Advanced Design Concepts for Ceramic Thrust Chamber Components of Rocket Engines

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Abstract

In the last two decades DLR spent a lot of effort in the development of ceramic rocket thrust chambers. A first system evaluation in the nineties led directly to the operative range of transpiration cooled inner combustion chamber liners because of the natural inherent micro-porosity of Ceramic Matrix Composites (CMCs). CMCs as high temperature resistant structural materials represent a relatively young class of materials, which shows high future potential for high temperature and in parallel structurally high performance applications.
A variety of basic empirical and numerical investigations of this technology has been conducted. The field of pure material research, system analysis and experimental works at relevant test benches for rocket engines at the DLR location of Lampoldshausen stood in the major focal point. Especially the P8 European Research and Technology Test Facility as well as the relatively new P6.1 Technology Test Bench are good platforms to demonstrate such interesting technology approaches. At these two test benches a lot of technology results and also development perspectives could be obtained.
The current development status shows high application potential of transpiration cooled CMC rocket engines, related to newest material knowledge in combination with a highly efficient operating of cryogenic rocket thrust chambers.
Suitable structure approaches of the fundamental thrust chamber components, in particular the subsonic ceramic combustion chamber section, a new injector design based on porous oxidic CMC material and a CMC supersonic nozzle extension are very promising concerning the demonstration of complete ceramic thrust chamber assemblies under cryogenic high performance environment in the near future. The CMC nozzle extension technology will be described in [3], not in this paper.
Apart from transpiration cooled systems also regenerative and radiation cooled thrust chamber systems are applicable considering newest CMC design skills. Consequently such alternative operations are of further interest relating to future business cases of multiple rocket propulsion applications.

1. Introduction

The intermediately well-known development program of transpiration cooled and cryogenically operated CMC rocket thrust chambers at DLR is structurally affected in general by the combination of CMC materials at the inner chamber liner and an outer load carrying shell made of carbon fiber reinforced plastics (CFRP) [2;7;15]. An illustration of the current design status is given in figure 1. The picture also presents an important demonstration test under relevant operation conditions at DLRs renewed P6.1 test facility.
The idea of a ceramic rocket thrust chamber came up in the middle of the nineties. Expeditiously the application potential of micro-porous CMCs aiming on transpiration cooled high temperature structures became visible. Consequently first system analysis and the investigation of structural chamber approaches started. In parallel numerical flow analysis has been and will be performed in the near future to handle the behaviour of the coupled coolant-hot-gas-flow. Figure 2 shows the roadmap of the previous works. After positive experience over the first years a de-coupled structural design crystallized as being constructive. It is characterized by significant system simplification, and as a consequence the reduction of weight and cost. Additionally higher operation reliability is expected compared to current flight hardware.
From the material point of view C/C (Carbon fiber / Carbon matrix) arose as helpful inner liner material, because of its representative homogeneous micro-porosity and a high melting point of approximately 3000 °C. Additionally it shows suitable thermo-physical properties which supported excellently the basic investigation of the hot-gas-wall-interaction. Apart from explicit disadvantages of C/C (e.g. high oxidation sensitivity) latest tests applying enhanced materials with different compositions predict the future fulfilment potential of all operation requirements in the hot-gas environment. Concerning the outer load carrying structure an outer CFRP load shell based on thermoset material proved as hydrogen tight and thermo-mechanically functional.

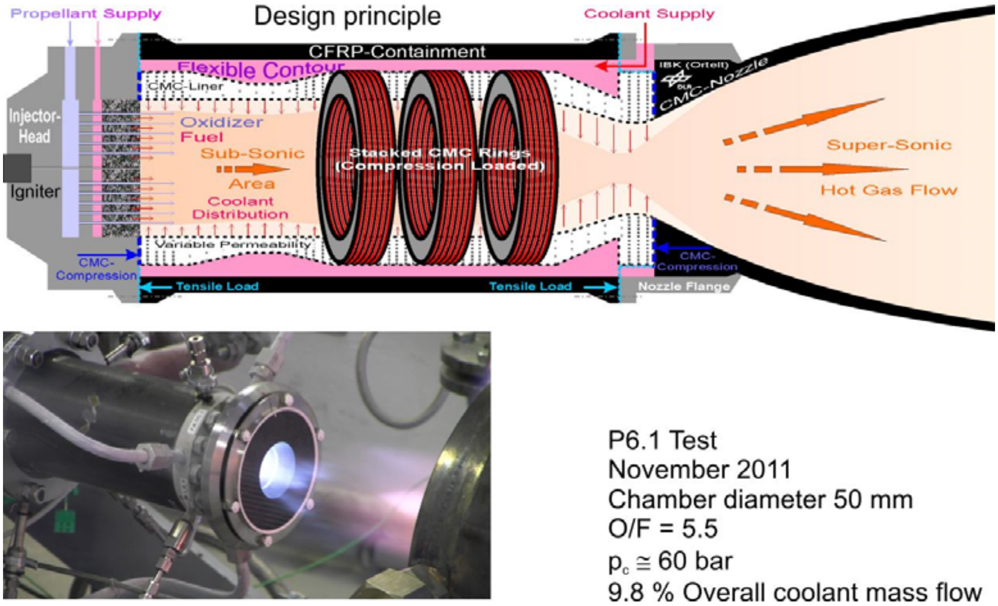


Figure 1: DLRs transpiration cooled composite thrust chamber assembly. De-coupled thermomechanical design principle and a representative demonstration test at the P6.1 test facility (MT5-A campaign [1;2]).

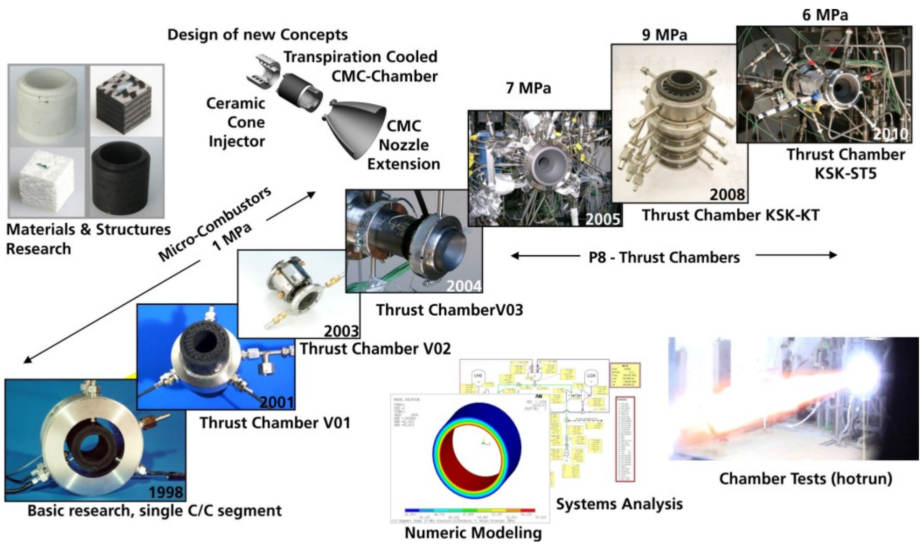


Figure 2: Roadmap of the ceramic thrust chamber development until 2010. First basic research of materials and structures, system and numerical flow analysis flew into integrated technology demonstrations.

A new ceramic injector design aiming on highly stable operation of both cryogenic and staged combustion under high temperatures has been kicked off meanwhile.
Finally the on-going research on the development of CMC bell nozzle shells, produced via filament winding, shall complete the demonstration of an integrated CMC thrust chamber design [3].
From 2006 until 2010 DLRs transpiration cooled ceramic thrust chamber program was integrated in the KSK-project, which was part of the national Propulsion 2010 research network. In Propulsion 2010 DLR worked closely together with the national space propulsion industry EADS Astrium ST.
Since 2011 DLR extends its development portfolio by the improvement of constructive CMC derivatives itself and by introducing CMCs into both regenerative and radiation cooled thrust chamber structures. New technology approaches promise further improvements also in these fields of cooling methods. Apart from this, new promising development results of DLRs ceramic rocket injector technology motivate further investigations on this field. The current works are embedded in DLRs Kerberos program, which is linked closely to the national research network continuation Propulsion 2020.

2. Research

Since the beginning of the ceramic thrust chamber development program multiple basic investigation steps could be completed. After first system evaluations principle structure approaches followed, accompanied by various numerical works.

2.1 System analysis

The system evaluation of some transpiration cooled rocket engine configurations gives an impression of the ranking of DLRs former test results in the KSK-KT (2008) [7] and KSK-ST5 (2010) [1;2], both in combination with the API injector [12]. In these test campaigns, using mainly oxidation sensitive C/C as inner liner material, the coolant mass flow could not be reduced significantly because of appearing material degeneration effects. Figure 3 shows the relation of combustion chamber pressure and coolant mass flow ratios. The amount of required coolant depends on the hot gas conditions, the inner surface area and the allowable wall temperature. The required coolant ratio decreases with larger chamber diameters and high pressures [4]. The current chamber design was successfully operated with coolant ratios around 7% at chamber pressures around 60 bar in the previous test campaigns. Scaling of this design leads already to required coolant ratios below 1% at thrust levels above 1000 kN. There is however room for further reduction of the required coolant ratio. New CMC materials show extreme thermochemical resistance without any damage formation. There is also the possibility to decrease the characteristic chamber length from the current value of approximately l* = 1.84 m, to values below l* = 1 m, assuming the availability of a suitable injector.

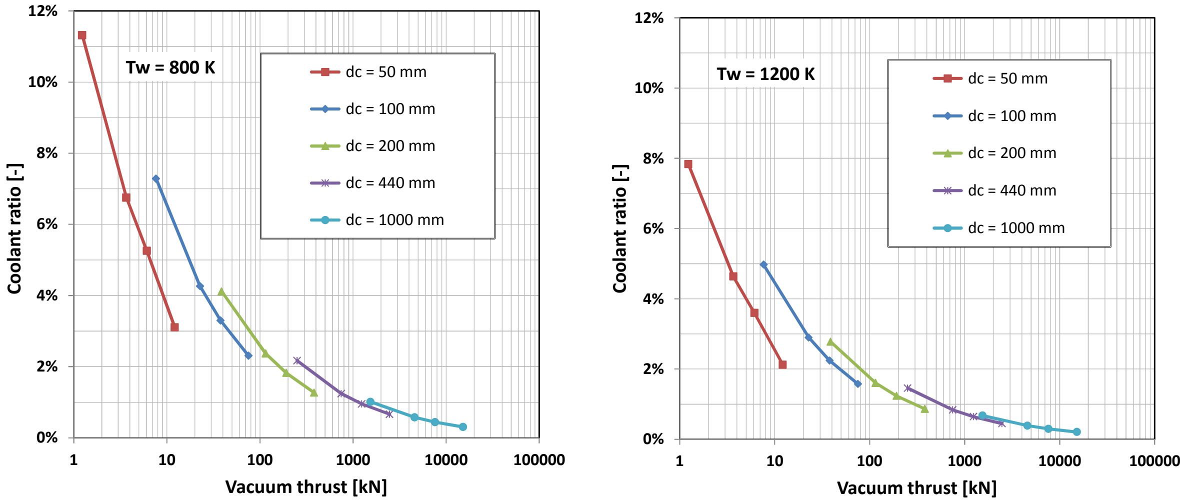


Figure 3: Scaling of thrust chambers and resulting required coolant mass flow ratios [4].

Using carbon fiber based materials like C/SiC (PIP – polymer infiltration process or CVI – chemical vapor infiltration process; table 1, WS1-A series, segment No. 3 & No. 4), C/C-SiC (LSI process, DLR) or oxide CMCs like OXIPOL (DLR), WPS (Walter Pritzkow Spezialkeramik), or others, all of these partially hybrid material derivatives show suitable thermochemical resistances, under relevant cooling conditions. Hence today's available materials are appropriate.

2.2 Structure development

DLRs structural CMC chamber concept shows predominantly and specifically de-coupled single parts (figure 4)[2], which prevents thermo-mechanical constraints and structure degradation:

1) The inner CMC liner,
2) The outer load carrying housing made of CFRP, which shows a pure hollow-cylindrical shape,
3) Metallic flanges at the front edges adjacent to CFRP and CMC bodies.

The structural operation principle can be described by the following aspects: Firstly the inner liner is assembled by ring segments which are extracted from flat CMC plates before. The advantage of this practice is given on the one hand by the high grade of material homogeneity as well as highly reproducible material quality, and on the other hand by the simple material production process causing lower manufacturing costs. Subsequently the sorted and aligned segments are stacked together, whereas they are centered one to each other. The complete inner liner assembly will be inserted into the outer CFRP shell without being bonded. To fix the stack securely, the whole inner liner component, which shows the characteristic of a mechanical spring in axial direction, will be compressed from the front edges when being mounted at the outer housing. For this reason additionally a suitable bolt interface has been developed and qualified for the technology demonstration.

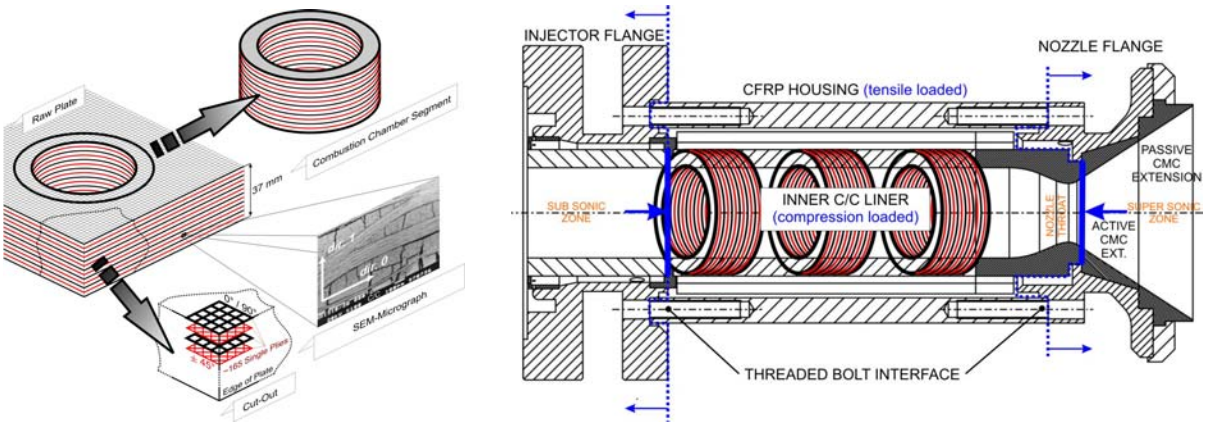


Figure 4: CMC thrust chamber assembly. All single parts of the thrust chamber body are assembled without bonding.

The specific design allows flexible fiber lay-up's or stacks of varying CMC ring segments along the chamber axis. Even rings showing completely different material properties can be stacked without inducing additional thermo-mechanical problems, caused by the mechanical de-coupling (figure 5). Depending on changing chemical hot gas formation along the inner hot gas flow from the injector to the nozzle throat, different material resistance requirements can be adjusted excellently by choosing suitable chemo-physical material properties, ring thicknesses and coolant permeability.

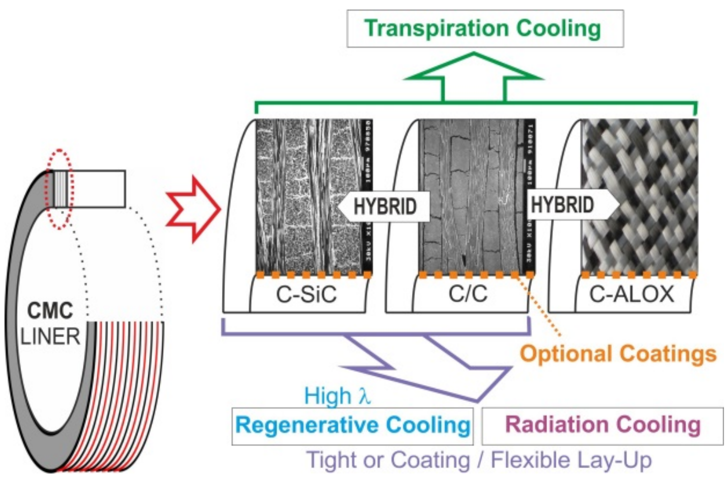


Figure 5: Flexible inner liner design. Stacks of completely different material segments are feasible.

Close to the injector a higher amount of free oxygen must be expected near the inner liner surface. In this region the use of highly permeable oxide CMC is beneficial. More downstream the coolant diffusion can be reduced by lower material permeability and in parallel the heat conductivity can be increased by the use of carbon fibers, for instance. In the convergent sub-sonic nozzle region also higher heat conductivity and also higher permeability can be of advantage, just as given in figure 1.

Hardware Pre-Qualification

From the structural point of view typically three general classes of preparatory qualification works have to be done before considering demonstration tests at the rocket propulsion test benches: Structural analysis, thermo-mechanical pre-tests and leakage checks.
The thermo-mechanical pre-qualification is performed in electromechanical or hydro-mechanical test machines

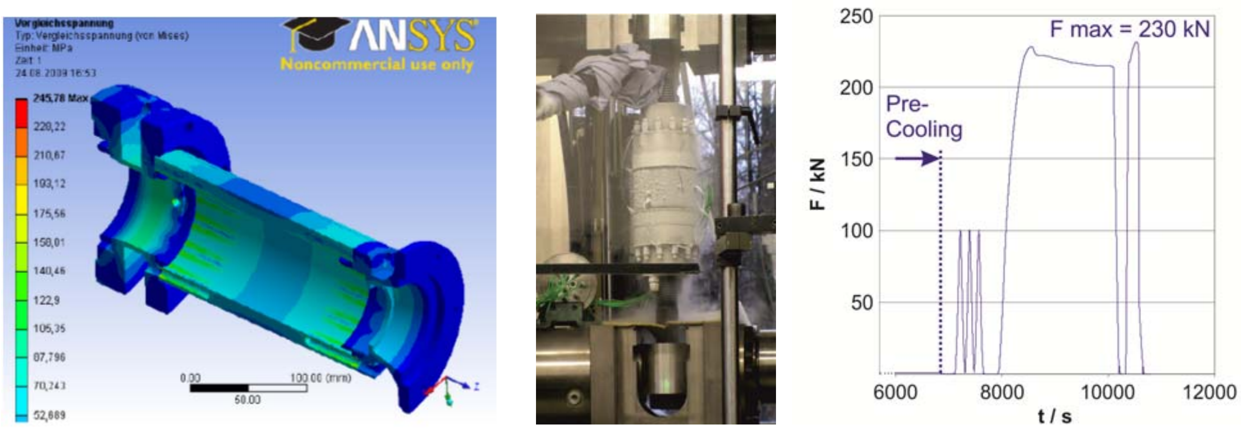


Figure 6: Thermo-mechanical verification. Numerical design verification and structural tests in an electro-mechanical test machine (Type: Zwick) under ambient and cryogenic temperature conditions. As foreseen the metallic bolt row is the dimensioning component, without any impact on the metal-CFRP-interface.

(figure 6). The principally de-coupling design philosophy proves as to be free of interfering loads besides the nominal operation loads. The feature of carrying nominal loads only, extremely simplifies the structural dimensioning effort for every structure component.
Concerning tightness the test benches require leakage values lower than $1 * 10^{-4}$ mbar l / sec of leakage rate under 5 bars He-pressure. The thermoset material shows no leakage difference compared to regular metals used in standard test samples.
The last step of hardware pre-qualification consists in water pressurization tests. Hereby the load carrying chamber housing will be filled with water. Subsequently the inner pressure of twice the nominal test conditions will be applied by a hand-service pump.

2.3 Numerical investigations on the transpiration cooled thrust chamber

Since the beginning of the ceramic thrust chamber development one major focus was represented by the evaluation of flow characteristic in porous media. In particular the coolant diffusion and the coupling of coolant and hot gas flow are of high interest. Several approaches for the flow investigation were initiated. Two major directions in this evaluation are established, both a pure flow-coupling method and a structure-flow-coupling method. Standard flow computing systems, e.g. ANSYS CFX [11] or FLUENT, are effectual in pure flow coupling. In 2003 DLR started a further approach, wherein the coolant diffusion was calculated by solving entropy equations (based on the PANDAS tool, usually applied in the building industry) [6]. In a preliminary development phase, simplified simulations could be conducted, generating good qualitative results (figure 7). The current effort is targeting on the coupling of ANSYS CFX and DLRs TAU-code development with the aim of a complex flow-structure-coupling-tool. Apart from this several analytical evaluations of the heat balance in transpiration cooled inner liner structures are on-going [4] or have been done [10;14].

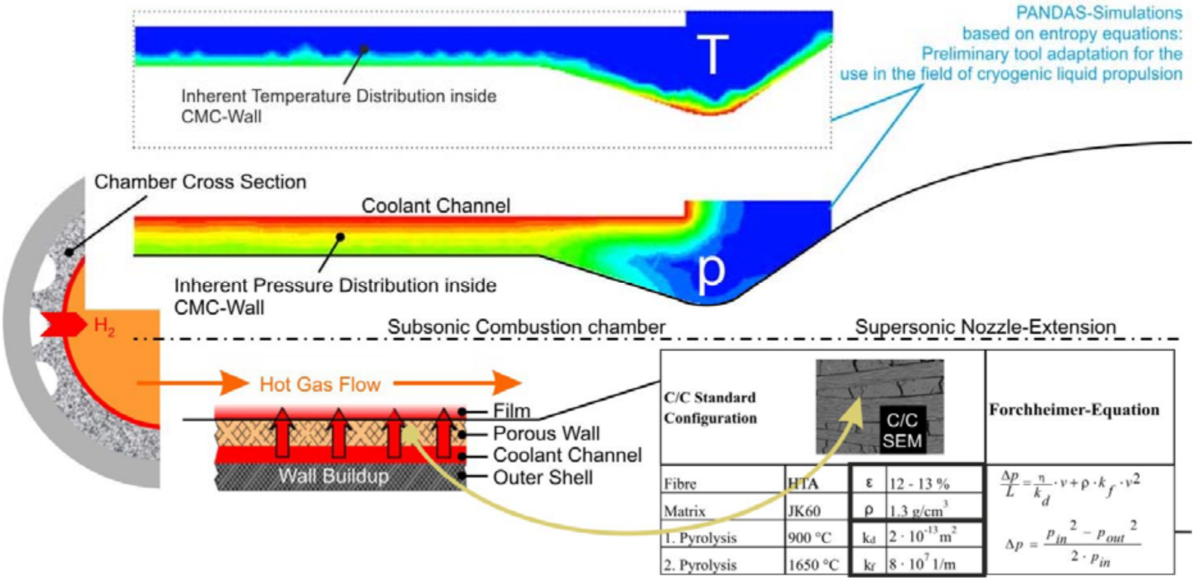


Figure 7: Flow analysis. Based on entropy equations or more specifically on the Darcy-Forchheimer approach a variety of flow simulations have been done, e.g. a simulation based on the PANDAS tool.

3. Technology demonstration

After successful principal technology demonstrations in the past, predominantly performed at the M3 and the P8 test bench as given in figure 2, specific questions concerning thermo-chemical resistance of the materials became of higher interest. To investigate adjusted inner liner material derivatives the renewed P6.1 test bench was used for the tests since 2011. The P6.1 delivers liquid oxygen (LOX) and gaseous hydrogen (GH2), which is pre-cooled by liquid nitrogen using a jacket cooling system in the fuel supply. Further progress related to the question of coolant mass flow reduction as well as material selection, was reached within the two latest P6.1 test campaigns, MT5-A [1;2] at the end of 2011 and WS1 at the end of 2012. Whereas the MT5-A campaign, described in [2], showed the potential of safe coolant mass flow reduction to less than 10% related to the overall mass flow on 50 mm diameter subscale level, the newest WS1 tests showed further coolant mass flow reduction potential in conjunction with stable thermo-chemical resistance accompanied by an extended material selection (table 1; figure 8).

3.1 Improvement of materials and structures

Based on famous coolant diffusion properties of C/C as well as oxidic WPS-AvA-Z-ISC material for the transpiration cooling in the past, improved materials were selected for the next material development step in 2012. As a sample platform served the segmented KT chamber module [denver] for the material investigations, the coaxial TRIK injector [1], and the ST5 nozzle segment (figure 9). Inside the KT module four cylindrical CMC segments could be inserted in a row, each separately supplied with coolant. At the end of the actively cooled inner liner section the Laval nozzle segment, which was already used in the MT5-A campaign, was placed in the ST5 nozzle segment holder and was over-cooled to ensure a safe chamber operation. The cylindrical segment size was similar to the KSK-KT tests in 2008 [7] at the P8 test bench (figure 2). The WS1 tests were split into two parts, WS1-A and Ws1-B. The WS1–A tests have been performed at a hot gas pressure range of 55 ÷ 60 bar. The injector mixture ratio O/F amounted to 5.5. These tests should demonstrate the thermo-chemically safe operation of the material under reduced coolant mass flow ratio's compared to the MT5-A tests in 2011. The WS1-B tests targeted to non-cooled operation at a mixture ratio of about 1.8 ÷ 2.0. The intension was to obtain temperature and pressure profiles across the wall, to get additional data input for future numerical simulation of the transpiration cooling [5]. Within the WS1 test series the following materials were selected (table 1, figure 9).

Table1. Material selection of the cylindrical test segments - WS1 tests.

	Segment No. 1	**Segment No. 2**	**Segment No. 3**	**Segment No. 4**
WS1-A series transpiration cooled	OXIPOL I678R oxidic fiber	WPS AvA-Z-ISC oxidic fiber	C/SiCN IP500-2 Carbon fiber	C/C-HTA CVI-SiC coat. Carbon fiber
ρ [g/cm^3]	2.3	2.6	1.6	1.6
open porosity [%]	10	35	18	7
manufacturer	DLR	Pritzkow WPS	DLR	DLR/MT-Aer.
WS1-B series Non-cooled	C/C-HTA CVI-SiC coat. Carbon fiber	C/SiCN IP499-1 Carbon fiber	C/C-HTA standard Carbon fiber	C/C-HTA standard Carbon fiber
ρ [g/cm^3]	1.6	1.8	1.6	1.6
open porosity [%]	7	13	7	7
manufacturer	DLR/MT-Aer.	DLR	DLR	DLR

The major functional difference of the materials can be seen in the porosity, or the resulting permeability respectively. The order of the segments has been defined on the one hand by the feature ‘oxide segment’ (close to the injector) or ‘non-oxide segment’ (far downstream). On the other hand it has been defined by a suitable coolant deflation related to the question of wall-protective boundary layer formation along the flow direction.

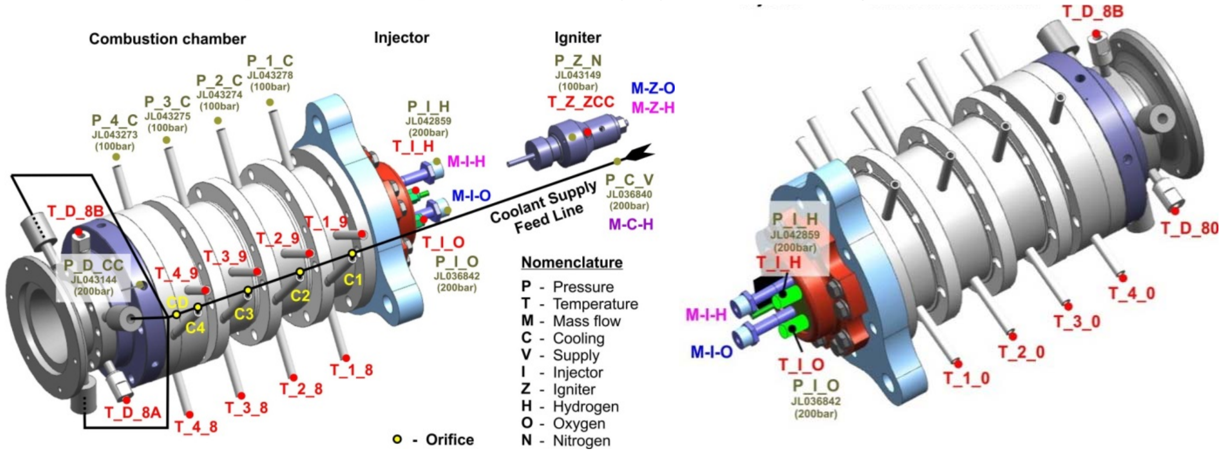


Figure 8: Sensor equipment of the WS1 chamber configuration.

The inner CMC liner was equipped with three rows of thermocouples (T_Seg.-No._**0**; T_Seg.-No._**8**; T_Seg.-No._**9**). Type’ _0’ was positioned in the coolant reservoir, the measure tip of type’ _8’ had a distance of 2 mm from the hot gas wall surface and type’_9’ showed 1 mm distance from the hot gas wall surface. The hot gas pressure was measured in the igniter (P_Z_N) and the segment reservoir pressures are represented by the sensor names P_1÷4_C. The mass flows were measured by flow orifices in the coolant supply pipes (C1÷C4 → GH2 cooled segments, LOX injector M-I-O, GH2 injector M-I-H) (figure 8).

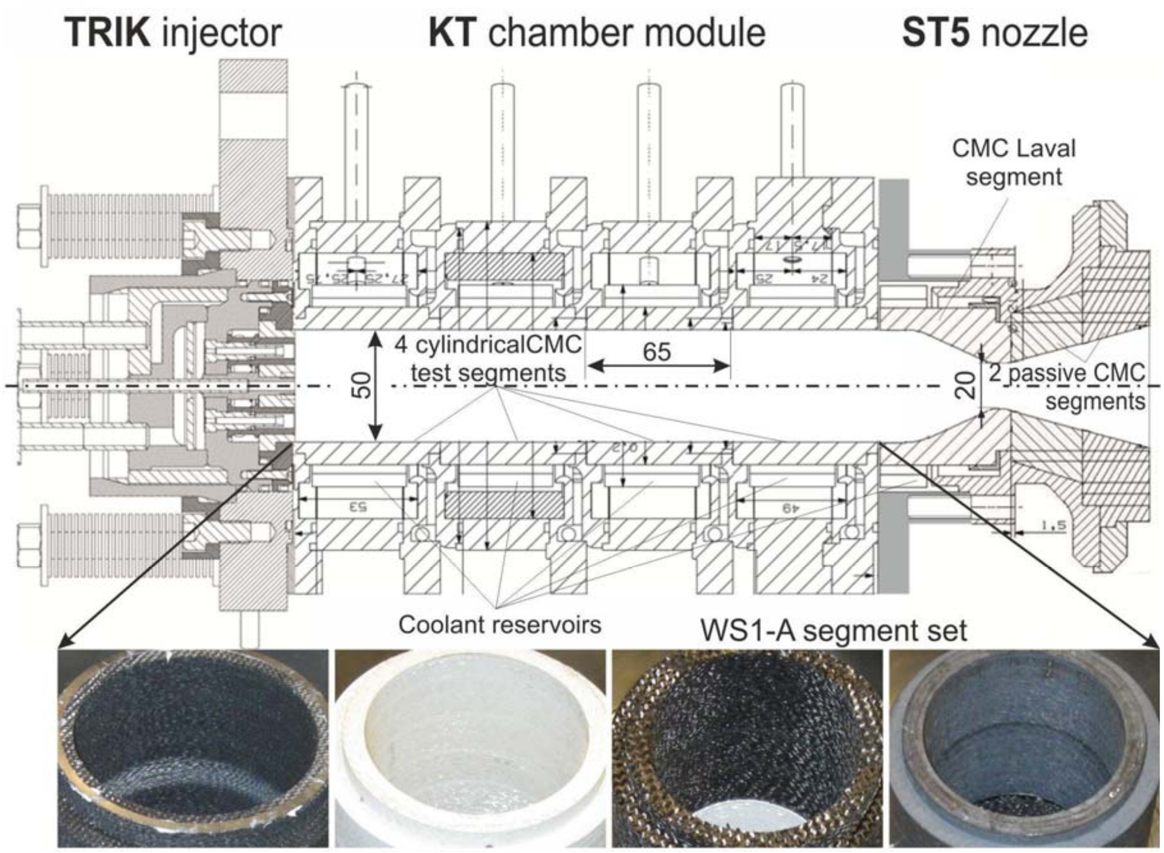


Figure 9: Test set up of the WS1 tests; WS1-A segment set before the tests.

The following diagrams show the relevant temperature, pressure and mass flow curves of the WS1-A-T04-RN1 test, which is representative for the WS1-A campaign, applying a coolant mass flow reduction down to 6.72 %, related to the overall mass flow.

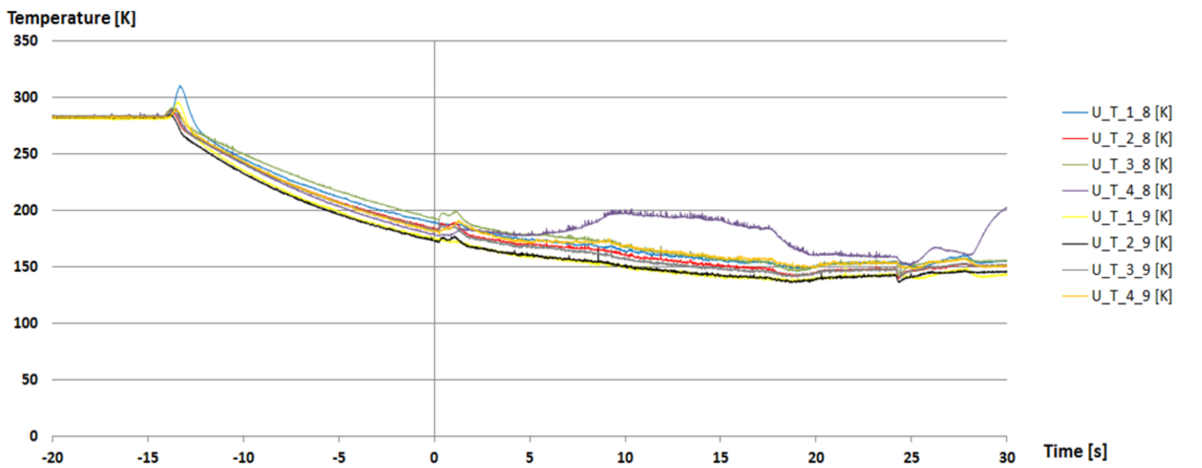


Figure 10: Material temperatures, Test-No. WS1-A – T04-RN1; O/F = 5.5; τ = 6.72.

Even at a coolant mass flow ratio of 6.72 the temperatures measured in the CMCs ranges at relative low levels, far away from realistic operational surface temperatures (figure 10). That promises further coolant mass flow reduction potential. The reservoir temperatures are given in figure 11.The representative mass flow and pressure curves are given in figure 12.

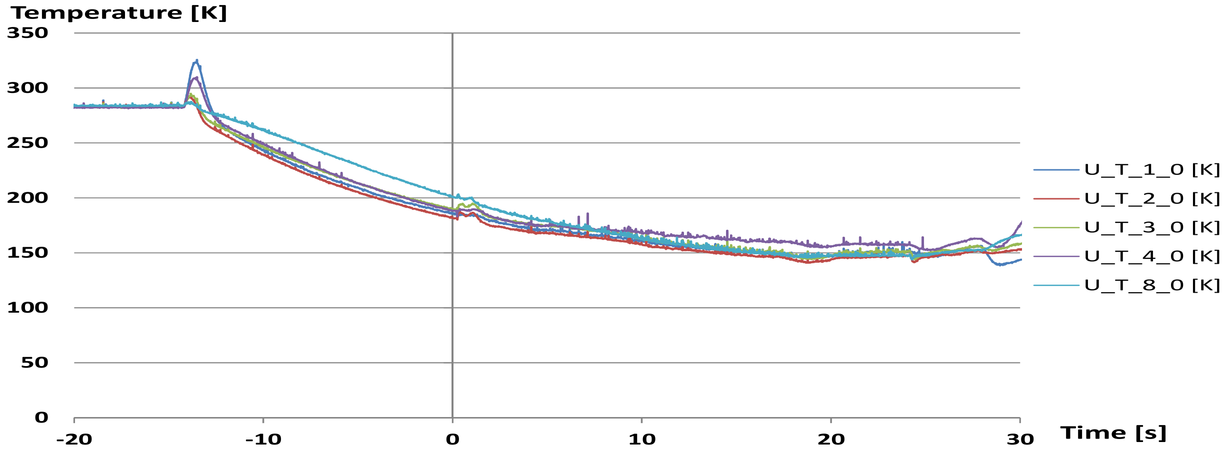


Figure 11: Reservoir temperatures, Test-No. WS1-A – T04-RN1; O/F = 5.5; τ = 6.72.

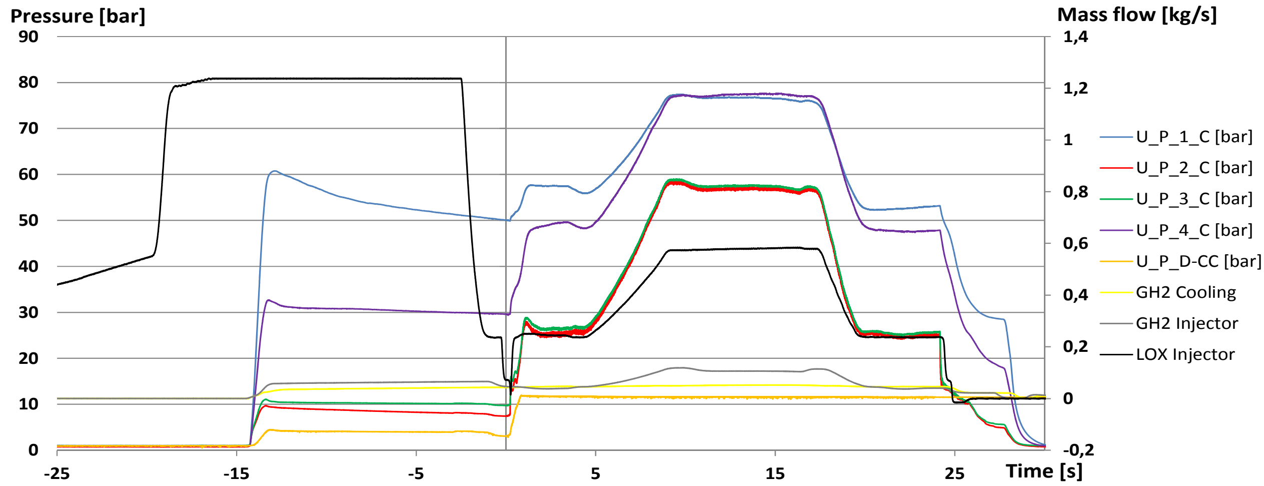


Figure 12: Pressure and mass flow distributions, Test-No. WS1-A – T04-RN1; O/F = 5.5; τ = 6.72.

After the WS1-A tests the relevant materials (OXIPOL, WPS, C/SiCN, C/C-HTA, CVI-SiC coated) didn't show any signs of surface degradation (figure 13). Detailed EDX and SEM analysis will follow, to get information about eventual changes of the microstructure or chemical changes. But the given macroscopic results of the cylindrical test segments demonstrate a significant technology progress (figure 13) compared to MT5-A and KSK-ST5.

The OXIPOL material was located at position No.1, close to the injector. It resisted the LOX attacks and showed a high pressure loss over the wall because of its low open porosity. The low level of resulting permeability could be attractive relating to a pressure loss minimum, which is necessary in case of further coolant mass flow reduction.

The WPS material was already known from other campaigns. It resisted the LOX attack too, as expected from former test results. Within the WS1-A test series enough local coolant mass flow remained, before surface degradation could have occurred, caused by local hot spots.

Especially the C/SiCN-material seems to be an interesting candidate for such an application, because its porosity can be adjusted accurately during the manufacturing process, so that the wall deflation can be optimized along the flow direction, in conjunction with the request of high thermo-chemical resistance. Additionally the possibility exists, to adapt the thermal conductivity by the choice of high thermal conductivity fibers like NGF YHS-50A (Nippon Graphite Fibers). This material type has been used in the WS1-B test section, positioned as segment No. 3 (table 1).

The CVI-SiC coated C/C-HTA segment showed similar coolant deflation behavior compared to the OXIPOL material. An additional advantage of this segment design can be seen in the fact, that the coating layer is accurately closed over the fiber tips at the hot gas surface, because no final grinding process was necessary.

Apart from the cylindrical test segments the Laval-segment (which was made of sensitive C/C) showed visible damages punctually in the convergent nozzle section, close to the nozzle throat. This phenomenon probably comes from an imperfect injector function. This fact affirms the high thermo-chemical resistance of the cylindrical segments, which resisted the same effect. In the next test campaign Laval segments will be applied, made of C/SiCN and CVI-SiC coated materials too. An adequate hot gas resistance will be expected, motivated by the WS1 results.

Figure 13: Demonstration of damage free (at τ = 6.72%) operated cylindrical CMC segments, after WS1-A.

Within the WS1-B test series the major objective consisted in the cooling deactivation during the hot gas run. After the regular pre-cooling and start-up sequence the coolant mass flow was shut down linearly from 5 seconds after ignition, within a 5 seconds long ramp down phase. Afterwards the cooling remained turned off for approximately 7 ÷ 8 seconds. A redline was defined at the reservoir thermocouples, to stop the test, when the reservoir temperatures climbed up to more than 650 K. The following diagrams show the results of the most important test WS1-B-T05-RN1.

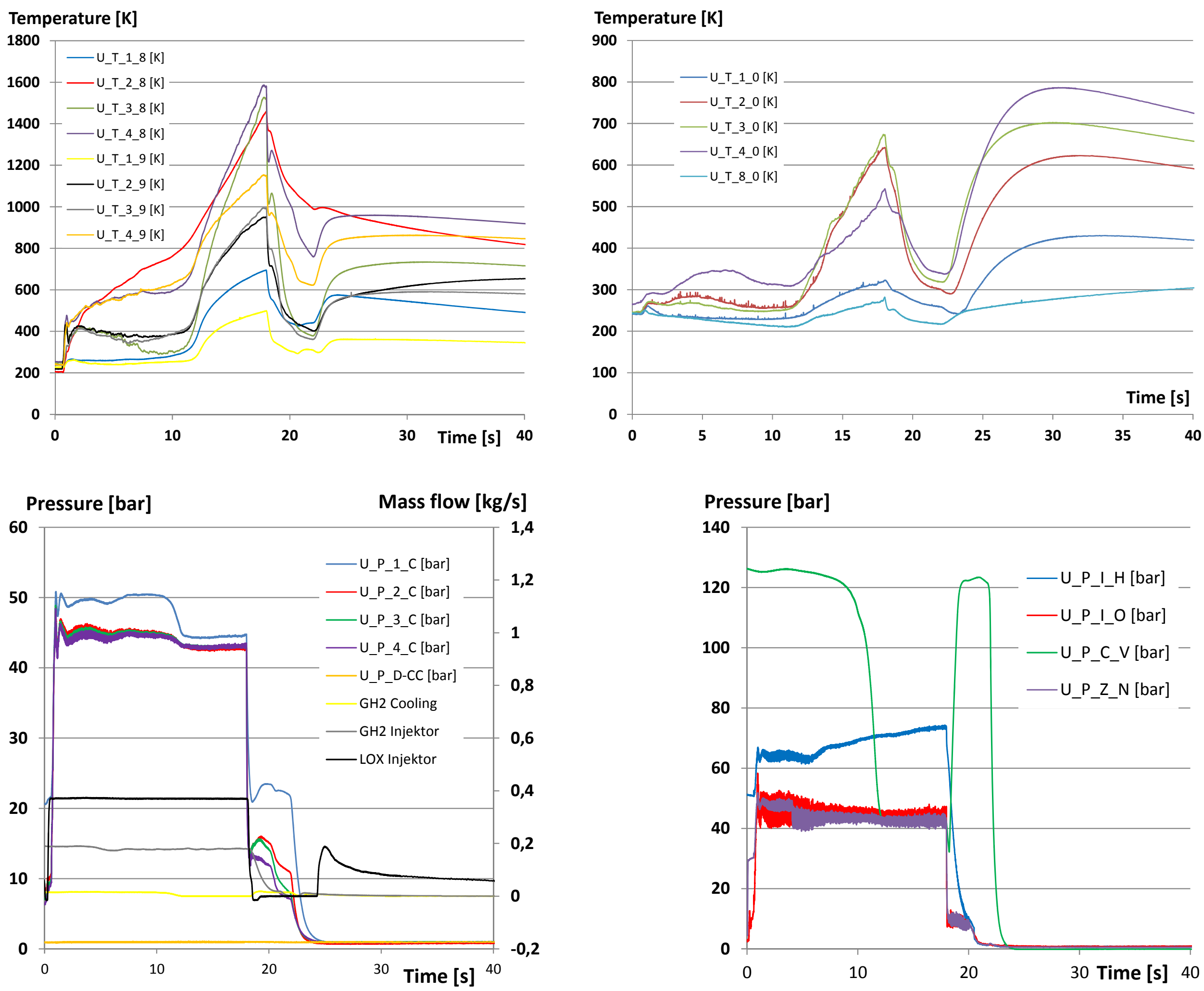


Figure 14: Data acquisition of Test-No. WS1-B – T05-RN1; O/F = 2.0; τ = 5.0 ÷ 0.0; test with ramped cooling deactivation.

The most interesting feature in these tests was the high temperature increase at the hot gas surface. The extrapolation of the T_X_9 and T_X_8 temperatures hypothesize surface temperatures of about 2000 K maximum. Slight material degradations could be observed, but they seemed to stagnate after the first test, so that further tests didn't show additional degradation. This effect will be investigated accurately in the near future, within the WS2/IZ2 campaign.

3.2 CMC injector development

Since a couple of years DLR works on a new rocket injector concept, using highly porous CMC materials as injector elements [8]. The wide experience, obtained in the field of CMC combustion chambers, led to the idea of the implementation of such materials additionally into the faceplates of rocket injectors. The specific thermo mechanical properties of the CMCs allow applications with lower request of geometrical tolerances, accorded by better fatigue behaviour. In parallel they show adequate mechanical strength. Another significant advantage consists in the simple implementation potential of suitable channel structures to get high permeability. Concerning this matter, organic fibers will be inserted into the green body and burnt out later (figure 15, b). The new concept is called 'cone injector', because hollow conical CMC segments will be stacked one into each other, separated by conical segment holders. Alternating gaps will also be supplied by alternating propellant components, to get good spray formation. The principle is given in figure 15. The current design approach shows alternating placement of thin open gaps and gaps filled with porous oxidic CMC (WPS) elements. In the current application the LOX flows through the porous CMC elements and the gaseous hydrogen through the open gaps (figure 16, left). The centred element consists of C/C-SiC material, which shows low porosity and which is slightly cooled with GH2.

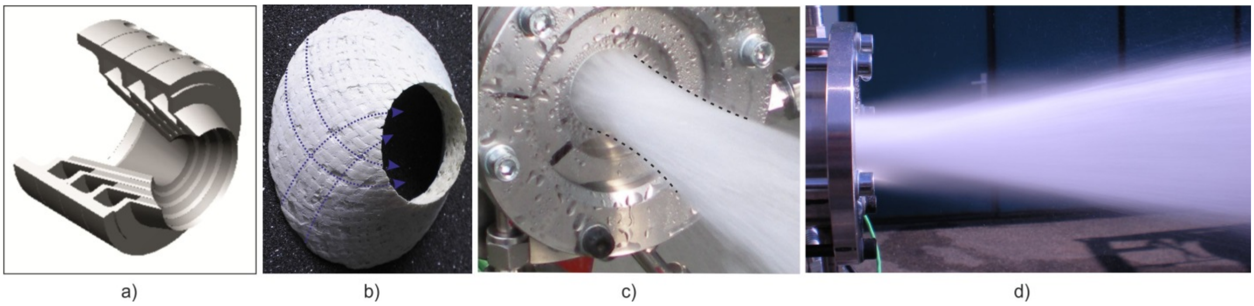


Figure 15: Cone injector – functional principle and cold flow demonstration. Design concept a), inherent LOX channel formation b); water injection (800 g/s, replacing LOX) c); spray formation (800 g/s H_2O plus ~ 60 g/s N_2, replacing LOX and GH2) d).

Before running first hot gas tests the injection has been calibrated, using water and nitrogen as fluid substitutes. Figure 15, c) shows the spray formation of a cold flow check, using water only, figure 15, d) the water mixed with approx. 60 g/s gaseous nitrogen (GN2). Figure 17 shows the cold flow calibration, evaluating the water and nitrogen injection. The water mass flow amounted to 800 g/s, which is enough, to perform a 60 bar test, comparable to the WS1-A tests. The spray contour, given in figure 15, c) is curved into the chamber. All the water jets (approx. 500) together create a hyperboloid spray shape. Mixed with GN2 a compact and finely homogeneous spray can be observed (figure 15, d). At the end of 2012 the first ignition tests have been conducted at the P6.1 test bench within the IZ1 campaign phase. The cone injector was attached to the ST5 chamber module including additionally a transpiration cooled transition segment from 30 mm faceplate diameter to 50 mm chamber diameter.

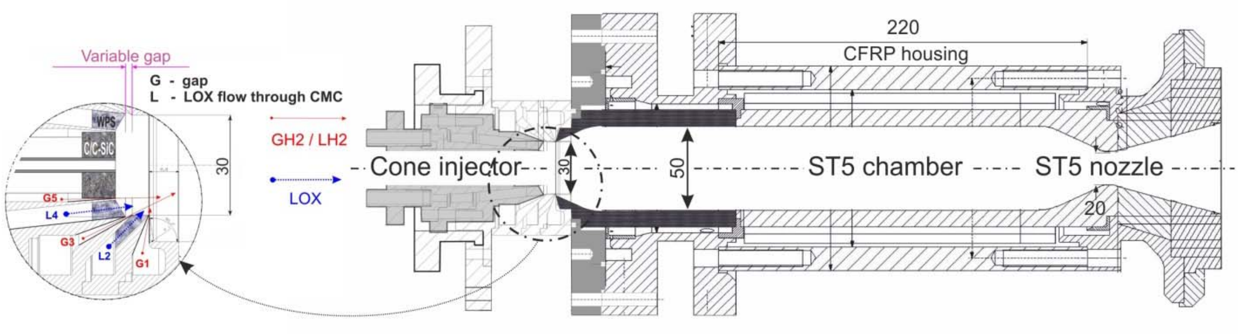


Figure 16: Test set up for the cone injector ignition tests. Faceplate arrangement (left), complete chamber configuration (right).

Higher expected We numbers promise good spray formation and good operation respectively. Table 2 gives some estimated performance parameters of the system in comparison to a coaxial injector system.

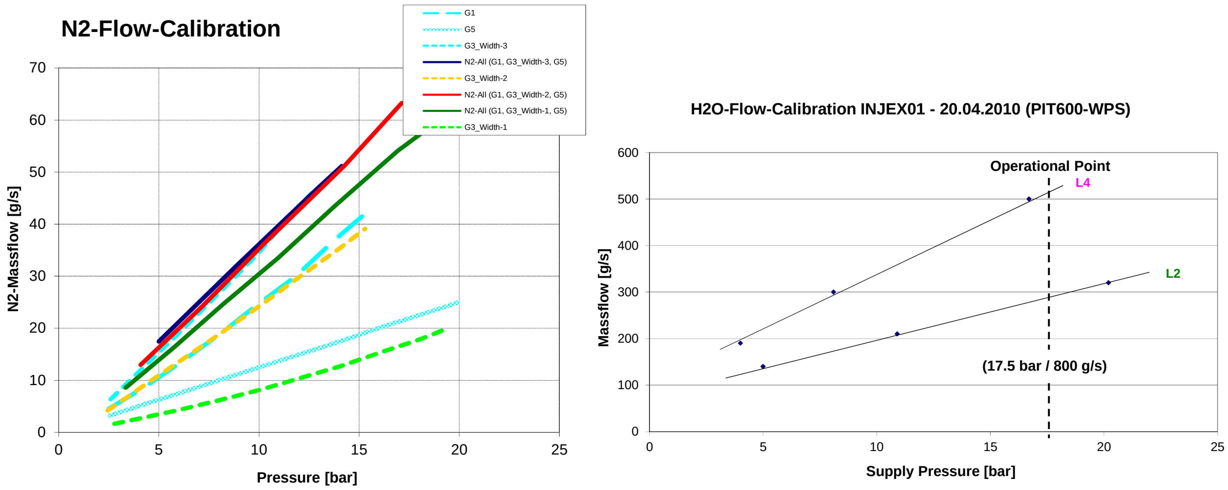
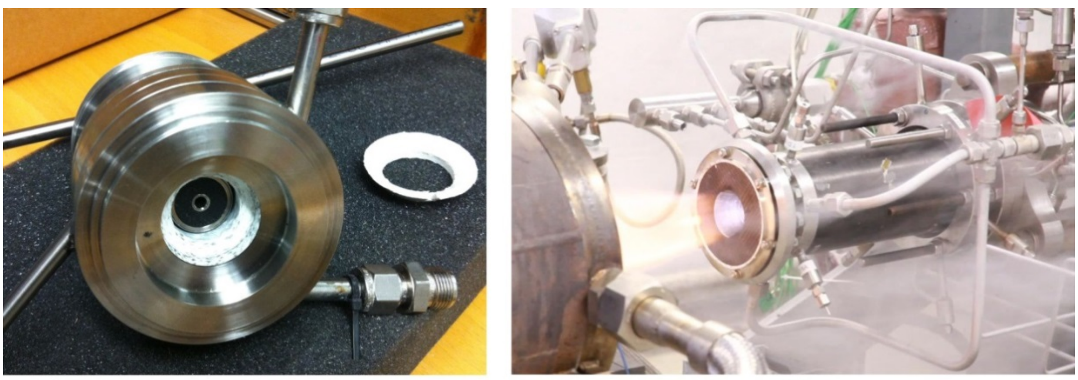


Figure 17: Cone injector – flow calibration; nitrogen flow check (left); water flow check (right).

Table2. Performance comparison of the 'coaxial injector' and the 'cone injector'.

	Combustion chamber with coaxial injector	**CMC thrust chamber with 'cone injector'**
d_{LOX} [m]	0.004	0.031
T_g [K]	125	125
p_C [MPa]	3 / 6	3 / 6
$\rho_g(T_g, p_C)$ [kg/m^3]	5.73 / 11.24	5.73 / 11.24
U_g [m/sec]	270 / 310	270 / 310
T_f [K]	127	127
$\sigma_f(T_f)$ [N/m]	0.0046507	0.0046507
We_g [---]	3.57E+05 / 9.29E+05	2.77E+06 / 7.20E+06
$(We_g = \frac{\rho_g * U_g^2 * L}{\sigma_f})$		

L – characteristic length; U – injection velocity; σ_f = surface tension



a) b)

Figure 18: Cone injector – mounted test sample a); first ignition test (snap-shot at $p_{combustion}$ = 35 bar), using LOX and cold (~120 K) gaseous hydrogen b).

At the end of the WS1 campaign section the short campaign section IZ1 was added. Within the marginal remaining test time one important ignition test could be performed. Figure 18, a) shows the mounted test sample and figure 18, b) the hot gas test after ignition (at approx. 0.75 s). The test was stopped by a redline signal after 0.8 seconds, but within this short operational phase the ignition could be completed. Figure 19 shows the pressure and the mass flow curves. Significant is the high LOX pressure loss across the CMC elements, which amounted to maximum 53 bar at the nominal mass flow of 240 g/s. The high pressure loss led to a phase transformation inside the CMC, so that the oxygen was injected in gas condition. So the propellants have been mixed excellently and inflamed very rapidly.

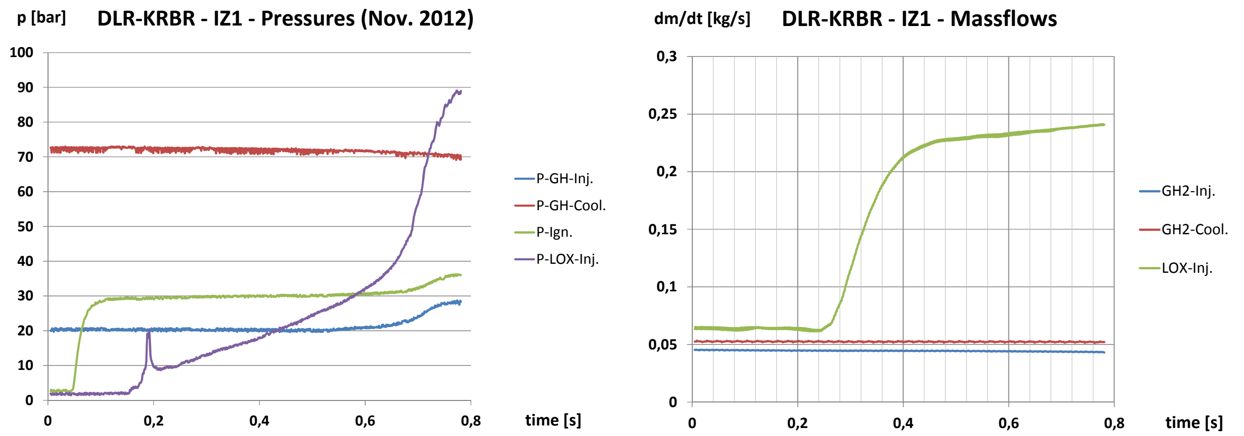


Figure 19: Cone injector – first ignition test data; chamber pressure ($p_{ign.}$), coolant reservoir pressure ($p_{GH\text{-}Cool}$) and injector dome pressures (left);

4. Advanced concepts

Apart from transpiration cooled thrust chambers DLR will extend its CMC applications on regenerative as well as radiation cooled systems too, in the near future. New structural technology approaches arise to be very promising.

4.1 Regenerative cooling of CMC thrust chambers

For October 2013 a further P6.1 test campaign (WS2/IZ2) has been planned, investigating regenerative cooled CMC segments. Based on estimations concerning achievable thermal conductivity and high temperature resistance the potential of CMCs also in this application field arose. Since it seemed to be possible, to create thermal conductivities in the region of λ = 300 W/mK, in radial wall direction, CMCs became interesting candidates for regenerative cooling too (figure 21).. Considering equation (1) higher wall thickness becomes achievable (figure 20), which is important for the implementation of regenerative cooled CMC chamber structures, in conjunction with a light weight CFRP housing, which had been proven within the campaigns KSK-ST5, MT5-A and IZ1.

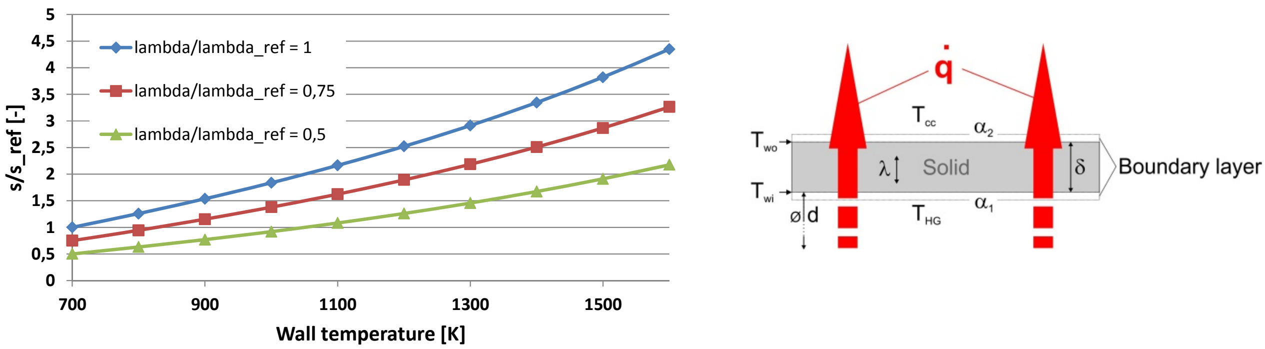


Figure 20: Wall thickness via radial thermal conductivity (left); heat transition principle (right).

$$\dot{q} \;=\; \alpha_1 \cdot (T_{HG} - T_{wi}) = \frac{\lambda_s}{\delta} \cdot (T_{wi} - T_{wo}) = \alpha_2 \cdot (T_{wo} - T_{cc}) \qquad (1)$$

The evaluated case assumed a hot gas temperature of T_{HG} = 3400 K, an outer wall temperature of T_{wo} = 200 K, and a cooling channel temperature of T_{cc} = 50 K. Hot gas parameters will be obtained from CEA [13].

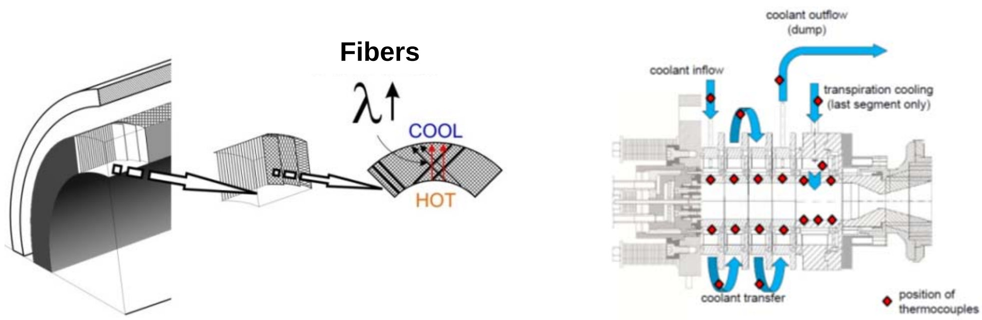


Figure 21: Radially oriented fibers enable high thermal conductivity (left); planned test set up (right).

4.2 New chamber structure approach

In conjunction with the hyperboloid spray shape of the ‘cone injector’ (figure 15 c) the idea arose, to adapt the whole chamber contour onto this geometry. Figure 22 shows the idea. The aim is the reduction of heat loads in the nozzle throat region, compared to conventional chamber contours. This may be managed by the continuously convex inner wall contour. Caused by flow lines, which are oriented continuously parallel to the inner wall contour, a reduction of the wall oriented momentum component should be expected. In particular the continuous second derivative of the contour function promises an effort. The physical correlation will be investigated in an upcoming diploma thesis in the middle of 2013. Regarding equation (2) as well as equations (3) and (4) (Bartz relation) [9], an analytical and numerical evaluation shall give first valuable information about the feasibility of this technology approach, in conjunction with a radiation cooled CMC chamber. As hot gas reference CEA [13] and Nusselt correlations [9] will serve.

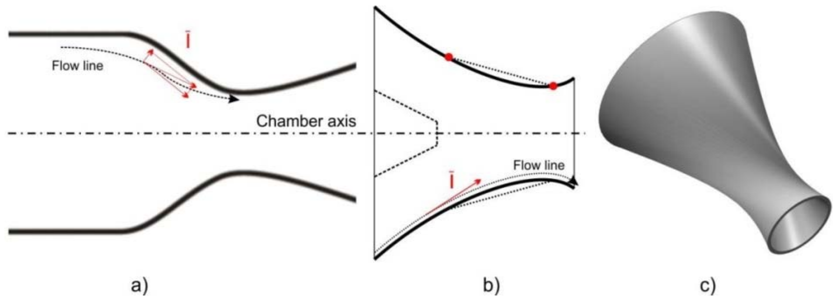


Figure 22: Conventional inner chamber contour a); hyperboloid contour with optional inner core b); 3D-model c).

$$\dot{q} = \alpha_1 \cdot (T_{HG} - T_{wi}) = \frac{\lambda_s}{\delta} \cdot (T_{wi} - T_{wo}) = \sigma \cdot \varepsilon \cdot ({T_{wo}}^4 - {T_{amb}}^4) \quad (2)$$

$$\alpha = \left[\frac{0.026}{{D_{th}}^{0.2}} \cdot \left(\frac{\mu^{0.2} c_p}{Pr^{0.6}}\right)_t \cdot \left(\frac{\dot{m}_C}{A_{th}}\right)^{0.8} \cdot \left(\frac{D_{th}}{r_{curve}}\right)^{0.1}\right] \cdot \left(\frac{A_{th}}{A(x)}\right)^{0.9} \cdot \sigma_B \quad (3)$$

$$\sigma_B = \frac{1}{\left[\frac{1}{2}\frac{T_{wi}}{T_t}\left(1+\frac{\gamma-1}{2}\right) Ma_c^2) + \frac{1}{2}\right]^{0.8-0.2\omega} \cdot \left[1+\frac{\gamma-1}{2} Ma_c^2\right]^{0.2\omega}} \quad (4)$$

(D - diameter, μ - viscosity, Pr - Prandtl No., $\dot{m}_c$ - chamber mass flow, A - area, r - radius, σ -Planck’s constant of the black body, ε – emissivity; indices: th - throat, t - total).

5. Conclusion and outlook

Since the beginning of DLRs transpiration cooled ceramic rocket thrust chamber development, multiple investigations concerning operational efficiency, structure and material verification as well as numerical validation predict nowadays a high level of feasibility. The cooling efficiency quasi could be proved, considering scaling aspects. Both structural integrity as well as thermo-chemical resistance exists, showing enough operational safety. It is supposed, that in the following P6.1 test campaign (WS2) at the end of 2013 all important technology parameters will be consolidated for the first time to complete the first global phase of DLRs CMC rocket thrust chamber technology demonstration. Combined with the light weight and low fatigue features it shows high application potential, especially for high performance applications. Beyond that, new technology approaches arise, to introduce

CMCs into regenerative cooled as well as radiation cooled systems, where current business cases seem more likely. Concerning regenerative cooling in particular the aspect of significant weight reduction potential makes this technology highly interesting. Apart from this, high reliability is expected, because of design simplifications and the reduction of thermo-mechanical constraints. Additionally a new CMC injector concept becomes very interesting. Apart from good performance a CMC injector could bring advantages related to high temperature injection. In the same way it could increase combustion stability in conjunction with ultra-cold injection, because of very finely distributed LOX jets and a resulting good propellant mixture. This will be investigated in detail in future campaigns. Concerning radiation cooling a new chamber contour approach, especially in combination with the CMC injector concept seems to be promising to reduce heat loads in the critical chamber sections. Apart from the hardware development multiple effort is been taking referring numerical tool development, to rule and to understand better the CMC rocket thrust chamber processes.

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