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Development of an Air Cooled Borescope for Infrared Thermal Load Monitoring in Industrial Gas Turbine Combustors and Operational Experience

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ABSTRACT

Within the last three years, Kawasaki Heavy Industries Ltd. and B&B-AGEMA have worked on a technology to support experimental tests for development of the Micromix combustor of pure hydrogen, allowing a very close online visual (Visible and Infrared light) access to the burner. The invented borescope has been designed by means of Conjugate Heat Transfer (CHT) and Finite Element (FE) simulations. Different design variations have been tested numerically. Within this course, the internal cooling pathways have been improved and the structure enhanced to ensure an acceptable life time of the highly loaded borescope head located directly downstream of the flame. Here, the local temperature reaches values around 1600 K.

After digital development and manufacturing, the first borescope prototype could have been successfully operated in two low pressure and two high pressure tests (two times with a visible light (VIS) and two times with an Infrared (IR) camera).

In the paper, the development process as well as the operational experience and the experimental test results are presented. The information on the Micromix combustor behavior revealed by the borescope technology help to better understand the behavior of the combustor, improve the design and plan the operation strategy within the real gas turbine.

NOMENCLATURE

AGP	Air Guiding Panel
BF	Black Furnace
CFD	Computational Fluid Dynamics
CHT	Conjugate Heat Transfer
CO_2	Carbon Monoxide
DLE	Dry Low Emission
DOV	Direction of View
FE(M/A)	Finite Element (Method/Analysis)
FOV	Field of View
GT	Gas Turbine
H2	Hydrogen
HP	High Pressure
IR	Infrared
KHI	Kawasaki Heavy Industries
LP	Low Pressure
MMX	Micromix
NG	Natural Gas
NO_x	Nitric Oxide
OEM	Original Parts Manufacturer
TBC	Thermal Barrier Coating
TC	Thermocouple
TIP	Thermal Index Paint
UV	Ultraviolet
VIS	Visible (light)
y^+	Dimensionless wall distance

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INTRODUCTION

Sustainable and renewable energy concepts are gaining in importance all over the world. Fomented by the necessity to reduce greenhouse gas emissions and stop the global warming process, today huge efforts are made in terms of research and development. Hydrogen may play a dominant role in the future concepts for several reasons.

Kawasaki Heavy Industries, Ltd. (KHI) is undertaking large R&D efforts for production, refinement, liquefaction, transportation, storage and utilization of hydrogen gas for electricity generation in industrial gas turbines. Burning hydrogen in conventional combustion chambers (diffusion or premixed type) is only possible up to a certain H2-fraction since the burning velocity of hydrogen is significantly higher and the explosion limits wider than for natural gas. The risk for flashback increases and the maximum peak temperature of the flame increases. The latter leads to increasing nitric oxide emissions (Thermal NOx).

In 2010, KHI started a long term cooperation with the Aachen University of Applied Sciences and B&B-AGEMA to investigate the potential of a DLE Micromix (MMX) for application to industrial gas turbine combustors. Between 2014 and 2019, KHI successfully transferred the principle to a combustion chamber for a 2MW industrial gas turbine [1].

Especially due to the high number of individual flames, it has been found that an online optical access to the combustor can strongly support the understanding of the combustor behavior and thus the development process for the MMX combustor. Most of the conventional measurement techniques, techniques such as thermocouples/thermistors, differential pressure sensors or exhaust gas sampling, only provide local information. This data can be assembled within a data analysis process to give an impression on the two or three dimensional and/or global performance or loads of the components in scope. The optical access allows a more differentiated view to the flame structure(s) and also allows identifying local hot spots in transient and steady state operation. Due to the possibility to observe the flame in real time, it can also be seen as part of a risk mitigation strategy for testing.

Despite the borescope is developed for the MMX combustor it can also support the development of conventional types firing liquid fuel or natural gas. For all kinds of modern combustors, the demands in terms of NO_x and CO_2 emission reduction are high. This guideline for environmental protection necessitates leaning out the flame and operating the burner close to its blow out limit. An understanding of the flame behavior close to the operational limits is consequently gaining in importance. Modern simulation tools strongly help to achieve the goals in this regard, but experimental investigations are still a central part of the development process.

The present paper describes the development process of an optical borescope to support the development process for MMX combustors. It has been conducted in two main steps:

1. Development of a borescope for visible light
2. Improvement and adaption of the borescope to allow IR based temperature measurements

The basic structure of the borescope has been developed and commercially distributed by the Institute for Steam and Gas Turbines (IDG), RWTH Aachen (now IKDG) and B&B-AGEMA. Different view angles of 0°, 70° and 90° and lengths were available and the external diameter of the borescope head was between 33.4 and 38 mm. From 1994 until 2003, more than 70 units of the VIS, air cooled borescope have been sold for experimental testing of F-class gas turbines (50, 60 and 90Hz). As can be seen in Figure 1, the harsh conditions did only allow a limited operation time. If exceeded by the operator, serious damages to the borescope head can occur.

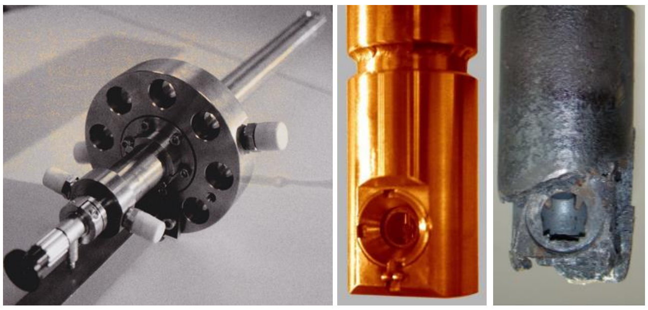


Figure 1. IDG/B&B-AGEMA Borescope Technology (1994-2003)

The paper shows the improvement and adaption of the borescope towards a smaller external diameter (22mm), the improvement of the cooling air pathway and life time extension by thermal load reduction and a material change.

After manufacturing, assembly and leak tests, the experimental tests have been conducted.

Two low and two high pressure tests have been successfully conducted for VIS and IR. Procedure and results are presented in the last section of the paper.

OVERVIEW OF BORESCOPE APPLICATIONS FOR GAS TURBINES AND FURNACE MONITORING

Borescopes and endoscopes are typically used for medical and industrial applications. Depending on the purpose, various sizes and designs exist. They incorporate different types of optical systems (visible light (VIS), Infrared Light (IR), Ultraviolet (UV)).

Here, only a selection of applications shall be presented to give an overview which systems are already available and completely or partially fulfilling the requirements for observation of the MMX combustor during full load operation (Exhaust gas temperature: 1200°C; Combustor pressure: 10.5 bar).

Gas turbine OEM utilize the borescope technology as a standard to check the conditions of compressor, combustor and turbine components by means of visible light (VIS) during planned inspection intervals. For this purpose, the machines typically feature separate access points. On the one hand-side, borescopes can help to access areas impossible to reach by the human eye only; on the other hand side, the it can save the dismantling procedure for the gas turbine and thus avoids the unnecessary maintenance-related downtime. Siemens Westinghouse furthermore claimed in 2003 that the borescope inspection can start 4h after shut-down with their lightweight high temperature borescope – without the required cool-down time is 24h before the standard inspection process can start. Finally, the technology safes approx. 12h of outage time and the corresponding costs for lost power generating revenue. The borescope itself is patented by Siemens and can be exposed to temperatures up to 537 °C (1000 F) [2].

Especially in the turbomachinery field, borescopes are also widely used for temperature measurements. In the harsh environment of combustor and turbine section, borescopes allow remote online excess to the component temperature information. They capture infrared radiation emitted by the parts which can be translated into temperature information by the Stephan-Bolzmann-law. According to the British Standard 1041 part 5, borescopes used for temperature measurement by means of IR belong to the group of pyrometers [3]. Today, pyrometers are commercially available for high pressure and high temperature application.

In 2012, Taniguchi et al. [4] presented the application of pyrometers to a newly developed industrial gas turbine and compared the measurement results to Thermal Index Paint (TIP) and thermocouple measurements with good agreement. As presented in Figure 2, the head of the applied pyrometer system needs to reach through the outer end wall of the turbine vanes into the hot turbine flow. Due to the high heat load on the pyrometer head, this can be tolerated only for a short period in time (20seconds).

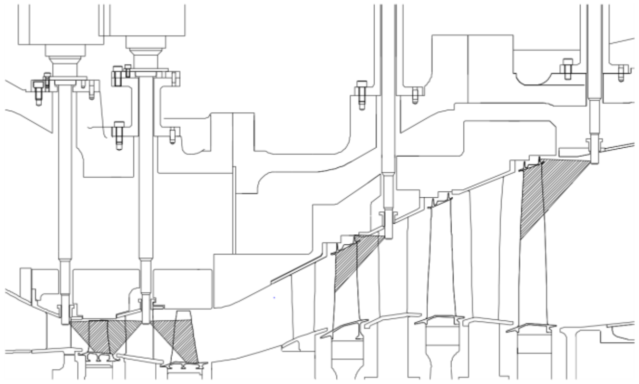


Figure 2. Pyrometer installation in KHI L30A Gas Turbine [4]

During the measurement, a mirror installed in the pyrometer head controls pyrometer view spot (/measurement point) to be captured on the blade surface. Finally, a data processing tool assembles the measurement data to visualize the complete surface temperature of the blade. After the measurement, the head is retracted by a traverse system. A clear drawback of the technology is the necessity to penetrate the turbine flow, which can lead to a disturbance of the flow by the pyrometer head. The necessary bushing in the upper vane platform furthermore needs to be purged by cooling air. Both can reduce the measurement accuracy.

A more simple application of the borescope technology for gas turbine has realized by Siemens for the SGT-750. A remote high speed online infrared monitoring system continuously captures high-resolution (2D) images of the pressure side, suction side and hub platform of the rotating first stage blades during gas turbine operation [5]. Since the borescope head is not reaching into the turbine section, a long term monitoring of the blade altering process (e.g. also for the Thermal Barrier Coating (TBC)) is possible.

Similar solutions for contactless remote 2D surface temperature measurements applied to gas turbine are based on phosphor luminescence (e.g. ultra-bright thermographic phosphors excited with lasers). Same as for the pyrometry, the method allows the measurement of a surface temperature distribution for rotating and non-rotating components in gas turbines. For the luminescence-based methods a coating needs to be applied which is excited by a laser beam. The reflected light frequency and intensity is captured by a camera and can be translated to temperature information [6]. It can be used up to combustion temperatures [7]. According to Eldridge et al. the phosphor luminescence technique offers distinct advantages against IR-based measurements and thermocouples. They overcome the attachment problem for thermocouples and the issues with unknown emissivity and interference by stray reflected radiation associated with pyrometry. The disadvantage of the luminescence based measurement is the necessity of the painting, which limits the application to test benches and short term measurements since the paint abrades over time if applied to a turbine blade or combustor component. Also it is not clear of the paint can be reliably applied on a TBC coated surface.

Besides the mentioned applications for gas turbines, high temperature borescope also exist for furnace temperature monitoring. Such systems typically feature an IR optical system for temperature measurement and the housing is water cooled. With a diameter ≥42mm [8] [9] , the systems are too large for measurements in the MMX gas turbine combustor. Also, the closed loop water cooling has a large drawback: In case of pump malfunctions and limited water circulation, the boiling temperature can be exceeded leading to a strongly increased pressure inside the borescope. The structure can be destroyed and water injected into the gas turbine. Steam inside the combustor or turbine section strongly enhances the heat transfer and thus the local thermal load as well as thermal stresses. Especially the latter can cause severe damages to downstream located components.

CONCEPT AND GEOMETRICAL DESIGN

As stated in the introduction, the development of the new borescope has been initiated with the intention to allow a close optical access to the Micromix flames up to machine equivalent full load conditions. Furthermore, the design should be applicable to other KHI combustors – installed on the engine as well as on test benches.

In order to allow the implementation of the borescope head into the MMX combustor, the diameter needed to be reduced to 22-23mm. Also, the allowable thermal load needed to be increased and the possibility for the adaptation to IR temperature measurements needed to be considered early in design.

Figure 3 and Figure 4 illustrate the principle borescope design and its integration into the combustor. In the lower picture the view spot is visualized. Field of view (FOV) and direction of view (DOV) have been chosen not to capture the entire MMX module but only a portion and the center cone. This results in a higher special resolution of flames and burner components by the camera sensor.

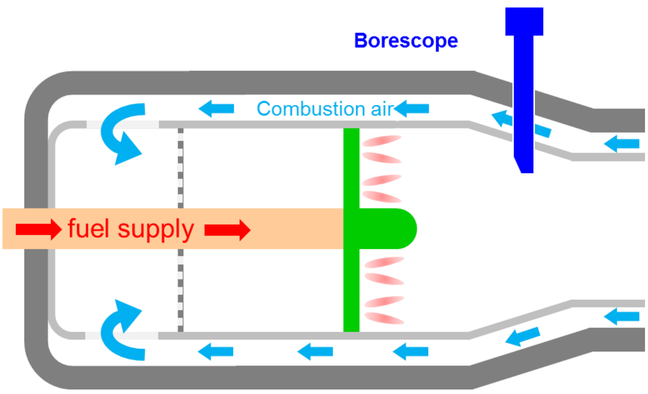


Figure 3. Principal sketch on the borescope implementation into the MMX reverse flow combustor

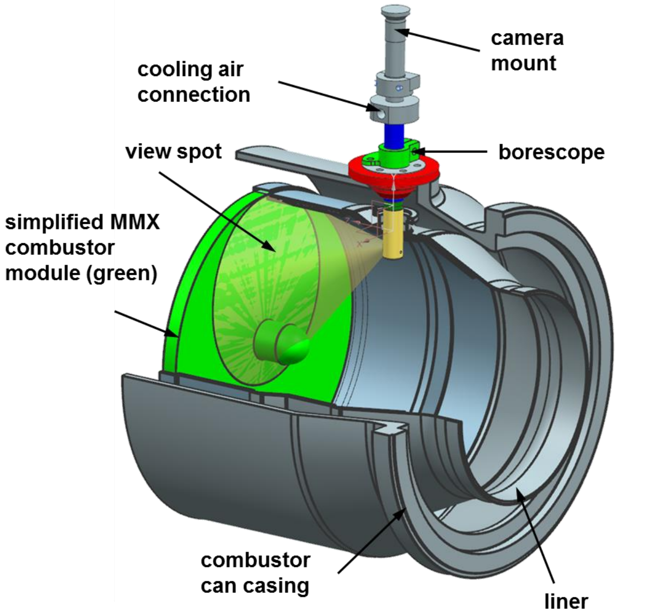


Figure 4. Borescope implemented in MMX combustor (3D CAD impression)

The geometrical design of the borescope is presented in Figure 5. It is basically a cooling jacket with an interchangeable optical system (endoscope; yellow). Endoscopes for visible and infrared light are available as (tailor made) purchase parts from different OEM. The outer diameter of the endoscope is 4mm. The FOV is 56° and the DOV 70°.

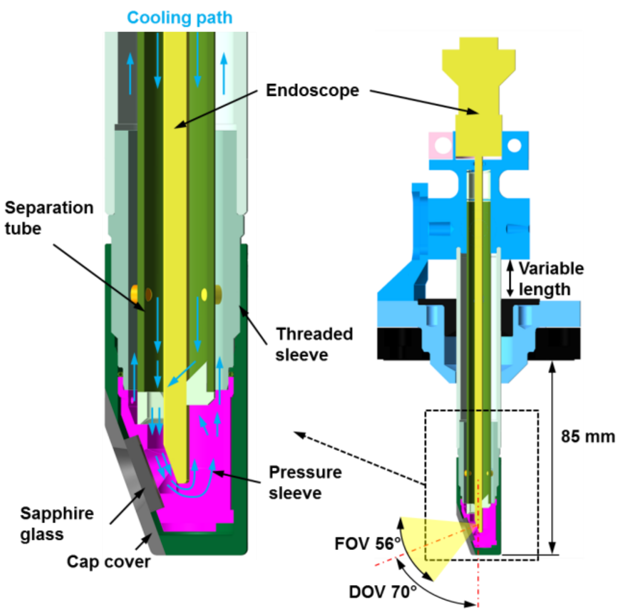


Figure 5. Borescope structure (Final Design)

The outer shell of the borescope is composed of a long cladding tube (length is adjustable), a threaded sleeve and the borescope head (dark green and grey). The cap can be dismounted, e.g. for repair. The pink "pressure sleeve" holds the sapphire window in place. The axial force is generated via the threaded sleeve. The cooling air enters the borescope from outside and first streams into the passage between the endoscope and the separation tube. Before leaving the separation tube, the flow is directed towards the sapphire glass region (here left). After impinging on the window and the pressure sleeve structure and cooling the head, the coolant is redirected by 180° and flows through the passage between separation and cladding tube (outer shell). On its way back to the outlet the coolant is strongly heated – especially in the flange region.

The sealing between cladding tube and flange is designed to allow an individual, stepless relative movement in axial and circumferential direction. This makes view spot adjustments possible.

DESIGN PROCESS

The design approach is presented in Figure 6.

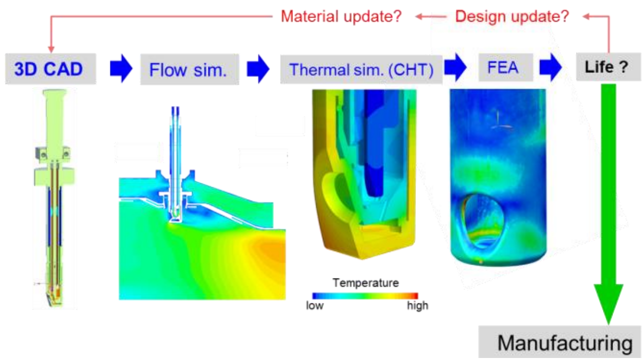


Figure 6. Borescope design workflow

The derived metal temperature distribution is imported into a Finite Element model. Stress and temperature information have been compared to creep rupture curves for the specific material in order get an impression on the components life. After the introduction design adaptions, the loop was repeated until acceptable parameters with respect to manufacturability and life could be obtained.

Temperature Loads

In order to derive the temperature distribution inside the borescope and the cooling air consumption, a conjugate heat transfer (CHT) simulation has been set up with the commercial software Siemens PLM Star-CCM+. The computational domain is presented in Figure 7.

The domain considers the combustion air approach flow of the reversal combustion chamber and the combustion zone downstream of the Micromix flames. Thus, two different main flows are modelled with two inlets and two outlets. Both flows are passing and heating the borescope at different positions. Flow (1) has a total temperature of 350°C and a total entry pressure of 10.5bar. Flow (2) represents the combustion zone. The temperature profile applied at the inlet has been provided by KHI. The Profile extracted from a reactive CFD combustion simulation is shown in the figure. The maximum total temperature is 1340°C. The corresponding hot streak is located at the same radial and circumferential position as the borescope head. The total pressure at inlet (2) has been set constant.

The liner sheets of the combustor are air cooled and form a cooling film on the inner sides to reduce the thermal load. The effect on the borescope head temperature is considered in the model by three additional flow inlets (Cooling inlet (1)-(3)). The cooling air enters with a total temperature of 350°C. The borescope head temperature is slightly reduced by the introduced liner cooling air but the most critical location is only internally (convection) cooled.

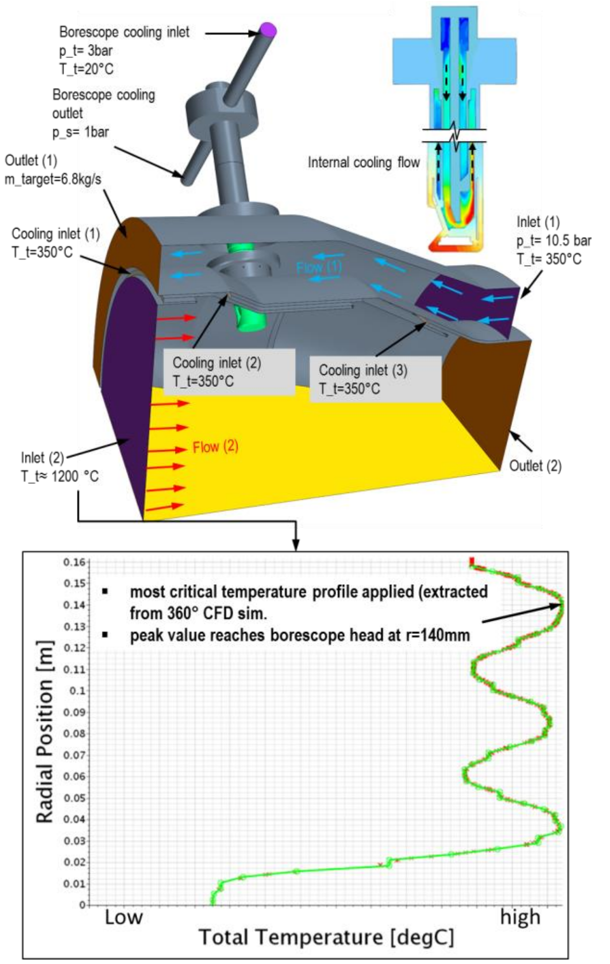


Figure 7. Computational domain and boundary conditions for the borescope (early design version) CHT simulation

In addition to the two combustor flows of the model (Flow (1) and (2)), the borescope fluid and solid has been modeled. The fluid flow path is illustrated in Figure 7 (top right). The borescope is supplied with a total pressure of 3barA and a total temperature of 20°C (ambient). At the borescope outlet, ambient conditions are considered (p_s=1barA). The combustor itself has been modeled with adiabatic, non-slip walls. The borescope is modeled as solid part with interfaces to the combustor and internal cooling flow. On the external surfaces of the borescope, which are not in contact to the combustor flows, are considered as adiabatic walls. Thus, the natural convention is neglected.

Temperature and pressure dependent properties of the combustion air as well as for the borescope solid (only temperature dependent) are considered in the CHT simulation by means of polynomial functions. The solid material properties represent steel Alloy 800H (specific heat capacity, thermal conductivity).

The mesh contains 3.9 mio. unstructured, polyhedral cells and prism layers on heat transfer interfaces (e.g. inside the borescope). Wall-y^+ values are below or close to unity.

A steady segregated solver has been applied with a Reynolds-averaged Navier-Stokes turbulence model. Turbulence closure is achieved via k-omega SST approach.

In Figure 8, the static temperature within the combustor flow is presented (borescope design version 2) in two different sections – one plane is intersecting the borescope axis and one is located at the symmetry plane. As visible, the high temperature streak prescribed at inlet (2) reaches the lower part of the borescope head. It can be seen that a recirculation zone is established downstream of the head (flow from left to right in hot region). However, no strong impact in this region can be seen to the upstream temperature and flow distribution. The Micromix flames are not affected by the borescope.

In the lower part Figure 8, the thermal load of the borescope is illustrated. The maximum metal temperature is around 1000°C and located at the lower edge of the borescope cap. The temperature in this region cannot be reduced efficiently by the internal cooling structure of the borescope. In the reference design (and design v2) the chamber below the pressure sleeve (see Figure 5) is not through flown by cooling air. Therefore, the stagnating air in the chamber has an isolating effect and the heat extraction from the critical position by the borescope cooling stream is limited.

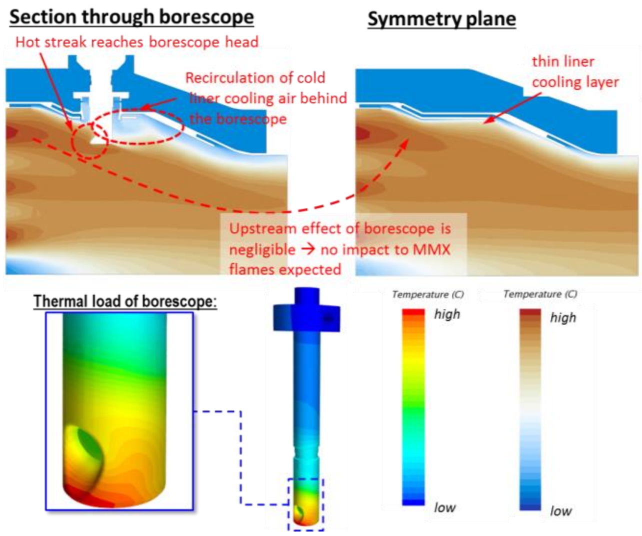
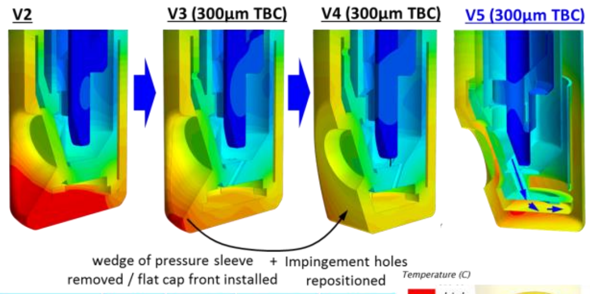
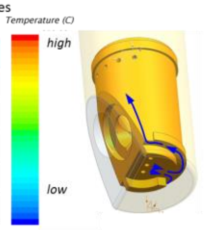


Figure 8. Static temperature inside the combustor and metal temperature distribution of the borescope head (from CHT simulation; reference design (v01)

Several design iterations have been tested for reduction of the thermal load on the borescope. In Figure 9, four steps are presented. V2 is comparable to the reference design (v1) presented in Figure 8. In Version 3, the chamber below the pressure sleeve is purged (impingement holes in the flow sleeve) and 300 µm TBC are considered (modeled as thermal resistance between solid and fluid defined as R=t/λ; with t: TBC thickness; λ: Thermal conductivity of TBC). This leads to a maximum metal temperature reduction by 123 K. The cooling air consumption (m_c) decreases by 4%. The average temperature of the endoscope (modeled as isotropic solid) increases by +3 K. This information is monitored since the OEM limits the maximum working temperature to 100°C for the VIS and 60 °C for the IR endoscope.

For design V4, the lower leading edge of the borescope has been removed and a flat front cap applied. Additionally, the angle and position of the pressure sleeve impingement holes is improved. Both measures lead to an additional maximum temperature reduction of 48 K. It can be seen that the maximum temperature is relocated to the lateral sides of the borescope head. In Design V5 therefore the impingement holes have been turned towards the back-side. This generates a strong vortex in the lower chamber and cools the lateral edges of the head structure more efficiently. Since the coolant is directed towards the sapphire window before leaving the separation tube, more of its dynamic pressure can be used to supply the cavity below the pressure sleeve within the impingement hole location featured by Design V5. This leads to an increase of the cooling air mass flow by +70%, an overall cooling air consumption of 109% and a maximum temperature reduction of 216 K compared Design V2 (-45 K compared to V4).





	V2	V3	V4	V5
ΔT_{max}*	0	-123 K	-171 K	-216 K
$\dot{m}_c$*	100 %	96 %	92 %	109 %
$\dot{m}_{imp}$**	-	100%	91 %	170 %
$\Delta T_{max,Endo}$*	0	+ 6 K	+ 10 K	± 0
$\Delta T_{ave,Endo}$*	0	+ 3 K	+ 3 K	- 1

*) Compared to design V2 **) Compared to design V3

Figure 9. Metal/Substrate temperature distribution of the borescope head for design V2-V5

Thermal and Mechanical Stresses

For estimation of the component life time only the borescope head has been considered. The 3D metal temperature information obtained with the CHT simulations described in the previous section have been extracted and mapped to an FE model. Additionally, static pressures have been mapped to the outer walls.

On the inner walls a constant pressure of 3 bar has been considered. The model has been set up in Siemens PLM NX Nastran as a linear elastic simulation (Solver type 101). Temperature depended material properties have been applied representing Steel Alloy 800H.

Domain and mesh are shown in Figure 10. In addition to the thermal and pressure boundary conditions, all nodes on the upper ring surface of the head have been fixed in space. Since this restricts a radial expansion, the stress distribution in the upper region of the borescope head cannot be analyzed.

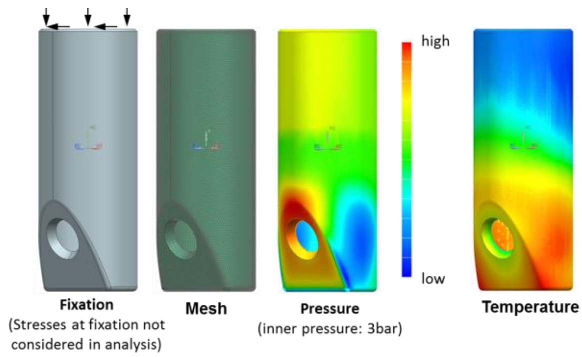


Figure 10. FE model and boundary conditions

The stress distribution obtained from the linear elastic FEA is presented in Figure 11 for Designs v3-v5. It can be seen that the shape adaption leads to a strong increase in thermal stresses at location (1), but as shown in Figure 9 and Figure 10, the temperature at the same location is reduced. The combination of local stress and temperatures governs the material creep. Therefore both information need to be considered as a pair for every location/FE-node.

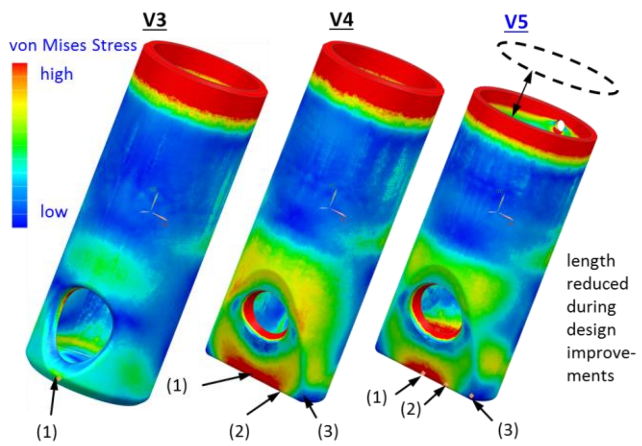


Figure 11. Von Mises stress distribution for borescope designs v3-v5.

Figure 12 presents the creep rupture life curves of alloy 800H. Three different points at the borescope head have been selected for a graphical evaluation of the creep life. Point (1) shows the highest stresses but for design v4 and v5 relatively low temperatures. Point (2) shows higher temperatures but slightly lower stress values. Point (3) shows the highest temperatures but the stress level is low.

The temperature reduction achieved with Design v5 at locations (1) and (2) leads to a life time extension from 2h to ≈10.5h. Point (2) instead of (1) becomes life limiting. In order to increase the life time more drastically, the life time for different materials have been investigated and the machinability and availability discussed.

Figure 13 shows the creep rupture life for the high temperature resistant Ni-base alloy 625 (IN625), the finally chosen material. With design v4 the life time is still under 700 h but around 10’000 h for design v5.

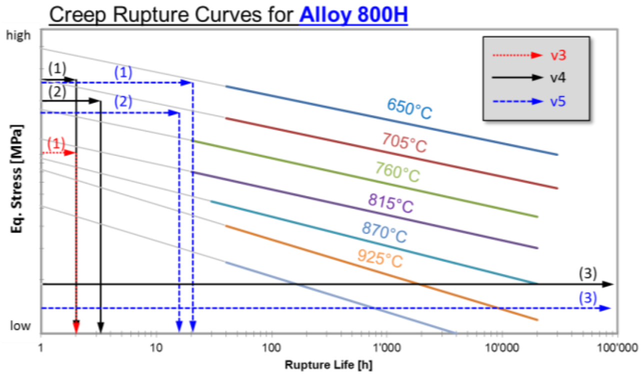


Figure 12. Estimated creep rupture life for borescope head design v3-v5 made of alloy 800H (log. stress scale; (reproduced from [10])

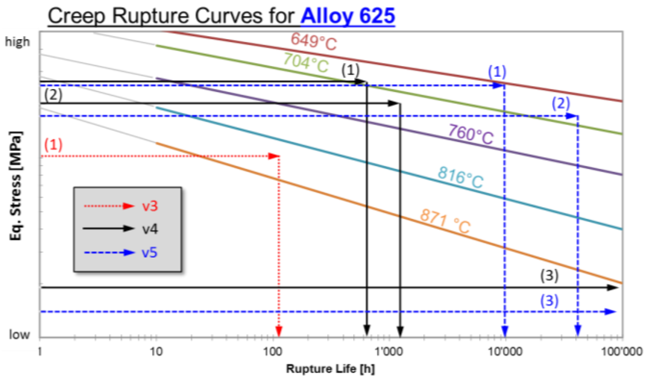


Figure 13. Estimated creep rupture life for borescope head design v4 and v5 made of alloy 625 (IN625) (log. stress scale; (reproduced from [10])

Manufactured Borescope

An impression on the final manufactured borescope structure is given in Figure 14 (Design v5).

Figure 14. Manufactured borescope (w/o endoscope optic) before installation

OPERATIONAL EXPERIENCE

During the borescope development process four experimental tests have been conducted in Akashi, Japan (Low pressure tests) und Aachen, Germany (high pressure tests) – each with the VIS and IR endoscope. Setup, results and operational experience is described in the following section.

Visible Light Tests (LP & HP)

The installation of the borescope for the low pressure test conducted in Akashi (as sketched in figure 5) is presented in Figure 15. Endoscope, camera and the borescope structure are visible. The cooling air inlet and outlet feature temperature measurement points. Additional thermocouples have been placed inside the borescope head – one close to the endoscope head and one on the bottom of the borescope head, where the highest thermal load is expected.

A view into the combustor after installation of the borescope is shown in Figure 16.

The setup for the HP tests is principally similar but with some extension for the data acquisition system and the mounting is sidewise.

A selection of the measurement results is presented in Figure 17. In the upper left, the view through the borescope before installation of the combustor to the test rig is shown. The MMX module is clearly seen. The recorded picture is sharp and undisturbed. The picture to the right shows the combustor at a part load point fired with a mixture of 10Vol% NG and 90Vol% H2. Only the inner two rings are fueled. The exhaust gas temperature is 750degC. The bright spot on the center cone is generated by a light source added during the tests. It is supposed to increase the light intensity during testing und thus allow reducing the exposure time of the camera and therewith increase the frame rate. However, the test results show that this measure is not necessary and cannot improve the visibility of flames.

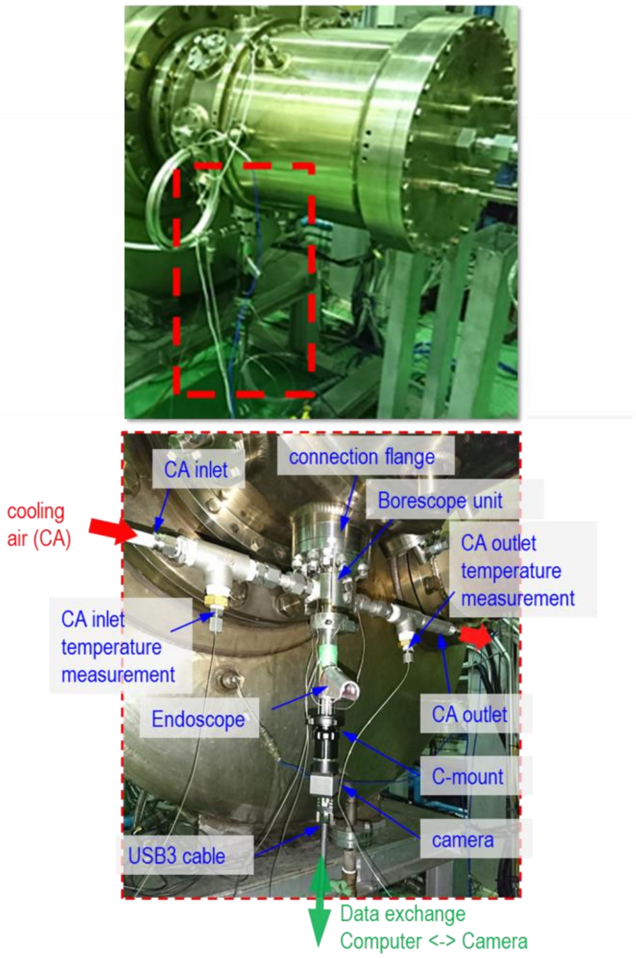


Figure 15. VIS borescope applied to the MMX combustor for low the first pressure test – outside view after attachment of the combustor to the test cell

In the record, the single Micromix flames are clearly visible and their transient movements can be observed. The footage gives information on the uniformity of the flame lengths, the flame shapes and the inclination with respect to the burner axis.

The central pictures show the same operational point with a higher camera frame rates of 30 and 140fps. Due to the lower exposure time, the brightness is clearly reduced but the flames remain visible and the additional information on the transient behavior of the flame movements allow additional conclusions on the combustor behavior at this part load point.

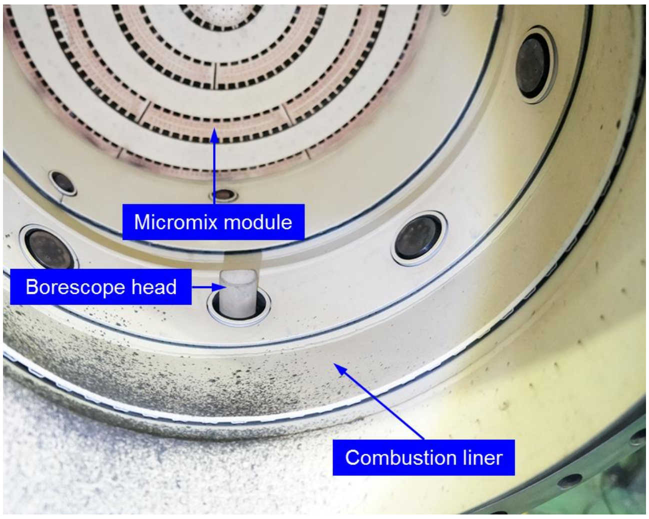


Figure 16. VIS borescope applied to the MMX combustor for low pressure test. Upstream view on liner and MMX module

The high pressure test results are basically comparable (see Figure 18). Due to the side mounting of the borescope, the perspective is different. During the test, vibrations of the combustor and the borescope reduced the sharpness of the footage. However, the flame shape can still be identified and the length can be estimated. Compared to the low pressure tests, the flame length is locally higher - especially around the cone.

At ignition (upper left picture), the central AGP begins to glow. At this point, only the outer ring is supplied with gas and the burner operates at relatively rich conditions. The high heat load on the AGP is quickly reduced with increasing combustion air velocities and reduced equivalence ratios.

At full load conditions and full pressure, the light intensity emitted from the flames reaches its maximum. But also the vibrations are on highest level. As observed in the LP test, the combustor components begin to radiate more strongly in the IR spectrum due to the high heat load and the picture recorded by the borescope becomes slightly red.

With the central and the lower picture on the right, the impact of the frame rate is highlighted. Even at 120 fps the flames can be identified and transient behavior analyzed.

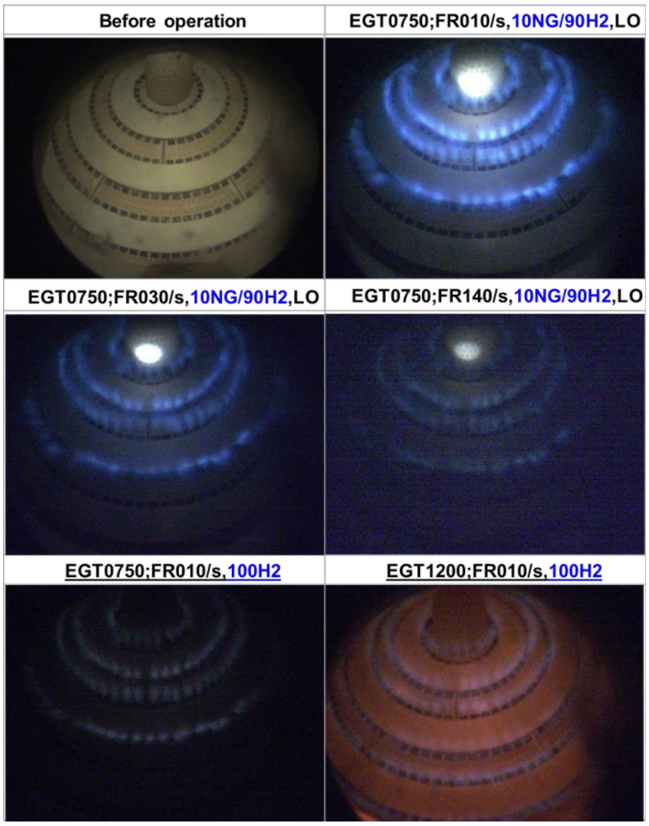


Figure 17. VIS, LP measurement; Different fuel gas mixtures (NG and H2), EGT 750C and 1200C and camera frame rates (FR)

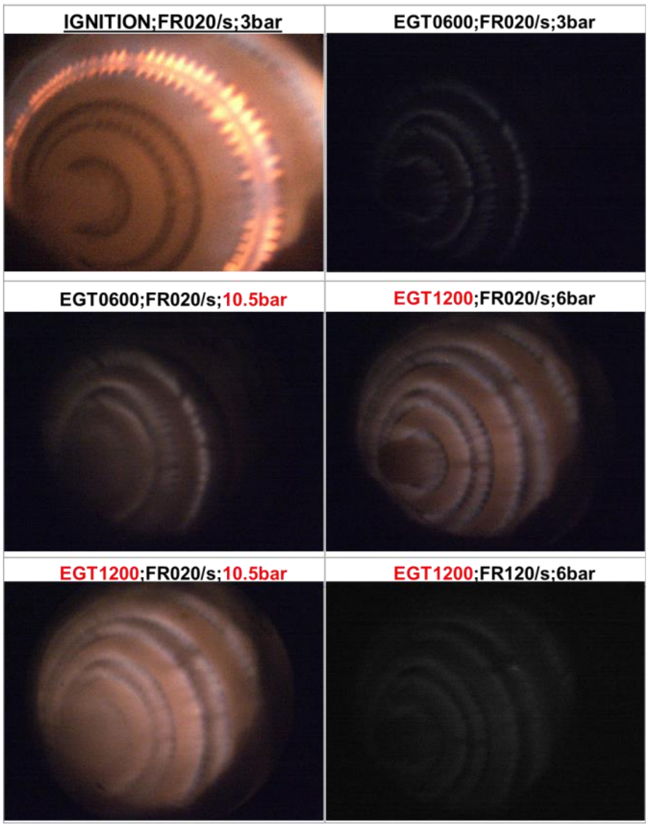


Figure 18. VIS, HP measurement; Hydrogen, EGT 600C and 1200C, different camera frame rates (FR) and pressures (3, 6 and 10.5bar)

Infrared Tests (LP, HP)

Visible light endoscopes do typically not transmit IR in the spectrum necessary for temperature measurement. Therefore a tailor made IR endoscope optic has been purchased for integration into the borescope. It features a high transmission rate between 780 and 1080nm, which corresponds to the sensor of the LumaSense MCS640HD camera used for the IR temperature measurements. The borescope itself furthermore features a sapphire window which has a high transmission rate in the IR spectrum. The sapphire is furthermore c-oriented and coated with an anti-reflection coating for the IR range. This reduced disturbances by reflections or light detractions. The borescope cooling has no impact to the IR transmission since air is used instead of water as in other applications.

As stated above, two experimental tests have been conducted with the IR borescope under low and high pressure conditions. The setup is presented in Figure 19. In the upper right picture, the borescope head, the liner and the MMX module are visible (upstream view). One quarter of the MMX module is painted with a high temperature resistant paint. The emissivity of the black paint is known and close to one. However, the evaluation of the IR temperature information within the sector was not reliable due to local discolorations observed during the test. The following evaluation is therefore focused on the information measured on the TBC coated surface.

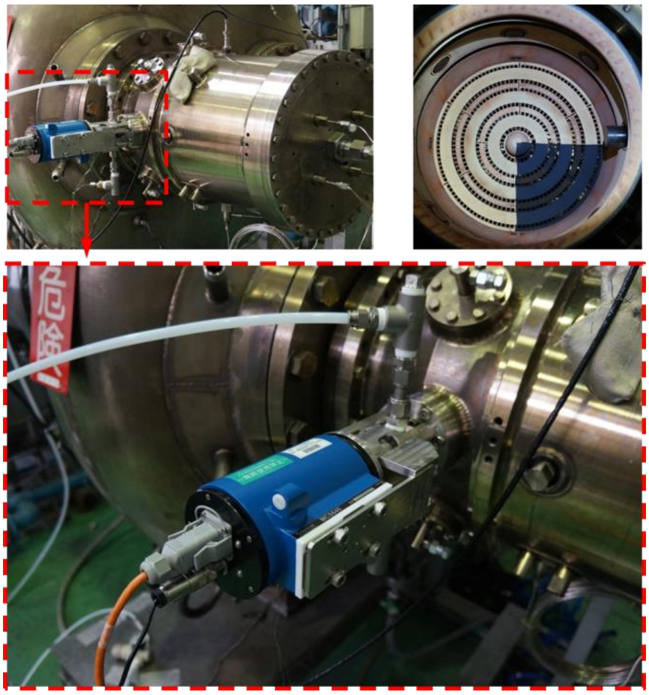


Figure 19. IR borescope applied to the MMXcombustor for LP test – outside view (left and lower); and view into the combustor before mounting (right, upper).

The measurement results for high and low pressure tests are presented in Figure 20.

In general, the records are all sharp and all details of the Micromix combustor can be distinguished. The qualitative representation accuracy is consequently on highest level. At low temperatures, the records become noisier which might be caused by the lower IR light intensity emitted by the burner components. Nevertheless, the picture is still clear and high and low temperature zones can be easily identified. During the HP tests it could be observed that the combustion air quality might have a considerable effect on the representation of the temperature distribution by the IR measurement. In all pictures captured on the HP test rig, flames are visible and disturb the graphical measurement of local burner part surface temperatures. On the LP test rig (higher air quality), no flames have been observed. As observed during the VIS test, the combustor oscillations at high pressure and temperature level lead vibrations of the combustor and borescope head. This results in a relatively strong movement of the captured picture. Nevertheless, the fine structures of the MMX combustor modules where visible during the high and low pressure test and the qualitative temperature distribution could be obtained.

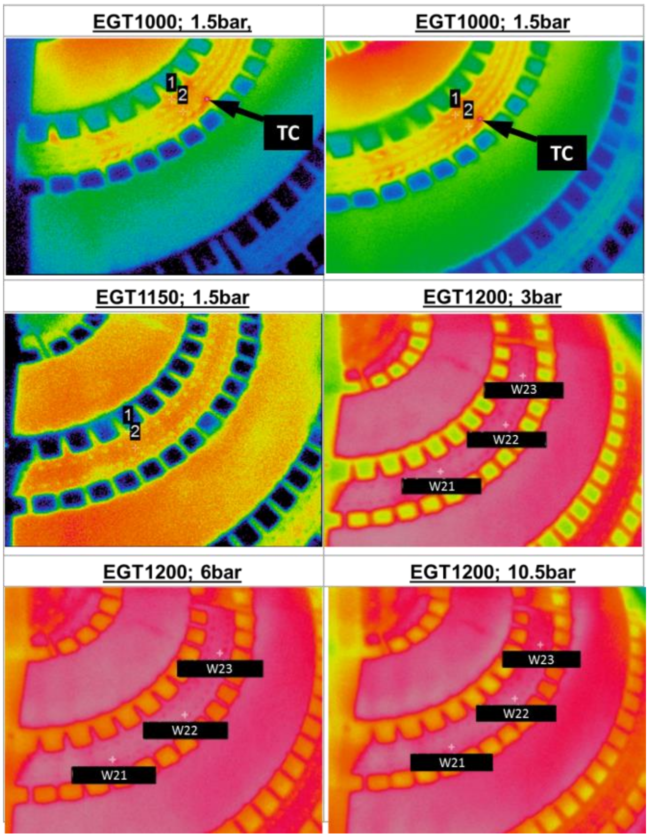


Figure 20. Temperature distribution of the MMX module measured with the IR borescope - Exemplary results for LP and HP tests (pictures cropped)

Besides the high quality of the qualitative temperature distribution shown, quantitative temperature values extracted from the IR records show large differences to the values indicated by thermocouples located on the air guiding panel. In the LP tests, the differences range from -21 up to +53 K (up to +118 K for temperatures below 600 C). Over time, the IR measured temperature values furthermore fluctuate by ±10 K (the standard deviation of the temperature signal is 2-3 K).

During the HP and LP tests, a correction via the preset camera emissivity setting has been done. By this measure it was possible to reduce the deviations to less than 5 K. Nevertheless, for the analysis of the 2D temperature information temperature it should still be considered that the measurement results are subject to a temperature dependent fluctuations (typically ±10 K above 600 °C) and the calibration is done only on local comparisons at a limited number of positions (here 3).

In order to better understand the quantitative accuracy of the measurements, calibration tests have been conducted. They are described in the following sub-section.

Infrared Calibration Tests

Calibration tests have been conducted in order to characterize the quantitative accuracy of the IR measurement and develop a strategy to calibrate the system. The two main tests are presented in Figure 21.

In test 1, a calibrated black furnace (BF) has been used. It features a black plate heated to an adjustable temperature value. The emissivity of the black plate can be considered as 1 and its temperature is continuously monitored and stable.

In test 2, a TBC coated Air Guiding Panel (AGP) as used for the MMX combustor has been heated and monitored with the borescope. This test resembles the Micromix module more realistically. Heating has been realized by a Bunsen burner up to temperatures around 680°C. The temperature distribution is consequently not homogeneous but the local temperature information has been monitored with a thermocouple located inside an effusing cooling hole (TC head is flush with the TBC coated surface and uncoated). The emissivity of the TBC is unknown. Therefore test have been repeated with an additional layer of heat resistant black paint on the TBC.

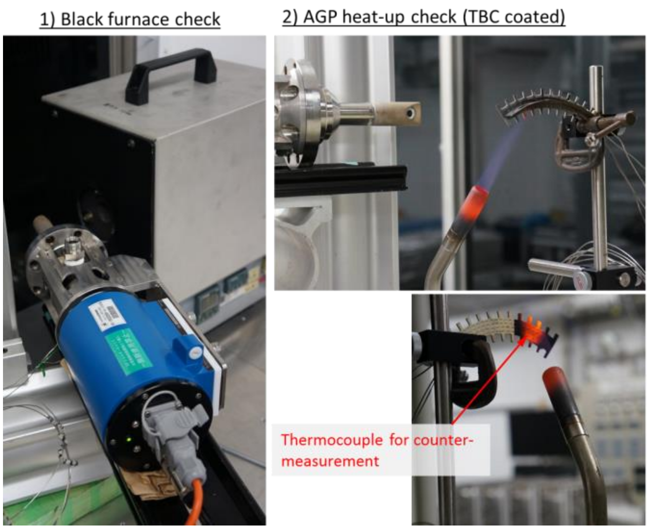


Figure 21. Calibration of the IR borescope with camera; Left: Black furnace calibration; Right: Air Guiding Panel (AGP) calibration with and without black paint.

The results of the black furnace measurement are analyzed in Figure 22. The graph shows that the difference between the BF and IR measured temperatures varies between 50 and 150 K and shows a linear tendency. In general, the black furnace temperature is underestimated by the IR result. The two applied ranges represent a software setting. According to the manufacturer, Range 1 is supposed to show more accurate results in the low temperature and range 2 in the high temperature range. This is also represented by the vertical error bands. For temperatures below 650°C (range 1) or above 800°C (range 2) the temperature signal captured by the IR camera shows strong fluctuations in the time domain (│ΔT│>10 K for range 1; │ΔT│>20 K for range 2).

For temperatures between 800 and 900 °C the standard deviation of the signal is only 1.8-1.2 K and the maximum temporal deviation is <4 K (w. range 1).

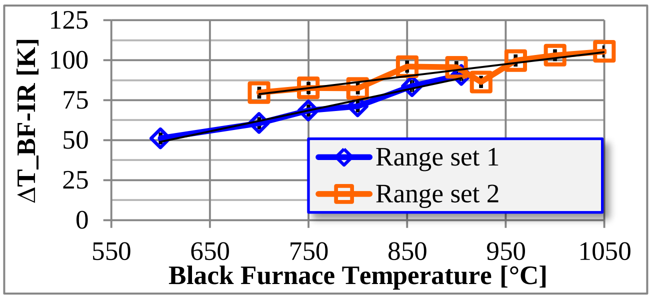


Figure 22. Black Furnace Calibration - Difference between BF and IR borescope temperature over the BF temperature range

The results obtained from the AGP-Heat-Up test are presented in Figure 23. Same as for the BF test, the temperature is underestimated by the IR measurement. The deviation between TC and IR temperatures ranges between -15 and 105°C (see Figure 23). However, graph shows a clear tendency. The deviation increases linearly up to approx. 675C and begins to form an asymptotic curve with a maximum deviation of 105 K at T_TC>775°C. Tests at higher temperatures are necessary in order to verify the observation.

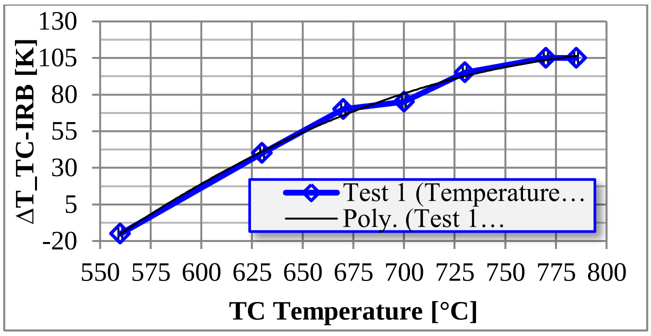


Figure 23. AGP Heat-up test - Difference between TC and IR borescope temperature over the TC temperature range.

From the calibration tests it can be concluded that temperatures indicated by the borescope might be approx. 100 K below the actual temperatures. However, the offset is relatively constant and predictable.

SUMMARY AND CONCLUSION

The paper presents the development of a borescope for VIS and IR measurement in industrial gas turbine combustors up to 10.5 barA and temperatures of 1340°C.

By means of CHT simulations, the cooling pathway and the outer shape is of the borescope improved and the thermal load on the head significantly reduced. Additionally, the material has been changed to a Ni-based alloy (IN625) and a TBC has been applied to increase the creep life from around 2 h to 10’000 hours (design v5).

For the flame visualization with visible light as well as for surface temperature measurement of the Micromix module, low and high pressure tests have been conducted and proof the concept. The pictures are clear and allow the analysis of the flame shape and length (VIS) as well as the temperature distribution of the MMX module with small details of only 1mm size (effusion cooling holes).

Calibration test of the IR system show that without adjustment of the camera emissivity, deviations up to 105 K (borescope is indicating a lower temperature) can be expected. By adjustment of the preset emissivity, the deviations can be reduced to values below 5 K. However, the calibration setting is not constant over the operational range. More sophisticated investigations are necessary if quantitative temperature measurements are intended. The qualitative temperature measurement is already on a high level and could have been used together with the VIS information to better understand the MMX combustor behavior under low and full pressure conditions.

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The numerical works (simulations and CAD) presented have been performed with the commercial software packages Star-CCM+ (CFD/CHT), NX (CAD) and NX NASTRAN (FEM) by Siemens PLM.

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