, requiring the most effective cooling and hence most outflow in this region. This can be solved through a improved fin design.

5 Conclusion and outlook

A study on the through flow and outflow characteristics on a transpiration cooled CMC fin as flown on the HIFLIER

sounding rocket flight experiment was conducted. While past characterizations of the outflow pattern focused on the investigation of simple geometries for fundamental research, this time a study was conducted on a more complex, realistic geometry for sounding rocket experiments. For the investigation of the general outflow pattern, a detailed study was conducted on a small 8 mm x 8 mm field in the center of the fin, with measurements at different distances and angles to the specimen surface. As a result, the general outflow pattern could be shown as a low-dynamic pressure outflow pattern dominated by single jets, distributed relatively homogenous over the surface, disrupted by single strong jets caused by small inhomogeneities of the pore pattern. Furthermore, the strongly anisotropic permeability properties of the utilized porous CMC material could be successfully shown. The outflow investigation of the whole fin showed that the highest mass flow rate is located at the center, which can be explained by the combination of the fiber structure and lowest wall thickness. Due to the high wall thickness, almost no outflow could be measured at the fin's leading edge. This behavior is not ideal, since in case of flight in hypersonic regime, the sharp leading edge is expected to be the region with the highest thermal load. On the other side, this highlights the importance of characterizing the cooling outflow, in order to identify the possible required design improvements.

From the results of the outflow investigations, three main factors for the improvement of the design of transpiration cooled fins can be extracted. First, the general outflow behavior could be improved by employing more homogeneous materials or improving the homogeneity of the used CMC material. However, the exact effect on the cooling effectiveness is still under investigation.

Furthermore, the design of the fin has to be adapted in order to have a high mass flow rate at the leading edge, which could be realized with a graded porosity pattern, leading to

high permeabilities at the leading edge and consequently a higher cooling mass flux. Concluding from the analysis of the outflow relative to the flight direction, it can be shown that a significant amount of coolant is flowing perpendicular to the flight direction. With an improved fin design, and the potential improvement of the material toward a single-directional pore structure, this potential source of coolant loss could also be minimized.

In addition, the correlation of the measurements presented in the paper with the aerothermal data collected on the same fin geometry during plasma wind tunnel tests [39] and during the HIFLIER flight could allow the definition and validation of suitable numerical models to support the design phase of future complex components. In this way, the investigation of the outflow pattern of a transpiration cooled structure could play a vital role in the improvement of the design for future thermally highly loaded spacecraft structures

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Data Availability No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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