Development of an endoscopic, absorption corrected and calibrated OH laser induced fluorescence probe system for high pressure combustion diagnostics

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ABSTRACT

We present the design and preliminary results of an endoscopic OH laser-induced fluorescence (LIF) system that is capable of acquiring 1D-line measurements in high pressure combustion processes within large-scale test facilities. The system can be exploited to acquire line-of-sight OH-chemiluminescence images and absorption corrected absolute OH-species concentration from which additionally temperature distribution can be extracted in case of lean mixtures in chemical equilibrium. Different critical components, such as light guides for high power UV laser pulses and flexible UV image guides, were first tested and characterized in a laboratory setup. Optimization regarding pulse energy and beam quality led to the selection of an 1m long hollow core fiber for laser light delivery as a central element for the experimental setup despite high losses caused by bending the fiber. The image transfer is accomplished by a 7m long flexible UV image bundle, which is preferred to the use of a rigid borescope in harsh environments. We designed the endoscopic UV optics using readily available parts and achieved an approximated image resolution of 21.6 line pairs/mm. Additionally, post-processing methods, such as flat-field correction, can improve the image quality substantially and remove the pixilation effect of the fiber bundle structure nearly completely. To validate the complete system, probe-based qualitative OH-LIF measurements were performed in a well-known laminar flame of a matrix burner, which serves as a mock-up for anticipated applications in an industrial test environment with a technology readiness level (TRL) greater than 4. The final step consists of the integration of the miniaturized optics into a cooled probe system which protects the sensitive optics against the harsh environment of an aero-engine sector combustor. For this purpose, two probe systems were designed to include, on the one hand, the endoscope optics together with the fiber image bundle end tip and, on the other hand, the laser emitting and receiving system for performing an absorption measurement needed to quantify the recorded LIF signal.

1. Introduction

Although numerical simulations are increasingly becoming more relevant for the development process of the next generation of combustor technology, validation testing remains an essential element of the development process. In order to improve the knowledge gain during costly high-pressure tests there is an increasing demand for advanced, ideally non-intrusive, diagnostics such as flame visualization or (optical) temperature measurements under engine-relevant operating conditions. Of interest are e.g. burner-burner interactions using unscaled combustor and liner hardware. Minor test rig modifications in the form of the introduction of small bores through the pressure casing is a promising way to allow the adaptation of more advanced optical measurement techniques albeit in a miniaturized form (e.g. endoscopic) [Hsu et al. 2018].

Given an availability of three optical ports it is considered possible to conduct a variety of optical measurement techniques as shown in Fig. 1. An endoscopic observation probe placed downstream is suitable for observing the flame emissions in the form of chemiluminescence. The corresponding image is transferred by a coherent image fiber bundle to a mechanically decoupled camera system located outside of the test rig. A dichroitic beam splitter allows the observation of the light emissions in different spectral intervals in order to distinguish the chemiluminescence signals of the species within the reacting flow (e.g. OH, CH and CO_2) [Goers et al. 2014]. This observation probe can also be used with a sufficient depth of focus to image the fluorescence of laser light which is coupled into the combustion chamber through a laser probe placed in front of a burner face plate.

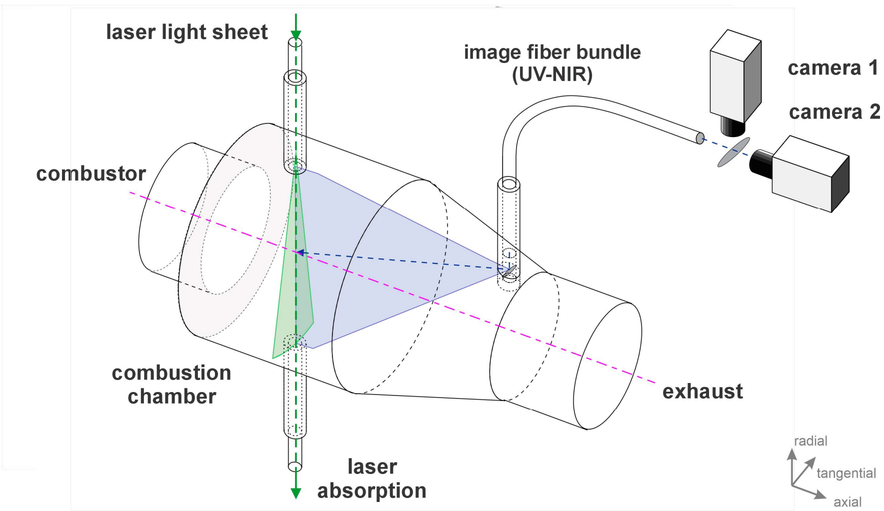

Figure. 1 Concept for a multi-method endoscopic optical diagnostic setup for high-TRL test facilities. This 3-probe arrangement is suitable for flame visualization and quantitative LIF measurement techniques.

Depending on the chosen wavelength, various species molecules are selectively excited and their stimulated emission is observed (i.e. laser-induced fluorescence, LIF). Using the hydroxyl (OH) radical it is possible to apply 2-line-OH-thermometry by exploiting the different temperature dependencies of two specific OH transitions [Seitzman 1993]. Since the intensity ratio of the corresponding LIF signals can be correlated to temperature the knowledge of absolute species concentration is not necessary for this method. A drawback of this method is the need for probing the two states simultaneously, which requires the use of two dye laser systems [Seitzman 1993].

An alternative method is based on the measurement of the temperature dependent OH-species concentration which requires only one laser system but assumes an unambiguous dependence of the OH concentration with respect to temperature almost independently of the stoichiometry. This relation for applies to lean mixtures in chemical equilibrium which defines the applicability of this thermometry method [Heinze 2011]. Determining absolute species concentration can be achieved by using an additional absorption probe that captures the light emitted by the laser probe and thereby allows a quantification of absorption along the transmission path, and ultimately yields estimates of absolute species concentrations, which is the approach pursued in the present work.

In this paper we describe the implementation of a 3-probe setup which is designed to operate in the UV spectral region, thus enabling 1D-line OH-concentration measurements via the absorption LIF technique using available UV hardware technology like hollow core fibers for light delivery and long, flexible image fiber bundles for image capture. In principle, 2-line-OH-thermometry without an absorption measurement could be applied in a planar version with divergent light sheets using only two access ports, one for emitting the laser light and one for observing the fluorescence signal OH-concentration measurements are restricted to a 1D version because of the severely limited optical access for the absorption probe (Fig. 1).

2. Characterization of endoscopic hardware

Light guides for pulsed UV radiation

Most laser-based spectroscopic methods rely on high energy laser light pulses, however, the transport of these pulses through solid quartz fibers is limited by known damage mechanisms like melting, solarization and mechanical fracture. The OH-LIF endoscopic system presented by Hsu [Hsu 2018] exploits a 6m UV-grade multi-mode fused-silica fiber with a 400µm core diameter. The energy of the transmitted double-pulses reached 100µJ at a repetition rate of 10Hz for 2-line-OH-thermometry without degrading or damaging the fiber material through solarization and cumulative thermal effects. Although this energy level is sufficient for LIF-experiments at atmospheric conditions, high-pressure testing for combustor hardware demands much higher energy levels (>1mJ) to account for the reduced OH-LIF quantum yield by increasing quenching at higher pressure levels up to 20 bar.

To overcome this limitation, hollow core fibers can be used as an alternative [Matsuura et al. 2004]. Since these fibers have no core material which can be damaged, this fiber type potentially allows for a significant increase in the transmission of the pulsed UV light. Another advantage of a hollow core fiber is the absence of solarization effects. While solarization in solid quartz fibers can be minimized to a certain degree for through enhanced OH concentration in the quartz material, the fiber degrading effect cannot be completely avoided. The drawback of this hollow core fiber type is its high sensitivity to bending which results in substantial transmission losses. These losses scale with the curvature radius R of the fiber approximately as $1/R$.

For this work, we compared the above described fiber types according to several criteria. Table 1 shows an overview of the main characteristics of both fiber types optimized for UV light – a solarization-resistant (SR), multi-mode fiber of 2 m length and 600 µm core diameter (Thorlabs FG600AEA) and an aluminum-coated, hollow-core fiber of 1 m length and 700 µm core (Guiding Photonics).

	SR multi-mode	UV hollow core
length (m)	2	1
core diameter (µm)	600	700
min. bending radius (mm)	100	200
max. pulse energy (mJ)	<1mJ	>2mJ
numerical aperture NA	0.22	0.06
transmission loss (straight)	0.25db/m	0.4db/m

Table. 1 Comparison of a common solarization resistant (SR) multi-mode fiber with an aluminum-coated hollow-core light guide.

While SR quartz fibers are available for lengths beyond 10 m, off-the-shelf UV hollow core fibers currently are only available as 1 m pieces requiring end-to-end coupling of multiple fiber segments at the cost of additional losses. Bending of both fiber types affects the beam quality and leads to higher losses. As mentioned, the hollow core fiber is much more sensitive to bending than the quartz fiber. Compared to a straight-line arrangement, we observed an additional drop-off in the transmitted energy of 63% for a bending radius of R = 250 mm in a quarter circle set-up. This loss can be offset by increasing the input energy to 10 mJ/pulse without damaging the hollow core fiber providing an output energy of 2.5 mJ/pulse. This is considerably higher than the energy output of 0.9 mJ observed for the quartz fiber for an input pulse energy of 2 mJ. Increasing the energy input for the quartz fiber led to damages in our test.

Although the maximum pulse energy is an important criterion for choosing the best fiber, another property is also relevant: Since the signal-to-noise ratio of an 1D-LIF experiment depends not only on the available laser energy but also on the diameter of the laser beam, the numerical aperture (NA) is of significance. Here the much smaller NA of the hollow core fiber allows for a better focus of the transmitted laser beam. Using a focusing lens (f = 40 mm) we were able to achieve a beam waist diameter of 3 mm at a distance of 185 mm from the fiber output. Since the resulting beam diameter scales with the product of core diameter and numerical aperture, the beam diameter using the quartz fiber would be a factor 3.14 times larger.

Therefore, we chose the UV hollow core fiber to be implemented in our endoscopic LIF set-up and tried to maintain the lowest possible curvature.

Coherent image fiber bundles

The harsh environments of full-scale component testing are associated with extremely high noise levels (>160dB) and vibration levels. To protect sensitive diagnostic hardware such as UV cameras and laser systems, it is essential to place the components in a sound-damped enclosure located at a safe distance of several meters from the test rig. Therefore, acquired UV images from inside the combustor also have to be transmitted through the pressure casing. For this purpose, rigid lens-based borescopes and flexible image fiber bundles [Udovich et al. 2008, Shabaz et al. 2023] are available.

Manufacturers of lens-based endoscopic probes for UV are faced with various challenges. The choice of materials for rod lenses with varying refractive index to correct for optical distortions like astigmatism and field curvature is limited. Often, doublet or triplet combinations of calcium fluoride, fused silica or sapphire lenses are used. Due to the significant lower hardness of calcium fluoride and to avoid stress induced birefringence, lens holders for calcium fluoride require a much more demanding mounting concept than fused silica optical designs. This limits the free aperture of small-sized lens holders, which are necessary for lens-based endoscopes. For our comparison study we used a 250 mm long UV borescope provided by Seika Corp.

The alternative image transfer method uses a flexible UV fiber image bundle provided by ILA R&D. Theses bundles are available at much longer lengths, up to 10 m, than a typical borescope system and consist of UV transmitting fibers with individual diameters of 17.5 µm. Approximately 17 000 single fibers are used for a circular active area of 4 mm diameter with a minimal bending radius of 100 mm and a numerical aperture of NA = 0.22.

Table 2 shows a comparison of the two different image transfer systems regarding their main advantages and disadvantages. As in the case for laser light guides, one can choose the best image guide depending on the demands of the optical access of the corresponding test rig.

The main argument for using lens-based borescopes is the far superior image quality, because they can provide higher image resolution and quality compared to the pixelated images from fiber bundles. All other criteria, like length, flexibility and especially transmission efficiency, are in favor of the fiber image bundle technology.

	lens-based borescope	flexible image bundle
length (m)	0.25m	7.0m
active area (mm)	6mm	4mm
min. bending radius (mm)	-	100mm
number of fiber elements	-	17.000
attenuation (@300nm)	-	0.1db/m
rel. transmission efficiency	1	25
optical resolving power	good	poor

Table. 2 Comparison of the main characteristics of 2 different light guides for UV image transport.

The main reasons for the low transmission efficiency of the borescopes are optical losses through multiple optical lens surfaces and inefficient light guiding. Lens systems suffer from aberrations and stray light, which reduces transmission efficiency. In contrast, once the light enters the fiber cores, it is guided efficiently with minimal losses due to total internal reflection at the core-cladding interface.

The limitations regarding the poor resolving power of the flexible image bundle lead to less demanding designs of the miniaturized lens systems for imaging the object (e.g. 1D fluorescence signal) onto the active area of the fiber image bundle front tip.

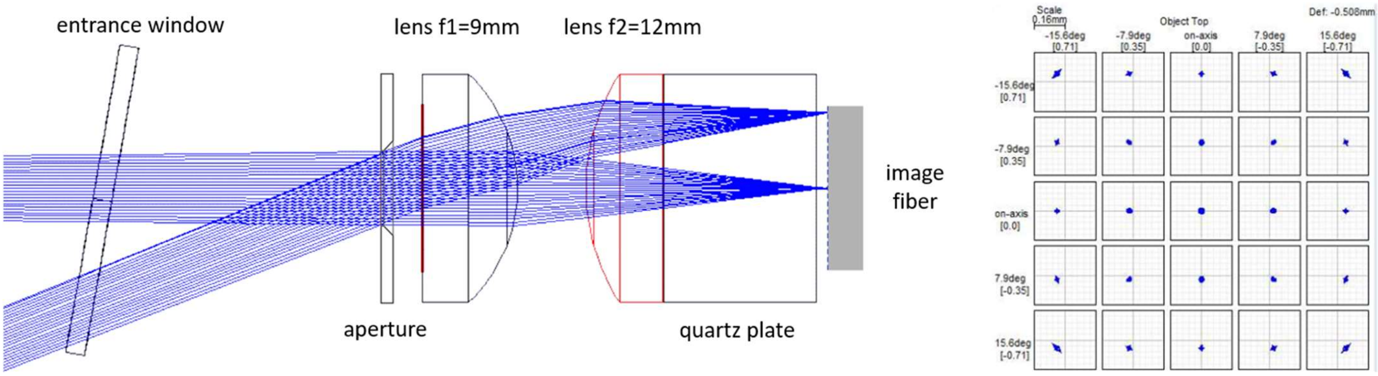

Figure. 2 Design of the optical layout for the endoscope containing an aperture of 1.9 mm in front of an imaging lens combination and a quartz plate (left). The resulting spot diagram for imaging laser induced fluorescence of 313 nm wavelength at a working distance of 94 mm is shown on the right side.

The endoscope optics for the configuration shown in Fig. 1 must be able to image, on the one hand, the spontaneous OH-chemiluminescence of the complete combustion volume and therefore require a sufficient depth of focus and wide field of view. This can be achieved with the use of short focal distance lenses (e.g. f = 4 mm – 12 mm). On the other hand, the lens system must also be able to acquire sharp images of the laser-generated 1D fluorescence signal at a defined distance. With the depth of focus requirement met, the second requirement is easily fulfilled. An example of a typical optical design is shown in Fig. 2. It uses a pair of lenses ($f1$ = 9 mm, $f2$ = 12 mm, diameter 6 mm, Edmund Optics) which are readily available and constitute a cost-effective solution. An aperture of 1.9 mm is placed in front of the first lens to reduce vignetting effects with respect to the limited numerical aperture of the image fiber bundle of NA = 0.22.

Additionally, the use of post-processing methods can greatly enhance the image quality of the endoscope. Flat field or white field correction uses a homogeneously illuminated image of a structure-less object. This is done by placing the endoscope directly in front of an integrating sphere. A division of the signal image by the flat field image removes the pixilation effect nearly completely and also accounts for any sensor inhomogeneities across the image plane (Fig. 3).

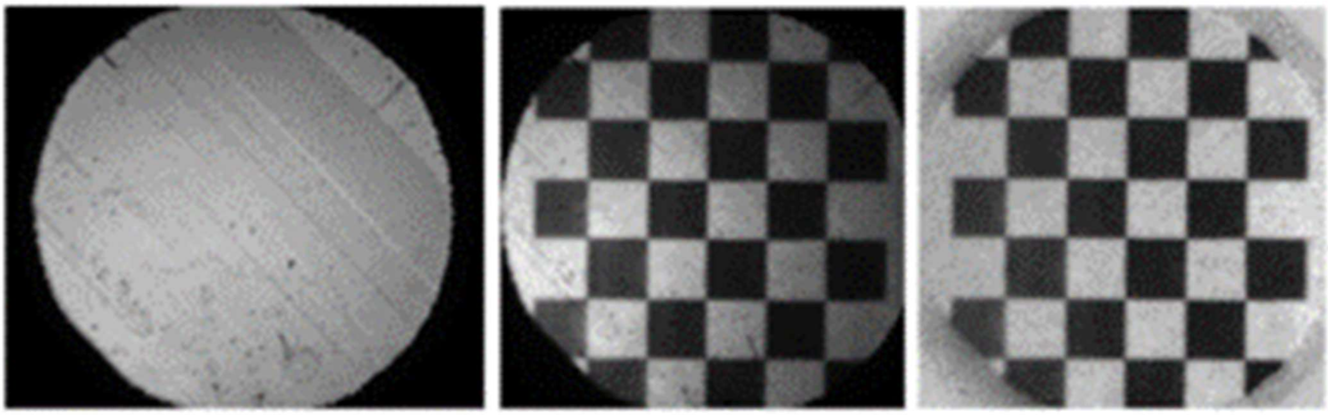

Figure 3. The flat field image of the flexible image bundle end tip shows the individual fiber structure with a fiber and diagonal structures of the manufacturing process (left). The raw signal image (checker board, middle) is then divided by the flat field image to produce the final flat-field corrected image on the right.

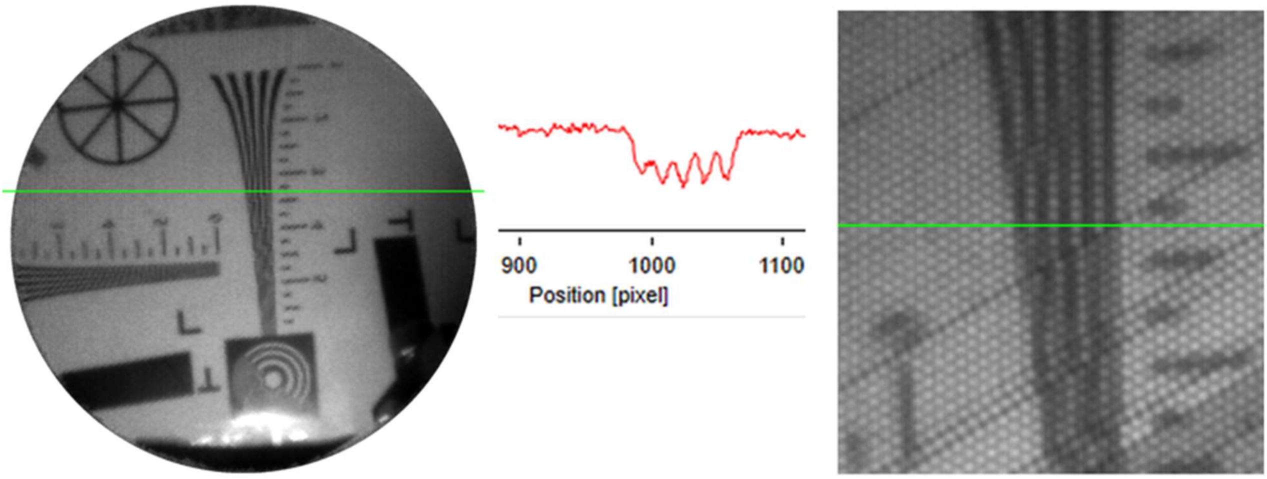

Figure 4. Left: photometric result of ISO 12233 chart (without binning). The chart height is 206.5 mm. Zoom of intensity profile across green line (middle). Right: zoomed version of the uncorrected ISO 12233 chart image indicating resolution limits due to effective image fiber diameter.

The optical resolving power of a typical endoscope system was tested as follows: A test chart with a uniformly spaced cross pattern was illuminated with an Hg(Ar) pen-ray lamp. Multiple images of the chart were recorded and averaged over 50 images (Fig. 4). After a flat field correction, a column intensity profile was extracted, normalized to maximum intensity and analysed. Taking into account the image magnification, the approximated image resolution was estimated at 21.6 line pairs/mm.

3. Laboratory set-up for endoscopic, absorption corrected OH-LIF

The experimental setup for testing the final mock-up for the absorption-corrected LIF method [Heinze et al. 2011] is shown in Fig. 5. Laser radiation at a wavelength of around 284 nm, corresponding to the spectral range of the OH $X^2\Pi \rightarrow A^2\Sigma$ ($\nu''=0 \rightarrow \nu'=1$) transition, is generated by a frequency-doubled dye laser pumped by a pulsed, frequency-doubled Nd:YAG laser. For the fiber transmission tests the UV-laser pulse energy can be varied in the range of 0.01-20 mJ using an external variable attenuator. The spectral UV-laser line width of 0.2 cm^{-1} is small compared to the OH absorption line width in order to enable a meaningful absorption measurement later.

The UV laser beam is then coupled into a 1 m long UV hollow core fiber with a core diameter of 600 µm. The output beam is imaged with a lens (*f* = 40 mm) to a spot diameter of 3 mm at a distance of 185 mm. Before and after the laser beam traverses the flame of the matrix burner system (McKenna laboratory), a small portion of the light is sampled via beam splitters and coupled into two multi-mode fibers (length 2 m, core diameter 200 µm, SR type, Thorlabs).

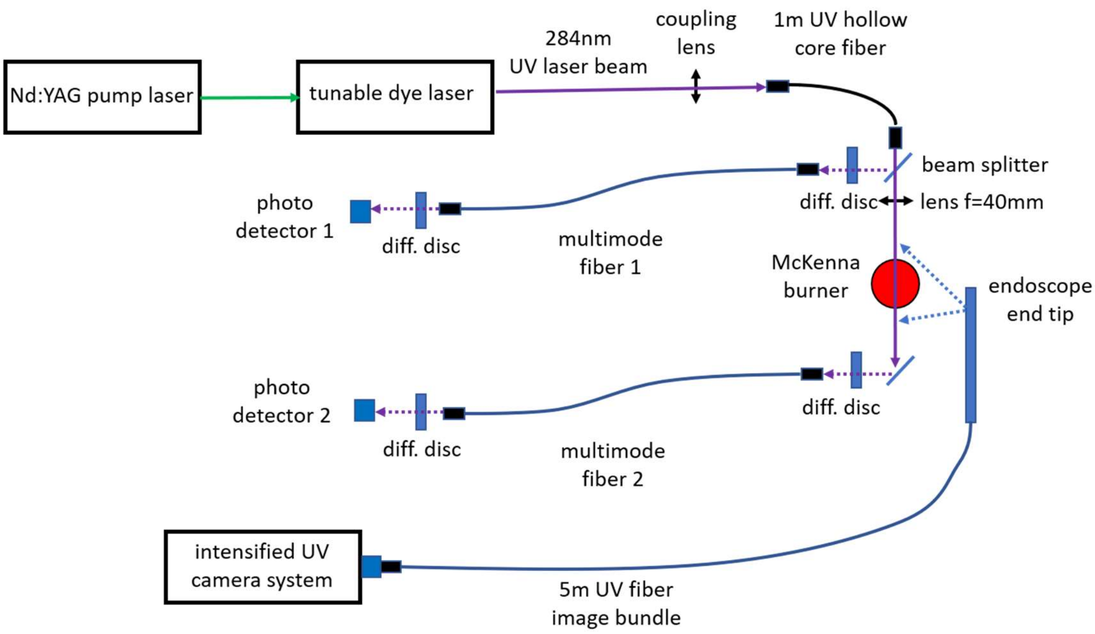

Figure 5. Experimental setup for testing of the endoscopic optical components (e.g. laser light guides, endoscope optics and UV image fiber bundle).

After exiting the fibers, the relative energy levels of the transmitted pulses are measured by two photodiodes. This arrangement is particularly suitable for endoscopic applications and allows for a correction of the LIF intensity signal with respect to absorption due to the high OH concentration of the flame: In the end, the simultaneous LIF and laser absorption measurements provide an absorption corrected and absolute calibrated OH concentration measurement along the laser beam. The fluorescence emitted along the probing beam is collected and captured by the UV endoscope (Fig. 6). After image transport through the fiber image bundle, the end tip of the endoscope is imaged onto the detector of an UV intensified camera using a lens combination of a reverse Polytec UV-triplet with f = 25 mm and a UV-Nikkor objective lens with f = 105 mm.

The UV hollow core fiber delivered 300 µJ pulse energy output, which is sufficient to prevent saturation effects in atmospheric flames and to measure single-shot signals. This value can be increased up to 2 mJ for high pressure measurements. Typical raw data images are shown in Fig. 6. The laboratory burner was operated with an ethylene-air-mixture (Φ = 0.82).

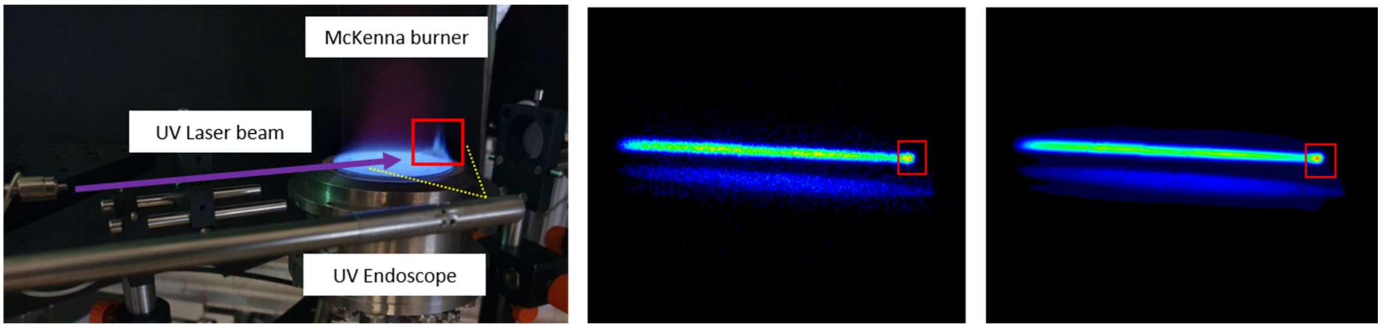

Figure 6. Left: Laboratory „proof-of-principle" experiment using a UV hollow core fiber for laser beam guiding and an UV fiber bundle for image transport. The heightened flame boundary (red box) is clearly visible in the OH-LIF signal intensities. Middle: Single-shot OH-LIF image with 300 µJ pulse energy to prevent saturation effects in atmospheric conditions. Right: Average OH-LIF image calculated from 100 single shot images, background not subtracted.

Although quantitative measurements of the absolute OH-concentration could not be carried at the time of writing, the good raw data quality serves as a positive indicator that this system can be successfully applied in the relevant environment of a high-pressure combustion test rig. To accomplish this goal, the miniaturized optical components have to be integrated into a suitable probe system, which will be described next.

4. Probe Integration

Observation probe

To protect the sensitive optics of the UV endoscope against the thermal load of the exhaust flow (Fig. 9) the designed optics with the flexible UV fiber image bundle must be mounted in a suitable cooled, pressure-resistant probe system (Fig. 7).

This system consists of an upper part, which connects the probe mount to the test rig while allowing the probe tip to be moved axially using a pneumatically controlled piston. Also, cooling water and purge air connectors for the probe window are located in the upper part. The lower part contains the probe tip with the endoscope optics protected by a quartz window, which can be purged with air. This tube part can be retracted into a "parking" position during rig operation, keeping it outside the hot exhaust flow when not in use which extends the lifetime of the system. The fiber image bundle can withstand temperatures up to 80°C and is sufficiently protected since the cooling jacket is designed to maintain an inner temperature of 20°C. An additional thermal barrier coating of the probe tip further reduces the thermal stress from hot exhaust flow. The outer diameter of the cooling jacket is 30 mm while allowing for an inner endoscope diameter of 10 mm.

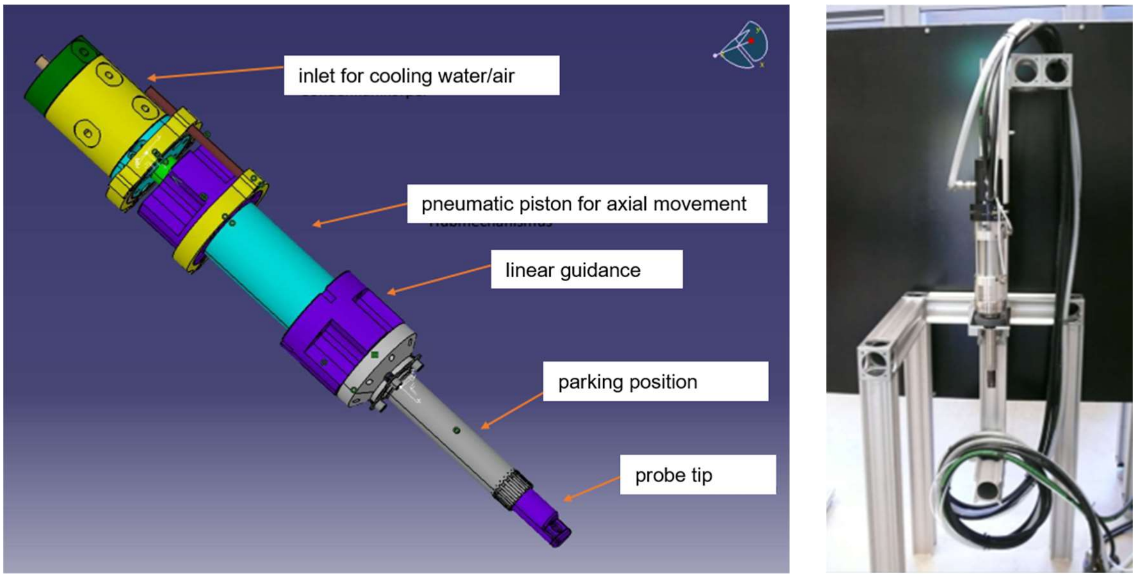

Figure. 7 CAD drawing of the cooling jacket system with probe mounts, pneumatic piston control and parking position for the probe tip (left) and the first assembled prototype with supply cabling and connections for water and air flows (right).

Laser probe

To implement the absorption-corrected OH-LIF measurement technique, the laboratory setup (Fig. 5) has to be adapted to a second probe concept. This "fork" probe system (Fig. 8) is designed to surround the combustion chamber of a typical aeroengine burner. It emits a laser beam from the bottom to the top of the chamber through 8 mm cooled quartz windows and collects the beam after traversing the measurement volume.

The lower probe part contains the previously introduced 1 m UV hollow core fiber, which guides the laser beam from outside the pressure vessel to the inside of the test rig. The multi-mode fiber collects a small part of the light which passes through the first bending mirror. This signal I_{in} is proportional to the incoming laser beam before absorption takes place. A second multi-mode fiber is placed inside the upper probe part and collects likewise a second part of the laser beam after traversing the primary zone of the high-pressure combustion (I_{out}). Both signals, I_{in} and I_{out}, can be used to correct for absorption effects [Heinze et al 2011].

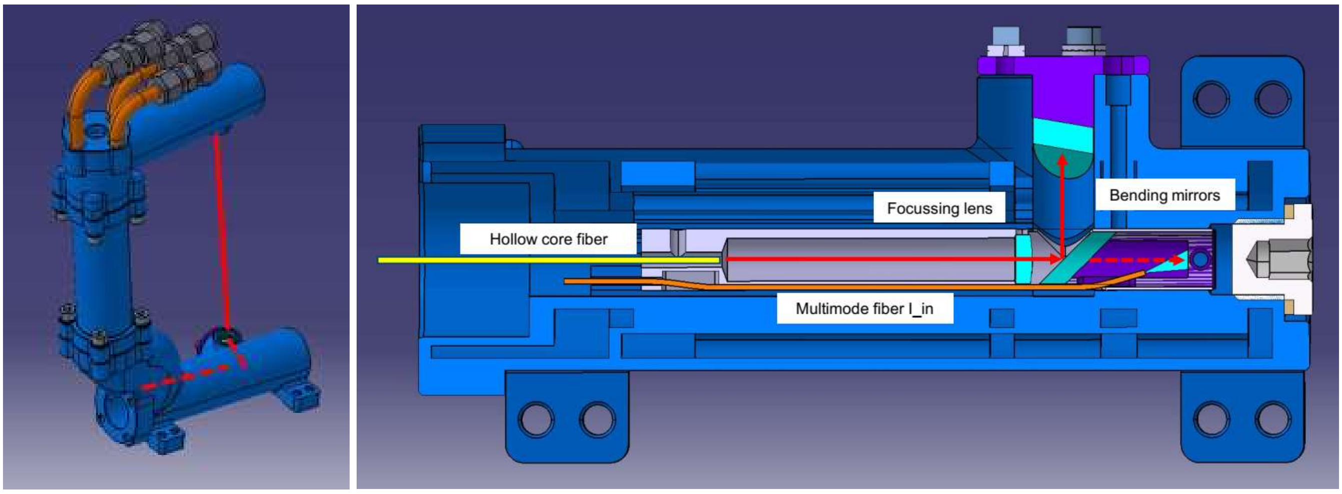

Figure. 8 Design of the laser-"fork"-probe concept for emitting a laser beam and measuring the absorption (left), design of the inner arrangement of the necessary optical components for the emitting part (right).

This concept of a single probe structure was chosen because of better mechanical stability against thermal expansion effects of the test rig during operation.

5. Conclusion and Outlook

An endoscopic set-up for quantitative OH-concentration measurement (LIF + absorption) which can be modified for additional diagnostics was introduced. The material provided a characterization the UV hardware and presented the probe designs for emission of high-power UV laser pulses, collection of laser light for absorption measurements and signal observation with a 7 m flexible UV image guide. A laboratory mock-up test measurement proved the viability of the chosen imaging and illumination concepts in the context of later applications in full-scale, high-pressure combustion test facilities. The details on the implementation of miniaturized optics into protective cooling jackets which have been shown to withstand temperatures up to 2000K and pressures up to 40 bar were described. In the near future it is planned to apply the proposed 3-probe system on a test rig for aero-engine sector combustors where the observation probe has been already tested.

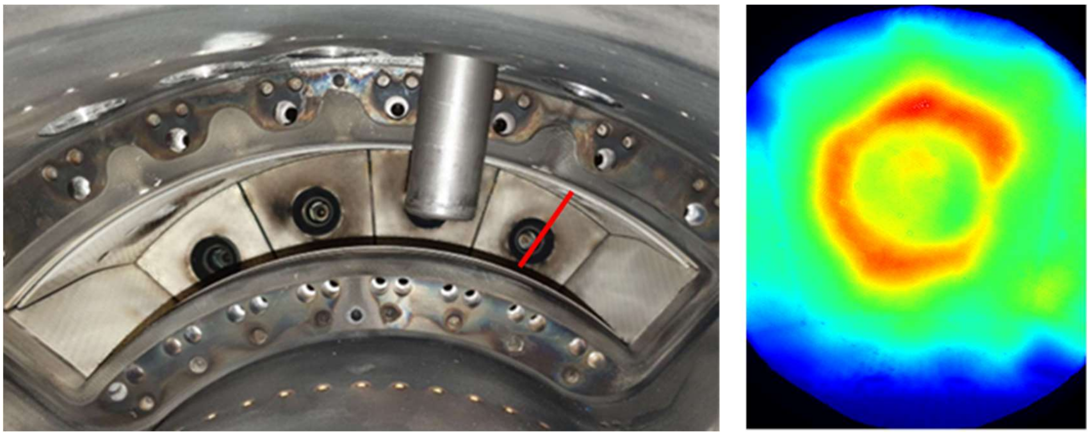

Figure. 9 Left: Installation of an UV observation probe inside a high-TRL test rig for sector combustion using a 7 m flexible UV image fiber bundle. The location of a probe laser beam for a 1D-OH-concentration measurement is indicated with a red line. Right: typical OH chemiluminescence image visualizing the heat release downstream of a single fuel injector influenced by air jets from mixing ports.

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