Application of optical diagnostics as an experimental tool for the development of combustors for stationary gas turbines

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Introduction

Over the past decades, stationary gas turbines have become highly reliable, economical, clean, and highly efficient sources of electricity generation. To maintain this position within the volatile energy market, the technology that is used in the gas turbine should be continuously updated or renewed. The combustion system has a major impact on the overall performance of the engine, and therefore on the position of the gas turbine (GT) technology in the future market. Hence, new and improved combustion systems are crucial to maintain a strong market position in the future. However, when looking at market trends in various regions, it becomes clear that there is no longer a single, most important performance parameter to focus the GT development on. Consequently, the development efforts for future combustion systems need to be flexible and adaptable enough to support multiple market requirements. Moreover, being competitive in the volatile energy market requires being innovative and coming up with better products than the competitors. For example, in Europe, US and some parts of Asia (like Korea or Japan) high efficiency (H-class) engines are expected to get increasing market shares. Besides CO and NO\textsubscript{x} emission-compliant operation from below 50 % relative load up to base load, H-class engines especially require high combustion temperatures combined with low base-load NO\textsubscript{x} emissions [1]. Therefore, crucial physical parameters for the optimisation of H-class combustion systems are fuel/air mixture uniformity (in space and time) and resulting uniform temperature profiles, reduction of cooling air consumption, and low combustion dynamics amplitudes over a wide operation range. These parameters are usually calculated upfront with various modelling approaches. However, currently used state-of-the-art approaches like RANS CFD show limitations e.g. by simulating the temporal mixing/temperature inhomogeneity or the complex interactions leading to combustion dynamics. On the other, new modelling approaches like Large Eddy Simulations (LES) still require high computational effort and, moreover, adequate experimental data for validation and optimisation. Hence, for the development and optimisation of future gas turbine combustion systems, expensive rig testing is still a mandatory step. In order to make this rig testing as effective as possible and in order to generate relevant data for the validation of numerical tools, advanced diagnostics systems are required.

In this context, especially measurements of local species concentrations (fuel/air mixture), flame behaviour (e.g. during occurrence of combustion oscillations) and wall and gas-phase temperatures (cooling-air reduction) are of interest. Widely used classical measurement approaches for these quantities are suction probes (species concentrations) and thermocouples (temperatures). However, physical probing can easily perturb the complex heat and species transport in combustion processes and generally is limited in its spatial and temporal resolution. In contrast to that, optical measurement techniques allow the non-intrusive in situ investigation of a system. Hence, they have become state of the art in a wide range of laboratory-scale experiments and are indispensable in modern combustion research [2]. Because of the on-going advances in the development of robust and reasonably priced light sources (particularly lasers) and detectors (e.g. photodiodes and cameras), these techniques have also become attractive for industrial-scale applications such as gas-turbine combustors. Therefore, cooperation between the Siemens AG and the University of Duisburg-Essen was initiated aiming at the selection and qualification of optical measurement techniques to support the development process gas-turbine combustion systems. In a first step it was planned to focus on techniques that have already been demonstrated in realistic environments. However, the application of these scientifically established measurement techniques to industrial large-scale experiments still poses particular challenges. The technical realisation of optical access to full-size test rigs operated at gas turbine relevant temperatures and pressures is not trivial, especially if the investigated system should not be affected (e.g., by large water-cooled windows). Further-
more, the sensitive optical arrangements and the typically complex and sophisticated measurement equipment are usually not designed for the harsh conditions in industrial laboratories. Nonetheless, laser-induced fluorescence (LIF) with acetone as a tracer for imaging of the fuel/air mixture [3] had been established for large-scale applications before. Additionally, flame chemiluminescence imaging [4] had been applied for the advanced evaluation of the flame behaviour during full-scale high-pressure combustion tests with an optical probe to avoid windows. The presented methods and exemplary test results were derived from a dissertation which is currently in preparation for being published.

Acetone LIF-imaging applied to gas-turbine combustors

Experiment

The presented LIF fuel/air mixture measurements were performed at atmospheric pressure and cold flow conditions. For the experiments the fuel was replaced by a mixture of up to 10 % acetone as fluorescent marker and nitrogen as carrier gas. The according acetone/nitrogen mass flows were scaled to an identical fuel/air momentum flux ratio as in the real engine. The air mass flow was scaled to atmospheric cold flow conditions by keeping the relative pressure drop across the burner identical to real engine conditions. A pulsed UV XeCl excimer laser was used to electronically excite acetone and induce fluorescence. The laser beam was formed into a thin light-sheet that defines the measurement plane. The acetone-LIF signal was recorded with a CCD camera with a UV-sensitive image intensifier and an f = 100 mm UV lens with an f-number of 2.8. The camera system was fixed on a stable aluminium rack located outside of the test rig. The viewing direction was against the flow direction towards the burner outlet perpendicular on the laser-sheet plane.

To enable measurements at realistic engine gas-turbine burners, two optically accessible full-scale single-burner test rigs were developed for different gas turbine frames (Figure 1). These test rigs are mainly made of acrylic glass. However, standard acrylic glass is not transparent in the wavelength range required for the laser-induced excitation of acetone (here: 308 nm). A standard material widely used for this purpose is fused silica, but unfortunately it cannot be machined into the complex geometries required to simulate important flow features of the real engine geometry. Consequently, the feasibility of various other materials was investigated. Finally,
a specific UV-transparent acrylic glass that was originally developed for medical and tanning bed industry applications was selected as base material for specific regions of the test rigs. High mass flows of tracer/carrier gas mixtures with well-defined composition were required for the measurements. As the acetone concentration in the tracer gas correlates linearly with the measured fluorescence intensity, it is important to ensure a high accuracy and reproducibility of the acetone dosing and mixing with the carrier gas. To fulfill these requirements, a tracer/ gas supply facility was designed and commissioned. A sketch of the tracer gas mixing facility is shown on the left side in Figure 2.

The main components of the tracer gas mixing facility are:

- Nitrogen supply line with a N₂ pre-heater and temperature, pressure and mass flow controllers (red)
- Acetone reservoir, pump and mass flow control unit (purple)
- Acetone evaporation unit with heat exchanger and steam generator (dark blue)
- Static mixer followed by five burner supply lines (green)

The electrical pre-heater for the nitrogen is required to avoid acetone condensation in the tracer gas mixture as a consequence of low nitrogen temperatures due to the expansion of the nitrogen from the high-pressure cylinder bundles. The nitrogen mass flow is controlled by a mass flow controller (MFC). The acetone is pumped by a mass flow-controlled pump into the heat exchanger for evaporation. The heat exchanger was fed by steam (160 °C) coming from a steam generator operated within a closed steam/water cycle. After evaporation, acetone and nitrogen are mixed using static mixer to ensure a homogeneously mixed tracer gas. Afterwards, the mixture is split on up to five lines with pressure valves to adjust the split between the single lines. The lines were directly connected to different burner fuel stages. The burner supply lines were optimised for different mass flow regions between 1 g/s up to 80 g/s to stay within the defined mass flow measurement accuracy of ±1 % for each mass flow range. All mass flows were measured with Coriolis mass flow metres to guarantee a sufficiently high measurement accuracy independent from the flow medium temperature, pressure and density (e.g. for varying acetone concentration).

The right frame in Figure 2 shows the experimental setup with the SGT5-4000F test rig, the excimer laser and a traverse unit with the laser light sheet-generating optics. Besides the optics also an energy monitor and a beam homogeniser are installed on the traverse unit. The energy monitor extracted a small portion of the beam and measured the respective laser pulse energy for every single laser pulse with a photo-diode. This laser energy value was required for the post-processing to normalise all recorded images to the same reference laser pulse energy. The beam homogeniser was used to compensate spatial fluctuations of the laser energy distribution in the laser beam and, furthermore, to expand the laser beam to a sheet. For details of the working principle of the beam homogeniser please refer to [5]. By using the traverse unit the measurement plane, which is defined by the laser light sheet, can easily be adjusted for different burner configurations and can be moved to different locations downstream of the burner outlet. The ICCD camera used for recording the acetone fluorescence is not shown in this figure.

Results

In the following exemplary test results of LIF measurements performed at a real engine SGT5-4000F burner are presented. A sketch of the burner is shown on the left side of Figure 3. The burner consists of an outer main burner and an inner pilot burner. Both stages have swirler vanes that include injection holes where the fuel gas (red) is injected for premixed combustion operation. The LIF measurement plane for the presented test results is indicated in orange.

In the upper right corner of Figure 3 four typical examples of post-processed instantaneous “snap-shot” images recorded at base load reference conditions are shown. The intensity scale of all images is normalised to perfect premixing, i.e. green means perfectly mixed, blue and red indicate fuel-lean and rich zones, respectively. All images presented in this section have viewing directions upstream against the flow direction. It can be seen that the mixture field in the pilot region is comparatively homogeneous and does not significantly change from image to image. The main burner region, on the other hand, shows a larger variation in signal over time and thus a wider range of mixture composition. Towards the outer radius the fuel/air mixture becomes more inhomogeneous due to a decreasing relative fuel penetration depth caused by the increasing distance between the swirler vanes from the inner to outer radius. Additionally, a trend towards forming a rich and a lean ring is seen in the region between the main and the pilot burner.

The stationary features in the mixing fields e.g. for varying hardware or boundary conditions, can better be seen from averaged images. To visualise the local level of concentration fluctuation, images of the temporal standard deviation (STD) are calculated. The lower the value in the STD image, the lower is the temporal variation in the set of single images at the corresponding location. Hence, the STD images can be interpreted as a 2-D distribution of the temporal mixture fluctuations. Typical averaged and STD images are shown on the bottom right of Figure 3. The averaged image shows that the pilot region is well
mixed. In the main burner region again the circumferentially periodical change of rich and lean regions between the single vanes can be seen. Additionally, a ring with lean mixture can be seen that surrounds the pilot cone followed by a fuel-rich ring zone. The lean ring can be attributed to the improved mixing in the shear layer between the pilot and the main burner flow. Compared to the instantaneous images, the maximum relative concentration is generally lower. Based on this observation, it can be assumed that the averaged images typically show a more homogeneous fuel distribution compared to reality. However, the standard deviation image shows significantly lower values than the averaged or single images. This means that the overall temporal fluctuations of the mixture profile are low in comparison to the spatial variation. Especially the pilot region shows a very low standard deviation so that it can be assumed that the pilot has a temporally quite stable mixture profile. The main burner region shows a slightly higher standard deviation which is increasing from inner to outer radius and also seem to be slightly higher on the right side (viewing against the flow direction). Moreover, the lean and the rich ring around the pilot also seem to be temporally quite stable. A higher standard deviation can be observed in the area of the rich and lean streaks of the vane channels towards the outer radius, but not in the region where the highest fuel concentration is measured, but directly next to it. This means that highest temporal mixing fluctuations occur as an envelope of the fuel rich streaks in the outer main burner region. However, it should be mentioned that the experimental conditions are isothermal meaning that all combustion chamber pressure-induced fluctuations are missing and only cold flow turbulence is present.

**Comparison to CFD**

One goal of the LIF measurements was to generate reference data for validating CFD simulations of the mixing process. In a first step, steady RANS simulations were run in an integral model of the complete test rig and at identical boundary conditions as the LIF experiments. Exemplary results from the LIF measurements and the RANS simulations for two representative cases are shown in Figure 4.

It can be seen that the RANS simulations (Figure 4, right) tend to predict less fuel/air concentration variation compared to the measurement (Figure 4, left). It is believed that this is mainly caused by the limitations of the RANS approach regarding the modelling of turbulence which directly affects the fuel/air mixing. The potential impact of the turbulent Schmidt/Prandtl number on the simulations was investigated in this context and an improved setting for future CFD simulations with a decreased Prandtl number was found. However, general trends of the mixing for different fuel splits or mixing lengths showed satisfactory agreement. Hence, steady RANS CFD simulations may be used as a reliable tool to systematically investigate and compare the effect of slight modifications on the mixing field with reasonable effort.

**Endoscopic chemiluminescence imaging applied during high-pressure combustion tests**

**Experiment**

The presented chemiluminescence measurements were performed at a Siemens high-pressure combustion test rig operated at the German Aerospace Center (DLR) in Cologne, Germany. External compressors and air pre-heaters allow operation at engine-like thermodynamic boundary conditions. With an adjustable back-pressure valve the test rig can be operated at different pressure levels up to full-engine pressure. The test rig itself consists of a pressure vessel with a so-called flow box inside. The flow box mimics a full-scale single-burner section of including relevant flow features of the gas turbine mid-frame like the compressor exit diffuser, the burner inflow and the combustion chamber outlet. The flow box can be changed to represent different gas turbine frames. The test facility and a sketch of the test rig with an installed SGTS-4000F flow box are shown in Figure 5.

Optical access to the combustion chamber was achieved by using a water-cooled optical probe with a UV-transparent imaging fiber-scope installed inside. The probe was designed to withstand operation at pressure levels up to 21 bar and temperatures up to 1,900 K. Hence, it features a sophisticated water-cooling system and a probe tip with thermal barrier coating (TBC). The total length of the probe without detection head is about 1,600 mm. The outer diameter of the probe is 35 mm so that the impact on the observed system is minimised. The probe tip can be exchanged to provide viewing angles of 0°, 30°, 80°, and 90°. All probe tips are equipped with an exchangeable sapphire window with nitrogen purging to prevent window fouling. The fiber scope inside the chemiluminescence probe features 50,000 single fibers with a high transmittance down to the UV range (see Figure 6 left). The optical elements of the probe assembly are anti-reflection coated for the UV range down to 300 nm. The resulting transmittance of the assembly of the fiber scope and the optical elements is shown in Figure 6 (left).

For imaging measurements of the flame chemiluminescence, the detected signal was filtered with various combinations of band-pass filters. The transmittance curves for the applied optical filter combinations are shown in Figure 6 (right). To obtain comparable images independently from changes of the axial flame position, a lens with a high f-number and accordingly high depth of field was used.
The chemiluminescence probe was located in the test rig sidewall, approximately 3 D (D = burner diameter) downstream of the burner outlet, viewing perpendicularly on the burner outlet plane. The insertion depth of the probe can be adjusted continuously. To quantify the effect of the probe on the experiment, tests with and without the probe inserted. By varying the intrusion depth of the probe an optimised probe position was found that had no significant effect on the combustion stability or emissions. However, with this arrangement, the centre of the burner is not aligned with the image centre. In combination with the line-of-sight signal integration of chemiluminescence measurements and the resulting loss of spatial information, this poses challenges to the interpretation of the chemiluminescence measurement (Figure 7).

**Results**

Figure 8 shows representative spectra of a SGT5-4000F combustor recorded at part load (blue) and base load operation (red). The spectra were recorded with a fiber-coupled USB UV-VIS-spectrometer at real-engine conditions scaled to 9 bar and were corrected by the spectral sensitivity of the optical probe. However, the spectral range below 300 nm should be treated with caution, because the probe sensitivity in this range strongly decreases with decreasing wavelength (Figure 6). Additionally, black-body radiation for a temperature of 1,600 K (green) and the estimated portion of CO$_2^*$ broad-band emission (dashed orange line) are indicated in Figure 8.

The spectrum for base-load operation is dominated by thermal radiation of the very hot ceramic heat shields inside the SGT5-4000F combustion chamber, which clearly demonstrates the necessity of effective optical filtering to avoid overexposure of the detectors. Furthermore, the characteristic peaks from OH$^*$ and CH$^*$ can be observed. Both radicals are frequently used as indicators for the flame front, as they mainly occur as an intermediate in the reaction zone. For more information on chemiluminescence spectra measured at GT burners refer to [7, 8].

For the imaging measurements series of 1,000 to 10,000 single images with recording rates between 25 and 10,000 frames per second and with integration times between 75 μs and 500 μs were recorded for each steady state test point. All recorded images were post-processed with dark image subtraction and were normalised to an identical reference intensity scale to allow direct comparisons of all images. Additionally, all images were corrected by a reference sensitivity map of the camera/intensifier/endoscope system recorded with the help of a UV-light source and an integrating sphere which compensated the vignetting of the endoscope system. Same as for the LIF measurements, the post-processed images were then used to calculate averaged images and the temporal 2-D standard deviation (STD) of the chemiluminescence signal. The averaged images were used to compare the local mean heat release distribution for different burner designs and operation conditions whereas the STD images help to identify temporal fluctuations of the heat release. Videos assembled from the single images were used to get an impression of the overall flame behaviour.

Figure 9 shows four exemplary averaged images recorded at different pilot-gas fractions. During the pilot gas variations, the total fuel mass flow was kept constant to maintain an identical thermal power. In addition to the chemiluminescence images the respective total NOx emissions measured in the exhaust gas are shown for each image. The values are normalised to the reference value at lowest NOx conditions.
The lowest NO\textsubscript{x} emissions were measured at reference conditions (middle right). With increasing pilot fraction, also the NO\textsubscript{x} emissions increased (right). A decrease of the pilot fraction to 0.87 of the reference value did not lead to a significant change of the NO\textsubscript{x} level (middle left) whereas a further pilot fraction decrease led to a steep increase of the NO\textsubscript{x} emissions (left). This leads to the assumption that the increased NO\textsubscript{x} emissions at lower pilot gas fraction were mainly caused by the main reaction zone (red and white: high heat release rate) whereas the higher NO\textsubscript{x} emissions at higher pilot gas fraction were mainly caused by the pilot reaction zone. Further results from the chemiluminescence measurements like load variations or the effect of fuel-gas preheating or a comparison of different burners at identical thermodynamic boundary conditions are presented in [9].

To investigate the behaviour of the flame during the occurrence of combustion oscillations, pressure fluctuations inside the combustion chamber were recorded simultaneously to the chemiluminescence measurements (Figure 10). The pressure fluctuations were measured by a pressure transducer located at the outer shell of the combustion chamber with an axial position close to the chemiluminescence probe location. These recorded time series were the basis for the subsequent off-line phase reconstruction and sorting algorithm as described in detail in [10, 11]. The phasesorted averaged images in Figure 10 show a fluctuation of the outer main stage, whereas the inner pilot stage stays nearly constant and stabilises the overall flame. This behaviour is consistent with the experience that an increase of the pilot fraction stabilises the flame, whereas a decrease of the pilot fraction may lead to flame pulsations up to a blow-off of the flame. Furthermore, it can be seen that after post-processing with the developed ray-tracing algorithm the steady RANS CFD simulation shows similar structures as in the experimental recording. The flame now also occurs in an arc-like structure with two separated maxima of the main burner and pilot flame. The signal decrease on the right hand side of the image is observable in both cases as well and, hence, can be assigned to the asymmetric optical setup and the line-of-sight nature of chemiluminescence measurements. The interpretation of the recorded signal is influenced by optical effects as well as by the flame shape itself. To support the explanation of certain observations during chemiluminescence imaging, a post-processing tool was developed to generate CFD images from standard RANS CFD simulations. The post-processing method exports the calculated OH\textsuperscript{*} signal distribution or another flame front marker into MATLAB where required input like the virtual camera position, viewing angle, and the detector efficiency can be defined. Afterwards, a line-of-sight integration of the flame front marker distribution is done by using a ray-tracing approach. However, for the first simulations potentially relevant effects like OH\textsuperscript{*} signal trapping or beam steering were yet not implemented.

The left frame in Figure 11 shows an iso-surface of the flame. As in the experiment, the view is slightly diagonal towards the burner and the image section is limited to the resulting field of view of the probe used in the experiment (Figure 7). In the middle the post-processed CFD image is shown. It can be seen that after post-processing with the developed ray-tracing algorithm the steady RANS CFD simulation shows similar structures as in the experimental recording. The flame now also occurs in an arc-like structure with two separated maxima of the main burner and pilot flame. The signal decrease on the right hand side of the image is observable in both cases as well and, hence, can be assigned to the asymmetric optical setup and the line-of-sight signal integration. The region of high intensity in the CFD results is generally spread wider than in the experimental recording which is most probably caused by the insufficient flame shape prediction of steady state RANS simulations and the used combustion modelling approach [7].

**Summary and outlook**

Acetone LIF imaging applied to a SGT5-4000E combustor at atmospheric cold flow conditions provided valuable information about the fuel/air mixture formation and
quality. In addition to averaged fuel/air mixture distributions which were previously derived from classical suction probe measurements at a limited number of probe locations (typically in the range several hundred), the LIF imaging measurements now provide information about the instantaneous fuel distribution and its temporal fluctuation. Furthermore, the suction probe method suffers from a coarse spatial resolution and is much more time-consuming than the LIF experiments because the entire mixing field is assembled from many subsequent measurements. Hence, the LIF approach is recommended as standard measurement technique for future measurement tasks in frame of gas turbine combustor development at Siemens. Results from steady RANS simulations with identical geometry and boundary conditions showed satisfying agreement with results from the experiment in terms of the prediction of trends. Similar simulations using LES are underway and will be compared to the reference LIF data soon.

The presented results from the endoscopic chemiluminescence measurements demonstrate the ability of getting more insight into the complex combustion processes at gas turbine combustion tests by using this comparably simple but robust measurement technique. The recorded images clearly show differences of the flame distribution, e.g. for different pilot fuel fractions. First findings of the image evaluation revealed a correlation between the main/pilot heat release distribution and the measured NOX emissions. The phase-averaged images gave insight into the flame behaviour during the occurrence of pressure oscillations which allowed identifying the spatial type of flame pulsation. Generally, it could be proven that the chemiluminescence probe design resists the pressure and the thermal load as well as the resulting mechanical stresses at high-pressure combustion tests with realistic gas turbine boundary conditions. The developed CFD post-processing method including a ray-tracing algorithm is an important step towards using chemiluminescence images for the validation CFD-based combustion simulations.

Currently Siemens is building a new burner test centre Clean Energy Centre (CEC) in Ludwigsfelde near Berlin [12]. Encouraged by the promising results presented in this paper, the application of optical measurement techniques will be intensified at this test centre. Hence, publicly co-funded cooperation projects with several research institutes were started including the enhancement of the chemiluminescence measurements towards multi-species high-speed imaging, a more flexible optical probe design, and the development of a tomographic reconstruction algorithm to derive volumetric flame information from simultaneous measurements at multiple positions. Moreover, the developed optical accesses will be used for the application of CO TDLAS measurements, FRS and surface temperature measurements using thermographic phosphors. These advanced experimental tools enable to increase the speed and the quality of the development of future combustion systems for a further increase of gas turbine efficiency and operational flexibility and reduced emissions.

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References


