Experimental investigations for cooling channel structure lifetime, rocket combustion chamber and cooling channel flow characterization

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The present study aims to contribute to the understanding of the thermal transfer and mixing processes for GCH4/GOX single and multi-element shear coaxial injector. The experimental data provide a benchmark for the validation of CFD numerical tools for the new propellant combination and offer an example of scaling methodology for multi-element and single-element chambers. A high-pressure facility operated at conditions typical of rocket engines is used. Experimental investigations as well as numerical simulations provide detailed information about the heat flux at the hot inner walls of the combustion chamber and a flame structure for pressures up to 20 bar. Heat flux was calculated by solving 3D unsteady heat conduction equation using the inverse method.

The set-up and the first tests of a fatigue segment for lifetime investigations of cooling channel structures under thermo-mechanical cyclical load are presented. This segment is placed downstream of the 5-injector-combustion chamber. The measurements show an expected behaviour mostly.

A 2 color laser induced fluorescence technique is applied in a duct flow with one heated wall. The experimental setup is described in detail and results are presented. Advantages of the 2 color technique over a 1 color technique are given bases on measurements and temperature profiles are presented.

1. Introduction

A key to improve the understanding of nozzle lifetime as well as the computational tools to predict fatigue failure are high-quality, well documented, reliable experiments comprising the three core elements. These are the hot gas flow, defining the flow state and the heat flux to the structural surface, the (local) structure of the nozzle, interacting with the hot gas flow and the flow in the cooling duct, while ensuring the heat transfer and withstanding the structural and thermal loads and the flow inside the cooling ducts, picking up the heat from the metallic walls.
The step-by-step approach proposed to face the complexity of the heat transfer problem and the combustion phenomena in a rocket combustion chamber, has required the design, manufacturing and testing of a single-element and multi-element combustion chamber. To allow the transfer of information from one hardware to the other a basic strategy is devised for the design and testing of the hardware. To scale between a full-size and a smaller-size combustors a practical approach largely used in the industry is the use of identical injector elements. Such an approach is preferable when it comes to combustion and performance studies. The injector element itself has the greatest impact on heat transfer, combustion stability and performance. Keeping the same element means therefore injector parameters which will match between the two chambers. Additionally, with a proper choice of the geometry, the Mach number, and so the convective processes in the chamber, can also be matched. In the context of this study this criterion has been selected to compare a single-element chamber and a multi-element chamber. The two combustors keep therefore the same injector element. Moreover, to maintain the same mean level of mixing in the developing combustion flow field, the contraction ratio of the hardware is identical, and so is the mean value of the Mach number. By maintaining the geometrical similarities previously described, the combustion parameters in terms of pressure and mixture ratio are kept the same. Keeping the same nominal combustion conditions results in a possible variation of the injection condition that could lead to different performance of the injector.

For modular life time experiments of the cooled rectangular sub scale rocket combustion chamber a fatigue section was designed and tested, which houses a replaceable fatigue specimen with 17 rectangular high aspect ratio cooling channels. This specimen will be loaded cyclically and inspected after each cycle. In the past some experiments on cylindrical sub scale combustion chamber structures were conducted, for example see Quentmeyer [1] and Anderson et al. [2]. In other experiments flat specimens were investigated, in which the hot gas flow was replaced by laser irradiation, for example see Gernoth et al. [3]. The novel approach is the use of a replaceable, rectangular specimen with hot gas flow and individually controlled cooling flow through the cooling channels, what leads to well defined conditions. Because of that the results can be used also for validation of numerical simulations.

To better characterize the flow in a high aspect ratio cooling duct with one heated wall, a study has been undertaken to measure instantaneous and mean temperature fields in two dimensions. Flows in ducts with rectangular cross sections and high aspect ratios are widely spread in technical applications. Many of these duct flows serve as cooling channels for surrounding surfaces or devices. Typical engineering examples of such flows range from cooling channels in hybrid electric vehicle motors to the cooling system in regeneratively cooled rocket engines. The flow in high aspect ratio cooling ducts is highly affected by secondary flow structures perpendicular to the bulk flow direction, which appear in the duct's corners. The velocity magnitude of the secondary flows is typically some orders of magnitude smaller than the bulk flow velocity.

A detailed understanding of these flows including the thermal fields is important for the cooling channel's optimal design and for lifetime predictions of the cooled devices. Hence, non-intrusive measurements of the velocity and the temperature fields are very interesting and useful.

This paper focuses on the measurement of the temperature field. A detailed description of the flow field in the duct is given in [4].

In the following sections a description of the set-up and operating conditions as well
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2. Combustion chamber

2.1. Experimental set-up and operating conditions

In this section a description of the instrumented subscale rocket chambers, injector geometry, and flow condition is presented. As mentioned in the previous paragraph, a basic strategy is elaborated such that the information and results obtained from the hardware set-ups can be interchanged and combined. Fundamental geometrical parameters like contraction ratio and characteristic length are kept constant for the two hardware.

The single-element rocket combustion chamber is depicted in Fig. 1, while Fig. 2 shows the multi-injector chamber. The modular combustion chambers have a square 12 mm x 12 mm and a rectangular 48 mm x 12 mm cross section respectively and they are designed for a testing time of up to 4 s at a chamber pressure of 20 bar and mixture ratio of 3.4. The cross section dimensions are so designed to provide the same injector-wall distance of 3 mm in both configurations. The same distance is also kept between the injectors in the multi-element chamber. The nozzle is a truncated trapezoidal prism with a rectangular throat section of 4.8 mm x 12 mm for the single element chamber and 4.8 mm x 48 mm for the multi-element chamber. A Mach number of 0.24, typical for rocket applications, is achieved with a contraction ratio of 2.5 for both chambers.

For the current study, a shear coaxial injector element is integrated. For simplicity, the GOX post is configured flush mounted with respect to the injection face. To ensure homogeneous injection conditions, in terms of temperature and pressure, two porous plates are placed in the oxidizer and fuel manifolds respectively. The injection head is kept consistent for both configurations: porosity and thickness of the plates installed in the manifold as well as the distance to the injection point are equal.

The capacitive nature of the chambers allows for the implementation of a large number of measurement sensors with a good space resolution. Thermocouples are embedded at a series of evenly distributed axial and transversal points to determine the temperature field in the chamber wall. A schematic presentation of the thermocouple pattern is given in Fig. 3 and Fig. 4. In the single-element chamber the temperature readings are installed only in the middle plane, while for the multi element chamber an additional pattern of thermocouples is mounted also in transversal direction, in order to

as an analysis of the obtained results for the combustion chamber, the life time and cooling channel flow experiments are presented. In the end a short conclusion is given.
resolve the injector footprint on the chamber walls. Along the chamber axis, the same spacing of 17 mm is kept in both combustors.

For a better understanding of the combustion processes, equally spaced pressure transducers provide for a well resolved measurement of the wall pressure distribution \( p(x) \) along the chamber axis. The spacing of 17 mm between the measurement positions in the multi-element chamber is doubled in the single element chamber due to hardware constraints. Further information about the hardware setup can be found in previous publication [5, 6].

The test matrix includes testing at pressure levels from nominally 20 bar down to 5 bar and at mixture ratios of 2.2, 3.0, 3.4 and 4 (4 only for the 5 bar case). The ignition of the chamber is achieved by a torch igniter using gaseous oxygen/gaseous methane. In the single element chamber, the igniter is mounted to the side wall of the combustion chamber at the end of the first segment, since previous studies [7] have shown its strong influence on the transient temperature measurements. In the multi-injector chamber instead it is installed in the side wall but in the region close to the faceplate. To operate the combustion chamber, a test sequence is programmed into the control system. Similar sequences are used for the operation of both hardware to eliminate the possibility of influences on the test results.

The burn times of the combustion chambers are chosen to reach stable operation, required for the thermal load measurements, and equal in both case to 3 s. Each of the operating points is run at least twice to ensure the repeatability of the recorded test data. Good agreement within 1% is obtained for all load points.

With regards to the scaling methodology selected for the current work, the same theoretical pressure is maintained on the two test set-ups and tests are performed at the nominal conditions of 10 and 20 bar and mixture ratios from 2.6 to 3.4.

2.2. Experimental results and discussion

The main goal of this investigation is to determine the thermal and pressure load distributions along the combustion chamber main axis and to compare the behaviour of the single injector chamber with the multi injector chamber, in order to be able to characterize the injector element and try to understand the influence of the injector-injector interaction as well as the change in geometry of the cross section. In the present paragraph the distribution of wall pressure, surface temperature, and the corresponding gradients in the combustion chamber wall along the chamber axis and their transient behaviour during the hot run are shown. As an example of the test results obtained in the present test campaign, in the following section the 20 bar combustion chamber pressure, 2.6 and 3.4 oxidizer to fuel ratio (ROF) test case is analysed in more details. Due to the transient nature of the problem, a time is taken at 2/3 of the hot run in order to minimize the influence of the transient at the start-up. Temperature and pressure distribution
Influence of the combustion chamber geometries

When coming to the comparison of the test results, the difference in combustion geometry has to be taken into account since this is one of the influencing parameters for the performance of the combustor. Cross section geometry and chamber length are the two most important features which have to be in focus. To try to isolate the effects resulting from the difference in cross-section and the interaction between the injectors, most of the geometry parameters are kept similar between the two chambers, as described in Section 2.1.

Once the necessary minimum characteristic length is reached, the chamber length, depending on the injector design, can influence the overall performance but often at a much slow rate. Injector elements, like coaxial injectors, which have a higher initial interpropellant mixing show little mixing increase with increased combustion chamber length [8]. As already described the two combustors have similar chamber length and characteristic length with a variation of less than the 4%<sub>o</sub>, which ensures that the residence time of the propellants in the combustion chamber is kept similar within the same margin.

Additionally, the two set-ups have the same injector design and the same contraction ratio. In this way the mean level of the mixing process in the developing combustion flow field is kept similar. The same mixing characteristic lengths and convective velocities of the fully developed flow can be ensured. The identical distance of the injector elements to the chamber walls provides similar interaction of the flame with the combustion walls. An overview of the parameters is given in Tab. 1.

Although most of the geometric parameters are maintained similar, a significant discrepancy is due to the different hydraulic diameter and the volume to surface ratio (V/As). These inconsistencies may cause difference in pressure losses due to the friction and heat losses to the chamber wall. To be taken in account is also the difference in mass of the hardware, since the multi-element chamber is having 35% more mass than the single element chamber. However, the thickness of the upper wall, where the temperature measurements are installed, is bigger for the rectangular chamber and the impact of the additional material present in the corner on the measuring positions is less relevant. The main effects coming from the differences in mass and mass distribution are visible in the temperature readings.

Figure 5 shows the temperature profile for the complete testing time of the single-element chamber and the multi-element chamber of the thermocouple positioned at two

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single-element chamber</th>
<th>Multi-element chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic length</td>
<td>$L^*$ $(m)$</td>
<td>0.749</td>
</tr>
<tr>
<td>Contraction ratio</td>
<td>$\epsilon$ (-)</td>
<td>2.5</td>
</tr>
<tr>
<td>Area per injector</td>
<td>$A_{e,nf}$ $(m^2)$</td>
<td>$144 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>Hydraulic diameter</td>
<td>$D_{hyd}$ $(m)$</td>
<td>$12 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Surface per unit length</td>
<td>$P$ $(m)$</td>
<td>$48 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Volume mass</td>
<td>$V_{At}$ $(m^3)$</td>
<td>$1.19 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Volume chamber to surface ratio</td>
<td>$V/As$ $(m)$</td>
<td>$3.10 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>$t$ $(m)$</td>
<td>$19 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

**Table 1.** Common geometrical parameters of the hardware.

along the chamber axis are calculated as mean values over a 0.5 s time interval around the chosen time.
different axial positions, one installed at the end of the first segment and the other positioned at the end of the second segment. The selected thermocouples are positioned at identical distances $z$ from the faceplates in both hardware. At the start-up, when the heat information has not yet reached the external surface, the difference in slope of the temperature profiles depends only on the different surfaces made available. Later on, the mass acts like a heat sink and decreases the steepness of the curve. No significant different is visible in the first part of the curves, where the increase in temperature is pretty similar between the two set-ups. A more significant change can be instead seen in the second part of the profile, where it is possible to recognize a more linear increase in temperature for the multi-element chamber compared to the more curved profile shown by the measurement readings in the single element chamber. The additional mass of the corners strongly impacts the temperature signal of the thermocouples in the middle plane of the single-element chamber generating the characteristic “round” shape, while it is not having an influence on the ones in the middle plane of the multi-element chamber. The difference in mass distribution is also visible at the shut-down. While in the quadratic chamber the temperature of the material cools down quickly, the rectangular chamber remains hotter. In Fig. 6 the slope ($dT/dt$) of the aforementioned temperature profiles is given for the complete operation time. At the starting time the slope of the set-up differs a lot due to the different start-up transient of the chambers, the same has to be noticed for the shut-down phase. After the thermal information has travelled the thickness of the material, the slope decreases progressively in a similar way and approaches a constant value. This value is the same for both chambers, and not significant differences can be highlighted. A small peak is present in the single element chamber after one second from ignition. Not exhaustive explanation could be found for them and a link can be hypothesize to transient phenomena, like the presence of condensation. Since the variation of temperature over time is a function of the heat load level on the chamber walls, comparable values of the heat flux have to be expected.

**Chamber wall pressure readings**

The approach adopted to compare the set-ups is to keep both the nominal combustion chamber pressure and mixture ratio constant in the combustion chambers. The combustors will experience the same propellant chemistry, flow mixture ratios and similar propellant inlet temperatures. Therefore, non-dimensional number like the Prandtl
and the Schmidt are kept constant. With similar pressures in the chamber and the Mach numbers hot gas velocities are identical. These hypotheses are necessary to obtain a scalability criterion for the chemical conversion time, as suggested by Penner. Additional information has to be given about the Reynolds (Re) and the Damköhler (Da) numbers to fulfill the “Penner-Tsien scaling rule”. The Reynolds number is a function of the hot gas properties and velocities, which have to be similar due to the similarity in geometry and operating conditions. The characteristic length for the Re of the flow, meaning the hydraulic diameter, is anyhow different and a higher Reynolds number has to be expected for the multi-element chamber. By combining the Da and the Re, like shown in Eq. (2.1), it is possible to draw a conclusion on the chemical reaction time \( \tau \). For the geometries under analysis, a higher chemical reaction time has to be expected for multi-element chamber.

\[
\frac{\tau_{\text{multi}}}{\tau_{\text{single}}} = \left( \frac{D_{\text{hyd, multi}}}{D_{\text{hyd, single}}} \right)^2
\]  

The residence time of the propellants in the chambers is almost identical due to the similar characteristic length \( L^* \), but the chemical reaction time for the hardware set-ups is not the same. Thus, differences could arise in the combustion process. In particular, even though the mixing process has to be expected similar, a possible deviation in heat release and in pressure decay along the chamber axis can take place. For the scaling approach chosen, to achieve the same nominal combustion pressure level in the two combustors, the injected mass flow needs to be scaled proportionally to the difference in cross sectional nozzle areas, since the contraction ratio is identical. The combustion chamber cross sectional area per injector \( (A_{\text{c,inj}}) \) is 20\% smaller for the multi-element chamber, meaning that 20\% less mass flow rate has to be injected to obtain the same mean chamber pressure. The smaller mass flow rate per injector leads to a directly proportional decrease in the velocity at the injector, with consequent different injection conditions in the two chambers.

Keeping this in mind, Fig. 7 and Fig. 8 show the comparison of the wall pressure distribution, on the left for a mixture ratio of 2.6 and on the right for a mixture ration of 3.4 for a chamber pressure of 20 bar. The figures show the pressure signal normalized with the last sensor value. Due to the combustion processes, the injected mixture accelerates from the injection velocity to the hot gas velocity for a full combusted flow. Consequently, the static pressure decreases along the chamber axis and tends to flatten when the reaction has reached is completeness. A pressure gradient from 4 up to 5\% can be seen for both load points and both hardware configurations. No considerable difference is visible in the pressure decay for the different mixture ratios. Similar results were also obtained for LOX/GH2 by Suslov et al. [9]. In the region close to the faceplate, a drop in wall pressure is observable. This drop is linked to the presence of a recirculation zone. The stagnation point, shown by the pressure peak, is located at an axial distance \( z \) of about 30 mm. It occurs for both hardware at a similar location and it is clearly identifiable for the multi-element chamber.

The curves anyhow show a difference in steepness of the pressure profile when comparing the two hardware configurations. A much steeper profile can be recognized for the multi-element chamber with a stronger flattening at about \( z=200 \) mm. For the single-element chamber it is visible a smoother decrease of the pressure along the chamber axis with a flattening only shortly before the nozzle. Both observations point to a shorter flame length and a faster combustion process for the multi-element chamber. The interaction between the injectors and the merging of the flames intensifies the mixing process.
and ensures zone with higher temperature, where the reaction kinetics is accelerated, promoting a faster development of the combustion processes and a major acceleration of the hot gases. The smaller injection velocities additionally support a shortening of the flame. Having less mass per injector allows an increase in exchange of the propellants in the radial component, which have higher probability to mix over the same combustion chamber length. Since the radial mixing is controlled by the same characteristic length, meaning same injector geometry and thickness of the oxygen post, the axial injection velocities are reduced. The time required for the mixing of the propellants will be therefore reduced. Not to be forgotten is also that the lower mass flow rate injected, hence the lower velocity at the injection, produces a faster acceleration of the flow. The flow in fact needs to reach the same combustion velocity (same pressure level and contraction ratio). Due to the different acceleration it would result in a difference in the turbulence of the flame, which would contribute to local mixing of the species and completeness of the reaction.

Fundamental information is also obtained by the observation of the absolute pressure values for the two configurations shown in Fig. 7 and in Fig. 8. Even when aiming at the same nominal value for the combustion chamber pressure and for the mixture ratio, the injection conditions slightly vary for each test and deviate from the desired value. Hence higher or lower mean chamber pressure can be reached with misleading results. A correction needs to be introduced to filter out the influence of the variations due to the deviation of the injection conditions from the desired nominal one. The throat area and the combustion chamber characteristic velocity $c^*$, the combustion chamber pressure is corrected as shown in Eq. (2.2).

$$P_{c,corr} = P_{c,test} \left( \frac{(\dot{m}c^*)_{nom}}{(\dot{m}c^*)_{corr}} \right)$$

A clear trend is shown in Fig. 9 and in Fig. 10: the measured wall pressure for the single-injector chamber is higher compared to the multi-injector chamber. Despite an intensified mixing process, favored by the stronger flames interactions, and a shortening of the reaction zone which would result in higher efficiency hence higher mean chamber pressure, additional effects have to be addressed. The heat transfer to the chamber walls is a convection driven mechanism. If Re and Pr have a similar value, comparable
level of convection heat transfer has to be expected according to the Nusselt correlation: \( \alpha \propto Re^{m}Pr^{n} \). As already highlighted, higher Reynolds number are expected for the rectangular chamber, due to the bigger hydraulic diameter, while Pr stays constant. Additionally, the V/As is 60% higher in the case of the multi-element chamber. Per unit length of the chamber a much bigger surface is made available to disperse the energy produced by the combustion. The energy per unit volume introduced in the system instead is slightly higher in the case of the multiple injections, but the variation is less than the 4%. Consequently, the rate of heat addition per unit volume by the chemical reaction and the rate of heat removed by the convection are not in the same relation for the two combustors. This would then justify the lower level of combustion chamber pressure achieved. Likewise, the throat area is 4 times larger for the multi-element chamber, while the thickness of boundary layer, which is a function of the Re in the chamber according to \( \delta/L \propto 1/Re_{\infty}^{0.2} \), decreases only by a small percentage. The resulting throat effective area and consequently effective contraction ratio is bigger for the rectangular chamber. This statement furthermore justifies the difference in chamber pressure level.

**Axial temperature readings**

Due to the steady combustion, the temperature increases monotonically along the combustion chamber axis until the reaction process is accomplished. For the current analysis only the temperature difference \( T^* \) between the signal at the evaluation time and at the initial time (before the hot run starts) is considered to compare the set-ups. 

Fig. 11 and Fig. 12 show the temperature reading of the thermocouples positioned at 1 mm from the hot surface along the chamber axis during the hot run for both configurations.

Due to the different heat capacity of the chambers, an equal heat rate distributed on the hot gas surface would lead to higher temperature level for the chamber having less mass to disperse the heat. Therefore, higher temperature level would have been expected for the single-element combustion chamber. From the experimental results, instead, a different tendency is observed. The temperature level of the multi-injector chamber is higher than the one of the single-injector chamber even though the wall is thicker, like reported in Tab. 1. This behaviour can be explained by considering the difference in distribution of heat flux on the chamber wall and material of the chamber. While for the rectangular chamber the measurement points are installed in the central
plane, far away from the corners, in the square chamber the corner are much closer to the thermocouple positions and tend to greatly influence the measurements, acting like a heat-sink. Furthermore, in case of multiple injectors the flame interaction results in a more homogeneous distribution of the heat flux on the chamber walls in transversal direction, which ensures a larger area with high temperature. The measurement points are positioned in a region with smaller gradients, and therefore with less dispersion of heat, which directly results in higher temperature levels. All curves present a steady rise along the chamber axis until a small plateau is defined in the last section, close to the nozzle, as indication of end of the reaction process. The axial position of the curve flattening is different between the two combustors. It happens in a more upstream position for the multi-element chamber confirming the shortening of the reaction zone compared to single-element chamber as already observed in Fig. 7 and Fig. 8. Pressure distribution along the chamber axis at Pc=20 bar, ROF=3.4. The steepness of the two profiles is also different and mainly two regions are identified. Close to the faceplate and up to z=90 mm, the increase in temperature is identical between the two combustors. For further downstream positions, the rectangular chamber shows a faster and steeper increase in temperature. The differentiation in the temperature behavior can be explained hypothesizing that at this axial position the flame touches the chamber wall for the first time and generate the sudden increase in temperature level. This increase is stronger and more visible for the multiple flames, due to the interaction between the flames and, as already discussed previously, for the different transversal distribution of the mass of the chamber to the heat loads on the chamber walls. Confirmation of this hypothesis is given by undergoing numerical investigations. In contrast to the pressure, the temperature at the end of the single-element combustion segment is still increasing. This increase is related to the high heating of the nozzle block and dissipation of this heat the downstream.

3. Fatigue experiment

3.1. Fatigue experiment set up

For lifetime investigations of cooling channel structures under thermo-mechanical load, especially the so called "dog-house" effect as structural failure mode, a fatigue segment
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Figure 13. Fatigue experiment set up

is placed downstream of the finalized combustion of the previous described GOX-GCH₄ 5-injector rectangular combustor. A replaceable fatigue specimen is loaded cyclically. One cycle consists of pre-cooling (2 s), hot run (20 s) and post-cooling phase (20 s). After each cycle the deformation of the specimen hot gas wall is measured by a laser profile scanner. The water-cooled inspection plate will be disassembled for it and allows an optical access to the fatigue specimen without the need to remove this. The fatigue specimen made of copper alloy CuCrZr is attached on the fatigue segment with a floating bearing which allows a free thermal expansion. It has 17 rectangular cooling channels with a height of 8 mm, a width of 2.5 mm, a fin thickness of 2 mm and a length of 100 mm. The hot gas wall thickness is 1 mm. Figure 13(a) shows a cut view of the fatigue segment and visualizes the fluid flows (red for hot gas, blue for coolant).

Supercritical nitrogen is used as coolant. To ensure well defined conditions in the 3 center cooling channels the mass flows here are controlled individually for each channel by a PID (Proportional-Integral-Differential)-control. The remaining 14 cooling channels are distributed in 2 mass flow controlled sections. The mass flow is measured in each of the 5 sections by coriolis flow meter downstream of the fatigue specimen. Also the inlet pressure is regulated by a PID-control. The temperature and pressure of the coolant are measured up- and downstream of the specimen in each section by thermocouples respectively pressure transducers. Furthermore, the specimen is equipped with a set of thermocouples in different positions and depths to measure the temperature distribution in the structure during each cycle. Figure 13(b) shows the top view of the fatigue specimen with the thermocouple positions T6-T23 (red for 3 mm and blue for 5 mm hot gas wall distance). The thermocouples have a space of 5 mm in axial and 4.5 mm in transversal direction. They are located in the symmetry planes of the fins and are pushed by a spring construction against the measurement locations in the eroded blind
holes. The set-up of the fatigue experiment is explained in more detail in [10] and its design process in [11].

3.2. Fatigue experiment results

The first experiments of the fatigue segment under hot gas load were executed. Table 2 shows the test conditions for these experiments. Because of safety reasons, for the first hot gas test the double coolant mass flow and the half hot gas pressure of the for the life time experiments planned values were used. Since this test was successful and the temperatures were in a expected frame, the coolant mass flow was bisected for test no. 2. This test was repeated to test the reproducibility, what could be verified, because the measurements have shown the same behaviour almost. For test no. 4 the hot gas pressure was doubled, but the combustion was not stable. Therefore, this test was repeated and executed successfully with a stable combustion. The hot gas flow duration is still limited to few seconds actually to protect the capacitive-cooled combustion chamber from too high heating. The preliminary tests of the water-cooled combustion chamber for experiments with longer hot gas flow duration are in progress currently.

Table 2. Test conditions fatigue experiment

<table>
<thead>
<tr>
<th>test no.</th>
<th>coolant pressure [bar]</th>
<th>coolant mass flow [g/s]</th>
<th>hot gas pressure [bar]</th>
<th>hot gas flow duration [s]</th>
</tr>
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<tr>
<td>1</td>
<td>70</td>
<td>680</td>
<td>10</td>
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<td>70</td>
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<td>3</td>
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<tr>
<td>5</td>
<td>70</td>
<td>340</td>
<td>20</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Figure 14(a) respectively Figure 14(b) show the temperature transients of the thermocouples in flow direction respectively transversely thereto for test no. 5 (full lines for 3 mm and dashed lines for 5 mm hot gas wall distance). After regulation of the coolant flow during the pre-cooling phase, the hot gas phase starts at about \( t = 15 \) s. Initially all temperature gradients increase, because of the hot gas flow development and the thermal capacity of the specimen. The temperature gradients decrease after about \( t = 16 \) s. One reason for it is the increased specimen hot gas wall temperature, what lead to lower heat flux. A second reason is the transient heat conduction and dissipation inside the structure. The temperatures reach there maxima at about \( t = 16.9 \) s, what is short after stop of the hot gas run (about \( t = 16.8 \) s) and decrease then during the post-cooling phase. As expected, the thermocouples in 5 mm hot gas wall distance react slower as adjacent thermocouples in 3 mm hot gas wall distance and reach lower temperature maxima.

Figure 15(a) shows the temperature distribution in flow direction at the end of the hot run phase, 1 and 2 seconds later. The origin of the coordinate system is the centroid of the fatigue specimen (see Figure 13(b)). The temperature increases in z-direction (equates the coolant flow direction respectively against the hot gas flow direction). This was expected, because of the heating of the coolant in z-direction and cooling down of the hot gas against the z-direction. Figure 15(b) shows the temperature distribution transversely to the flow direction for test no. 5 for the same points of time. It shows an approximately parabolic temperature profile. This was expected, because of the sepa-
rated flow at the combustion chamber corners, what leads to lower heat flux. A second reason is the heat capacity and the additional cooling channels of the specimen outside of the combustion chamber width. Thermocouple T19 deviates from the expected temperature profile. It seems, that it has a contact problem to the structure, because its maximum temperature is lower and its cooling is slower than expected.

After these first 5 experiments no deformation of the hot gas wall was measurable.

In the framework of TRR40 subproject D3 a thermal FEM-simulation of the fatigue specimen was provided. This simulation, what is validated by the thermocouple measurements, allows information about the hot gas wall temperatures, where transient temperature measurements are not possible because of the harsh environment conditions. It shows, that the hot gas wall temperature reaches approximately 900 K after 20 s hot gas flow for a combustion chamber pressure of 20 bar and a cooling mass flow of 340 g/s at 70 bar pressure. This is just below the desired hot gas wall temperature of 950 K. Therefore, it seems that these test conditions are suitable as start conditions for the planned test campaign with 20 s hot gas flow. For more information about the simulation and a comparison with the experiment see [12].
4. Application of laser-induced fluorescence technique in a duct flow with one heated wall

4.1. Principles of fluorescence and ratiometric LIF technique

LIF is an optical, non-invasive measurement technique that uses temperature sensitive fluorescent dyes excited by laser light to determine the temperature. The dye is activated by the photons of a laser light with an appropriate wavelength to an excited state. Fluorescence is the spontaneous transition from the excited state to the ground state. Part of the absorbed energy is emitted during the transition process to the lower state as radiation. Many dyes emit the radiation in a wavelength of visible light and can easily be detected. The fluorescence intensity $I$ is primarily based on the incident light flux $I_0$, the dye concentration $C$, an absorption coefficient $\epsilon$, and the quantum efficiency $\phi$:

$$I = I_0 C \epsilon \phi.$$  \hspace{1cm} (4.1)

In many organic dyes, quantum efficiency $\phi$ is temperature dependent and hence, fluorescence intensity $I$ is temperature dependent, too. The absorption coefficient $\epsilon$ can be temperature dependent, but its change is usually small. The incident light flux $I_0$ is, as mentioned above, not constant over time. When using continuous-wave lasers, fluctuations in the emitted laser light intensities are generally small. $I_0$ can be dependent of other disturbances, e.g. a change in refractive index in the fluid. In addition, pulsed lasers show the behavior of pulse to pulse variations in emitted laser light intensities. These fluctuations are a main error source and need to be avoided. One approach is the quantification of the incident light flux $I_0$ by the use of a second, additional fluorescent dye which is dissolved in the fluid. The second dye needs to have a different emission spectrum compared to the first fluorescent dye to be able to detect the fluorescent intensities separately. The ratio of the two fluorescence intensities $I_A/I_B$ can be obtained and is independent of the incident light flux $I_0$:

$$\frac{I_A}{I_B} = \frac{C_A \epsilon A \varphi_A}{C_B \epsilon B \varphi_B}.$$ \hspace{1cm} (4.2)

The second dye can show a temperature dependent or temperature independent behavior. This gives a temperature dependence through the ratio $\epsilon_A \varphi_A/\epsilon_B \varphi_B$ if the quantum efficiency $\varphi$ and/or the absorption coefficient $\epsilon$ of both dyes are temperature dependent. Rhodamine B and Rhodamine 110 from Exciton were used for all experiments. As a solvent, dechlorinated water is used.

4.2. Application in a duct flow with one heated wall

In this section the application of the LIF technique in a duct flow with high aspect ratio and one heated wall is described. The experimental setup of the generic cooling duct is described in [4, 13].

4.2.1. Flow cases

Different flow cases are considered herein. Mainly, the bulk temperature, the flow rate and the temperature of the heated wall are varied. Table 3 lists the ranges of the varied parameters: flow rates $V$, bulk temperature $T_b$ and wall temperatures $T_w$. In addition, the Reynolds number $Re$ range is given. $Re$ is calculated based on the hydraulic diameter of the duct. The approximated heat flux $\dot{q}$ is calculated based on experimental results of a similar problem [14], is given in the table. The heat transfer from the wall into the water is dominated by forced convection because the Archimedes number $Ar$ is $Ar \ll 1$ for all
cases. All thermophysical properties of water (i.e., density $\rho$ and viscosity $\nu$) are based on standard values and were not measured directly.

4.2.2. Flow field description

The flow field in the duct is described in detail in [4]. A definition of the used coordinates is also given in that paper. For this work it is important to mention that the secondary vortices are present in the duct’s corners. This yield to a thicker thermal boundary layer in the duct’s center plane (at $z \cdot 2/w = 0$) with a width of approximately $z \cdot 2/w = \pm 0.3$. The secondary vortices decrease the thermal boundary layer thickness next to the corners making it pretty difficult to measure the thermal field including the thermal boundary layer. Hence, the thermal field is measured only in the duct’s center plane.

4.2.3. Optical setup

A PIV double-pulse Nd:YAG solid-state laser ‘Brilliant Twins’ from Quantel is used for excitation. The laser has a wavelength of 532 nm and a typical maximum energy of around 140 mJ per pulse. A light-guiding arm from Dantec connects the output from the laser to the light sheet optic which focuses and forms the light sheet (plano-concave lens with a focal length of -50 mm, a plano-convex lens with a focal length of 100 mm and a cylindrical lens with a focal length of -25 mm). The laser light sheet thickness was set to 1 mm. To measure light sheet thickness, a high-quality vernier caliper was used: The distance between the jaws was increased in 0.1 mm steps and held into the laser light sheet repeatedly until the laser light illuminated the jaws no more. This process ensures a repeatable light sheet thickness when re-adjusting the laser. However, note that this is not necessarily the effective thickness, since the light sheet features some Gaussian intensity distribution and it cannot be determined, which incident light intensity is necessary to induce fluorescence. Furthermore, LIF is an integral measurement technique and it is not clear how the weighting over the laser sheet thickness assuming a Gaussian intensity distribution contributes to the total fluorescence signal. Also, the adjustment is done at low laser power, but the measurements at higher power. Therefore, the effective light sheet thickness might be different.

The light sheet optic is mounted on a traverse system which allows for movement in $x$ and $z$ direction. In addition, a manual linear positioner with a sensitivity less than 1 $\mu$m is used to position the laser light sheet as best as possible in the duct’s center plane at $z \cdot 2/w = 0$. PCO SensiCam cameras were used for the measurements, respectively one camera for detecting the Rhodamine B signal (“RhB camera”) and one camera for detecting the Rhodamine 110 signal (“RhB 110”). The SensiCams have a 12 bit dynamic range, a resolution of 1376 x 1040 pixel, a relatively low noise of approximately $5 e^\text{−}$ rms and a quantum efficiency of up to 65%. Hence, these camera type is well suited to be used for LIF measurements where the detected fluorescence intensities are relatively

<table>
<thead>
<tr>
<th>$V$</th>
<th>$T_b$</th>
<th>$T_w$</th>
<th>$\dot{q}$</th>
<th>$Re$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/ min</td>
<td>K</td>
<td>K</td>
<td>MW/m²</td>
<td>-</td>
</tr>
<tr>
<td>32 – 62</td>
<td>293 – 333</td>
<td>293 – 373</td>
<td>0 – 1.8</td>
<td>33,000 – 135,000</td>
</tr>
</tbody>
</table>

TABLE 3. range of the characteristic parameters for the configuration of the generic cooling channel experiment
low. The camera settings were held constant for all measurements. The experimental setup including the optical components is depicted in Figure 16.

Optical filters were used to separate the fluorescence signals from each other and from the laser light. Based on previous experimental findings [15], a longpass filter with a cutoff wavelength of 575 nm was used for filtering the Rhodamine B signal and a 532 nm notch filter and a shortpass filter with a cutoff wavelength of 550 nm were used. The optical density of the edge filters is 4 and it is 6 for the notch filter. All filters have a diameter of 50 mm and were mounted between the cameras and the lenses. Lenses of the type Makro-Planar T 2/100 from Zeiss were used. The apertures of the lenses were “full open” to maximize brightness respectively fluorescence intensity. A cover encloses the whole setup and prevents reflecting light entering the camera.

A two-dimensional calibration target was positioned at the AOI with its front surface being parallel to the laser light sheet’s center. The target is a planar glass plate marked with crosses with an equidistant spacing of 5 mm. The cameras were focused on that calibration target. Hence, the laser light sheet was aligned with the cameras’ focal points. Both cameras were positioned in that way, that they are able to have a free view on the AOI. The angle between the cameras was held as small as possible. Images of the calibration target were used to dewarp the image to account for the different viewing angles of the cameras. These corrected images now have the same correct world position and coordinate system. Figure 17 displays the sketch of the arrangement of all required components.

Rhodamine B and Rhodamine 110 from Exciton were used for all experiments. As a solvent, dechlorinated water is used. Parent solutions are created with each dye. The parent solutions are used to allot the desired amount of dye used for the experiments. This procedure ensures having an exact and repeatable concentration of dye in the experiments. Previous experiments showed that Rhodamine B concentrations in the range of $C_{RhB} = 20 \ldots 40 \mu g/l$ and Rhodamine 110 concentrations in the range of $C_{Rh110} = 300 \ldots 600 \mu g/l$ are best suited for this experimental setup. Hence, these concentrations are used for this experiments.

4.2.4. Data recording and processing

The data recording and processing of the LIF images was as follows. Several different types of images are recorded: perspective calibration images, dark images, white image,
temperature calibration images, and experimental images. All images are recorded for each of the two cameras. The perspective calibration images, which were taken with the calibration target in the AOI, were used to dewarp the images and to match both cameras coordinate systems. The real world coordinates are now identical in both camera images. This step is necessary to apply the 2c/2d method. The dark images, which account for the camera’s dark current, are recorded without any illumination. 10 dark images were averaged and this average image was subtracted from the temperature calibration and experimental images to account for the dark current. An average of 10 white images was used to account for spatial uneven distributions of light in the optical path and by the cameras. The temperature calibration images were taken using an in-situ approach. This means, that the calibration is performed with the exact same optical setup as it is used for the later measurements. The bulk temperature was increased in a range from 293 K to 338 K in $\Delta T$ of 2 K. 20 images were taken at each of this temperature points and these images were then averaged. Then, the averaged dark image is subtracted from each individual image and a image correction using the result of the perspective calibration is performed. Then, the images of the different cameras are divided to apply the 2c/2d technique. These images are now used for the temperature calibration. The experimental images were recorded at the specific operating point. Afterwards, the images are corrected for the dark image, they are corrected in space and the images of the individual cameras are divided. Then, the values in counts are converted into temperature values using the temperature calibration. The commercial software Davis 8.3.0 from LaVision was employed for all data acquisition and most steps of data analysis.

4.3. Results

First, the experimental results of the temperature calibration and a discussion of the measurement uncertainties are given. Afterwards, the parameter variations and the detailed analyses of selected cases are discussed.

4.3.1. Temperature calibration

The dark noise of the used cameras is appropriately 57 counts or 0.014 normalized intensity and it is nearly constant over all pixels. All measured fluorescence intensities are a multiple of this value. This means that the measured values are fluorescence intensities and not noise.

The results of a temperature calibration are plotted in Figure 18 for the two dyes independently and normalized by the maximum possible number of camera counts. Figure 19 shows the ratio (RhB/Rh110) of the intensities. The discrete measuring points as well as curve fitting using a polynomial function of second order are given.

The temperature dependence of the dyes fluorescence intensities $I$ can be described through a sensitivity coefficient $s$ [16]. The sensitivity coefficient describes the relative temperature change in fluorescence intensity defined as

$$s = \frac{1}{I} \frac{dI}{dT}.$$  \hspace{1cm} (4.3)

In the assumption that $s$ does not vary over temperature, fluorescence intensity $I$ can be described by

$$I(T) = I(T_0) \exp(s \cdot (T - T_0))$$  \hspace{1cm} (4.4)

with an arbitrary temperature $T_0$. This equation can be rearranged to determine $s$ only
by using the fluorescence intensities at two different temperatures $T_0$ and $T_1$:  

$$s = \frac{\ln(I(T_1)/I(T_0))}{T_1 - T_0}. \quad (4.5)$$

For this analysis, temperatures of $T_0 = 294$ K and $T_1 = 336$ K were used to get a most accurate estimation.

The Rhodamine B fluorescence intensity decreases by $s = 0.8\%$ in average, whereas the Rhodamine 11 fluorescence intensity increases by $s = 0.9\%$ in average. The ratio of the fluorescence intensities decreases with $s = 1.7\%$ in average. Hence, using the 2c/2d approach increases the temperature sensitivity in contrast to a 1c/1d technique. Rhodamine B fluorescence intensity changes over temperature because the quantum efficiency is temperature dependent whereas the absorption spectra is temperature independent [17, 18]. In contrast, Rhodamine 110 fluorescence intensity changes over temperature because the absorption spectrum shifts slightly with changing temperature. Because the laser light wavelength is at the edge of the emission spectrum, a slight shift in the spectrum has a remarkable impact. The individual measured fluorescence intensities (RhB and Rh110) have some small outlier from the fitted plot. These outliers occur in the RhB and Rh110 signal at identically the same times. A most likely reason is for them is that the laser hat fluctuations in the laser light intensities. When considering the ratio of the two signal in Figure 19, these outliers are not present anymore. This shows clearly the advantage of the 2c/2d technique over the 1c/1d technique.

It is mentioned that the temperature calibration includes crosstalk. However, this is not a significant issue, if the crosstalk does not dominate the signal intensity compared to the actual signal. Based on previous studies the optical filters were chosen in that way that they fulfill this requirement [15].

### 4.3.2. Measurement uncertainties

A particular attention should be paid to the measurement uncertainty of the measurements over time. Real measurement data of 50 independent frames is used to determine the uncertainty. The average intensity values of three areas, each with a size of $10 \times 10$ px, were used for these calculations. Hereafter, the different areas are referred to as position 1 to 3. The locations of the positions were evenly distributed in the AOI.
**TABLE 4. Standard deviation of measured temperature in K**

<table>
<thead>
<tr>
<th>position</th>
<th>RhB/Rh110</th>
<th>RhB</th>
<th>Rh110</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.30</td>
<td>2.96</td>
<td>2.73</td>
</tr>
<tr>
<td>2</td>
<td>0.31</td>
<td>2.70</td>
<td>2.58</td>
</tr>
<tr>
<td>3</td>
<td>0.33</td>
<td>2.45</td>
<td>2.36</td>
</tr>
<tr>
<td>Avg</td>
<td>0.31</td>
<td>2.70</td>
<td>2.56</td>
</tr>
</tbody>
</table>

No heating was applied and the bulk temperature was held constant at $T_b = T_w = 293$ K. That means, the temperatures should be constant over time.

First, the coefficient of variation, which is the ratio of the standard deviation $\sigma$ to the mean $\mu$, was calculated for each area. The standard deviation of the measured temperature is now obtained by dividing the coefficient of variation by the appropriate sensitivity coefficient $s$. These calculations were done for only the Rhodamine B signal, only the Rhodamine 110 signal, and the ratio of both signals for each area. In addition, the average of the different areas was calculated. Table 4 enumerates the results. First, it can be stated that the difference in standard deviation for all positions are negligible. This leads to the point, that the standard deviations of the measured temperatures are location-independent. Second, the standard deviations of the Rhodamine B and the Rhodamine 110 signals are one order of magnitude greater than the standard deviation of the ratio RhB/Rh110. This yields the result that a great part of the measurement errors is induced by fluctuations in the laser light intensity. This assumption is supported by Figure 20. Figure 20 displays the fluorescence intensities normalized by their average values over a discrete number of frames for position 1. The normalized fluorescence intensities values of Rhodamine B and Rhodamine 110 have almost identical curve progression. Hence, a change in laser light intensity affects both fluorescence intensities in a similar range. This influence almost cancels out when the ratio of the two fluorescence intensities is calculated.

Please note, that this analysis does not account for systematic measurement errors or errors in space. Hence, the real standard deviations will be larger than the just shown numbers. However, using the presented 2c/2d technique allows for an error reduction of the temperature measurement with a factor of 8 to 9. The application of a 2c/2d technique is highly recommended for this reason.
4.3.3. Parameter variation and contour plots

To further investigate the temperature distribution in the generic cooling duct, temperature profiles over y were created. An average in x direction was used to create the profiles. The temperature distribution for increasing \( T_w \), constant \( T_b = 293 \) K and constant \( V = 50 \) l/min is displayed in Figure 21 over \( y \cdot 2/h \). The graphs were blanked at values at \( y \cdot 2/h \approx -0.98 \). The temperature at values \( y \cdot 2/h > -0.7 \) is almost uniform for all measurements and equals the bulk temperature \( T_b = 293 \) K. An increase in temperature is visible at \( y \cdot 2/h < -0.7 \) for increasing \( T_w \). Figure 22 depicts the change in temperature distribution for increasing \( V \) with constant \( T_b = 293 \) K and \( T_w = 373 \) K. The temperature at \( y \cdot 2/h < -0.7 \) is always greater for cases with low \( V \). A sharp decrease in the temperature profile is visible at \( y \cdot 2/h \approx -0.75 \) in Figure 21 and Figure 22. The reason for this is an anomaly in the recordings, which is also visible in Figure 23. This anomaly is also present in the raw experimental images of the Rhodamine B camera, but not in the images of the Rhodamine 110 camera. It is believed that the optical path was disturbed. The data processing was not good able to account for this and hence, it is still visible in the result.

Figure 23 plots an instantaneous temperature field for \( T_b = 293 \) K, \( T_w = 373 \) K and \( V = 32 \) l/min. The increase in temperature with decreasing distance to the heated wall is visible in this figure. Structures of heated fluid (colored in white and inclined to the right / with flow direction) appear in the region \(-0.95 < y \cdot 2/h < -0.75 \). These structures change over time (not shown in this paper). It is assumed that these structures are turbulent structures induced by heat transfer from the warm wall into the fluid. Further investigations of the structures will be discussed in another upcoming paper.

5. Conclusions

Experiments are conducted over a large range of pressure (5 to 20 bar) and mixture ratio (2.6 to 4.0) in order to satisfy the need for a major understanding of the injection and combustion processes and of more reliable prediction of the thermal behavior for the propellant combination methane-oxygen. A single and a multi-element combustion chamber are designed and tested. Detailed wall temperature measurements and derived heat flux data sets are obtained for GOX/GCH4. These data sets are valuable for both injector design and code validation. Tests are performed for the same nominal
pressure and mixture ratio for both set-ups. The results obtained for the two geometries are compared. Temperature and heat flux traces show that the combustion process is accomplished towards the end of the chamber and at more upstream positions for the multi-injector chamber. The observation of the pressure profile normalized along the chamber axis confirms the shortening of the reaction zone due to the interaction of the flames and consequent benefit for the chemical reaction. Effects connected to the different geometrical shape of the chambers are also presented and the impact of the recirculation zone in the area close to the faceplate is shown.

For life time investigations of cooling channel structures under thermo-mechanical, cyclical load a fatigue experiment was designed and tested. This experiment is placed downstream of finalized combustion of the 5-injector rectangular GOX-GCH combustor. Supercritical nitrogen is used as coolant, its pressure and mass flow are PID-regulated. After each cycle, who consists of pre-cooling, hot gas run and post-cooling phase, the surface deformation is measured with a laser-profile-sensor. While the first experiments almost all of the measured temperatures, pressures and mass flows show an expected behaviour. These first tests were limited to short hot gas runs of few seconds, but will be extended soon. Because of the short hot gas runs no deformations were measurable so far.

A detailed description of the two-color laser induced fluorescence technique was given. The experimental setup including the generic cooling duct, the optical setup und data processing was described. A temperature calibration was performed showing that the used dyes, i.e. Rhodamine B and Rhodamine 110, are well suited for this application. Is has been shown that using a two-color LIF technique reduces errors induced by variations in the laser light intensity by a factor of 8. Finally, temperature profiles for different flow cases and a temperature field are given and discussed. The temperature distributions change with varying boundary conditions. Distinctive structures in the temperature field are visible.
Acknowledgments

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