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Wall Temperature Measurements in a Full Scale Gas Turbine Combustor Test Rig With Fiber Coupled Phosphor Thermometry

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Wall temperature measurements with fiber coupled online phosphor thermometry were, for the first time, successfully performed in a full scale H-class Siemens gas turbine combustor. Online wall temperatures were obtained during high-pressure combustion tests up to 8 bar at the Siemens CEC test facility. Since optical access to the combustion chamber with fibers being able to provide high laser energies is extremely challenging, we developed a custom-built measurement system, consisting of a water-cooled fiber optic probe and a mobile measurement container. A suitable combination of chemical binder and thermographic phosphor was identified for temperatures up to 1800 K on combustor walls coated with a thermal barrier coating (TBC). To our knowledge these are the first measurements reported with fiber coupled online phosphor thermometry in a full scale high-pressure gas turbine combustor. Details of the setup and the measurement procedures will be presented. The measured signals were influenced by strong background emissions, probably from CO₂ chemiluminescence. Strategies for correcting background-emissions and data evaluation procedures are discussed. The presented measurement technique enables detailed study of combustor wall temperatures and using this information an optimization of the gas turbine cooling design.*

INTRODUCTION

The cooling design of gas turbines plays an important role in the efficiency and overall performance of gas turbines. On the one hand a high turbine inlet temperature is desired to achieve high efficiencies. On the other hand cooling air is needed to protect the walls from excessive temperatures. Cooling air has an direct impact on the efficiency and emissions of a gas turbine. Therefore the exact knowledge of the wall temperature is important to determine an optimal cooling air flow. However, combustion tests of gas turbines are usually performed in test rigs, where only limited information from inside the gas turbine is available. While in- and outlet conditions, and cold-side temperatures are monitored, the surface temperatures inside the combustor are often unknown. An estimation based on cold-side temperatures and calculated adiabatic flame temperatures is only possible with limited precision. A precise determination with an online measurement technique would therefore enable new opportunities to study heat load of the combustor walls.

Various online and offline wall temperature measurement techniques exist. Thermocouples are widely used and can provide temperatures with good precision. The main drawback of this technique is, that it is intrusive and wiring can be difficult. Another online technique is pyrometry. It requires optical access to the combustor. However, due to interfer-

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ences from flame emissions and reflected radiation in the combustor the accuracy is limited [1]. Thermal indicating paint is a widely applied offline technique. The paint is applied to the wall before the combustion test and the color change interpreted after testing to obtain isotherms at the color change temperature [2]. The precision is however limited and only the maximum temperature during the test cycle is obtained.

Phosphor thermometry is a technique utilizing phosphorescent particles. These particles consist of a ceramic host doped with transition or rare earth metals. Temperature can be measured online with high precision [3–6], although also an offline variant exists [7]. Phosphor thermometry is based on the temperature dependence of the emission characteristics of phosphorescent materials. After excitation with light (preferably a laser pulse), these materials emit light, after several internal energy transfer processes. Non-radiative quenching reduces the lifetime of the phosphorescence at high temperatures. The temperature dependence of the lifetime is therefore a precise indicator of the temperature. For some phosphor materials it is also possible to use the intensity ratio of two emission lines to measure the temperature [8]. However, this approach is usually about an order of magnitude less sensitive [9]. In addition, the intensity ratio is prone to systematic errors especially, in the presence of interfering signals. In gas turbine combustors background from thermal radiation and flame emissions is unavoidable and the decay rate method is therefore advisable.

One of the challenges at large combustion test rigs is the limited optical access. Due to the arrangement of the combustor inside the pressure housing, a fiber coupled setup is often the only solution. Fiber coupled remote phosphor thermometry has been performed before on a stator vane doublet at atmospheric pressure [10]. A fiber bundle with different fibers for laser delivery and phosphorescence collection was used. The distance between fiber probe and phosphor coated wall was only 26 mm. A single fiber setup has the advantage of simpler and cheaper design and higher collection efficiencies. However, fluorescence and Raman scattering generated as the excitation laser pulse is transmitted through the fiber can interfere with the phosphorescence. To overcome this issue excitation of the anti-Stokes shifted phosphorescence has been proposed. This way, the emission wavelength of the thermographic phosphor is shifted to a region with less influence from interference generated in

the fiber [11].

The results presented here are a continuation of previous work, where the measurement technique has been tested under lab scale conditions in high-pressure and atmospheric flames [12]. Main focus of this work is the demonstration of wall temperature measurements under realistic conditions in a full scale gas turbine combustor. Here we present the first successful wall temperature measurements with fiber coupled online phosphor thermometry at the Siemens CEC test facility. Online wall temperatures could be obtained during high-pressure combustion tests up to 8 bar, using a Siemens full scale H-class large gas turbine combustor. During the campaign temperatures up to almost 1600 K were measured using the phosphor YAG:Dy. Single fiber phosphor thermometry with gated signal detection was used, to overcome problems associated with fast, laser induced interference signals. Details of the setup and the measurement procedures will be presented. Strong influences on the signal from flame emissions could be observed. We present strategies for correcting background-emissions to increase measurement precision and will discuss data evaluation procedures.

EXPERIMENTAL AND DATA EVALUATION

In this section, the optical access to the combustor wall will be explained first. Then the optical setup, the data evaluation procedures, and the calibration process will be explained.

Test facility and optical access

The probe was applied to a Siemens high-pressure combustion test rig, operated at the Siemens Clean Energy Center (CEC) test facility in Ludwigsfelde near Berlin. The facility holds three testbeds with exchangeable combustion rigs. External compressors and air preheaters provide engine-like thermodynamic boundary conditions such as maximum rig pressures of 4.0 MPa, and maximum air inlet temperature of 870 K at air mass flows up to 50 kg/s. The left side of figure 1 gives a schematic drawing of the test facility.

The combustion test rig consists of a pressure vessel containing an exchangeable flow box, which mimics all mid-frame engine features like the compressor exit diffuser and the first turbine vane section. One pressure vessel can hold different burners by simply replacing the flow box. To account for the

Fig. 1. Schematic of the high-pressure test rig with modular optical probe and optical setup.

different engine pressure levels, the rig pressure is adjustable by a back pressure valve.

To achieve optical access to the combustor, the fiber probe is guided through the pressure vessel and the flow box to the combustor wall. The feedthrough port in the pressure vessel serves as a pressure barrier and needs to meet all safety regulations of the pressure equipment directive. To minimize the required modifications on the pressure vessel, the feed-through approach is based on a non-centric port in a flange lid of the vessel, thus enabling different feedthrough positions by either turning the lid or by changing its position. A stuffing seal is attached to the lid to hold and seal the fiber probe while offering the opportunity to adjust the penetration depth to account for different length requirements for each targeted measuring position.

The flow box is located inside the pressure vessel, and thus, the pressure difference over its walls is negligible. Subsequently, the port definition was easier, and no seals were necessary. Despite this, the feedthrough in the flow box holds an important task, i.e., to stabilize the probe to avoid vibrational fatigue due to the high flow velocities inside the flow box. The basis of the port is a two-piece lid featuring a large round non-centric cutout for easy probe installation.

To secure the probe tip position at the combustor wall, a custom-made adapter was welded onto the can (fig. 2). It was manufactured using additive manufacturing (AM), which was an important key factor in realizing advanced functions of internal cooling and purge air distribution. In addition, AM enables to meet the free-form surface of the can, and to select the measurement position by fixing the probe slightly tilted. The head is tightened with screws and

Fig. 2. Schematic of the adapter for holding the probe head and nitrogen purging.

a high-temperature, pressurized metallic toric joint prevents leakage air entering the combustion chamber at the probe feed through. In addition to holding the head, the adapter also serves to inject nitrogen into the probe to purge the sapphire window of the probe and cool the probe tip.

Modular optical probe

Given the special experimental conditions, the probe had to meet several requirements. Besides the protection of sensitive optics, the probe had to be flexible and modular. Flexibility to allow different routing inside the rig and compensate thermal expansions and modularity for using the probe for different optical diagnostics by changing the optics and fiber in the probe. The probe consists of three main assembly groups. First, the modular probe head. Second, the flexible cooling body, and Third a rigid section at the end with the water supply. The probe assembly is shown in fig. 3.

The underlying concept is a tube-in-tube heat exchanger, thus providing efficient cooling in a

Fig. 3. Photograph of the assembled modular probe (left) and the probe tip inside the combustor (right) with a green alignment laser coupled into the fiber.

Fig. 4. Schematic of the modular optical head of the probe.

closed system. The inner tube served as the inlet section. This way the coldest water surrounded the sensitive fiber. The outer tube was the outlet section, cooling the metal portion of the probe. The head was mounted onto the customized can adapter and was produced by additive manufacturing. Consequently, fine inner cooling channels could be integrated into the head and the high-temperature alloy Hastelloy X could be used as material. The integrated cooling channels realized the reversal of the cooling water deep in the front of the probe head. The modular optics holder was made of Ampcoloy to take advantage of the higher thermal conductivity and thus improve the cooling performance of the optics.

The modular head (see fig. 4) contained the optics for laser delivery and signal collection. The front window holder at the tip of the head holds the front sapphire window (diameter 20 mm) that was sealed by two mica foil rings. The front of the probe head was coated with a protective layer of ceramic thermal barrier coating. Nitrogen was used for front optics purging and cooling. It reached all the way to the probe tip, where the nitrogen exited into the combustor,

forming a purging curtain to cool and clean the front sapphire window.

A large core multimode fiber (FVA1000, Laser-Components, high-OH, 1 mm core, silica/silica) was used for delivery of excitation pulses and detection of the laser-induced emission of the thermographic phosphor. The fiber was glued into the fiber holder, which was threaded into the optic holder and sealed from the cooling water by a FKM O-ring. The optic holder was threaded into the main probe head and sealed by a second FKM O-ring in the conical surface. A single fused silica lens (diameter 12.7 mm, $f = +20$ mm, UV-AR coated) was used to collimate the laser light and collect the phosphorescence.

Optical measurement setup

A mobile measurement container was used for the phosphorescence measurements. Using a 18 m long glass fiber allowed the container to be placed in a quieter auxiliary room near the test rig. This container protects all optics and electronics from vibrations and other environmental influences and simplifies setting up the experiment. A schematic of the optical setup is shown in fig. 1 on the right. A Nd:YAG laser (Spitlight 600, Innolas GmbH, 15 Hz repetition rate, 6 ns pulse length at 355 nm) was used for excitation of the phosphor coating. The laser beam passed a continuously variable attenuator to control the laser energy. Then the beam was focussed with a lens ($f=+75$ mm) with the focal point a few millimeter in front of the tip of a large core fiber. The laser radiation was guided with this fiber to the optical probe at the test rig. The collimation optics ($f=+20$ mm) in the probe formed a 30 mm laser spot on the TBC wall coated with thermographic phosphor at the opposing side of the combustor (distance about 40 cm). The efficiency of laser coupling and transmission was about 70 %. Using laser energies of 2.2 mJ the energy density on the TBC was about 0.2 mJ/cm^2 .

Phosphorescence light was collected with the same optics and fiber, and guided back to the measurement container. In the container the phosphorescence light passed a dichroic mirror to separate it from the laser light. An additional long pass filter (FELH0400, Thorlabs) was used to further suppress laser radiation and a cold glass filter (KG3, Schott) reduces thermal radiation. A band pass filter centered at a Dy emission line (center wavelength 458 nm, bandwidth 10 nm) reduced remaining interfering emissions. The transmitted light was collected

with a photomultiplier tube (PMT) with gate function (H11526-20-NF, Hamamatsu). The gate function of the PMT was necessary to avoid saturation of the PMT due to thermal radiation in periods between the laser pulses and even more important to suppress a short intense spike at the beginning of the decay trace. The gate was switched on for 1 ms before the laser pulse to capture the offset level from background radiation. Then the PMT gate was switched off for 1 μ s and switched on again to capture the phosphorescence decay trace. Sample decay traces with the gating scheme are shown in fig. 7a). PMT signals were captured with an oscilloscope (DSO7034B, Agilent Technologies, 350 MHz, input impedance 500 Ω) and transferred to a computer running a LabVIEW program for online signal processing and data storage. The main parameters of the optical setup (laser energy, filter selection and gating of the PMT) could be controlled remotely from the rig control room.

Data evaluation

The phosphorescence signal can be described as an exponentially decaying curve

$$I(t) = o + A \cdot e^{-t/\tau} \quad (1)$$

with intensity I at time t , amplitude A , offset o and decay rate τ . The decay rate is typically determined with a nonlinear fitting process. However, in reality the decay curve shows multi-exponential behavior. As a result the obtained decay rate depends on the section of the decay curve used for the data evaluation, when a mono-exponential fit is used. Therefore the mono-exponential model is combined with a carefully controlled fitting window. One approach proposed by Brübach *et al.* [13] defines the start and end time of the fitting window ($c_1 \times \tau$ and $c_2 \times \tau$) based on the decay rate. Therefore an iterative fitting process is needed to determine τ . In this investigation $c_1 = 0.2$ and $c_2 = 2$ were used. The selection of c_1 and c_2 is a trade-off between signal quality and usually interfering signals at the beginning of the curve. A late fitting window shows more noise because the signal is weaker, but the beginning of the curve is sometimes affected by interfering signals like fluorescence.

Fig. 5. Emission spectra of YAG:Dy using HPC and LRC binder after 20 h at flame conditions. A photograph of the coating is shown in the insert. The size of the coated areas is $15 \times 30 \text{ mm}^2$.

Phosphor coating and Calibration procedures

Phosphor coatings were applied with a mixture of a commercial binder (LRC and HPC, ZYP coatings) with the phosphor powder (YAG:Dy, Phosphor Technology, particle size $d_{50} = 4.2 \mu\text{m}$). A mixing ratio of 0.2 g phosphor powder to 1 mL binder was used. The mixture was spray painted onto the surface with an air brush (Badger 100). To increase homogeneity of the coating, several layers were painted and dried with a heat gun after each layer. In previous lab experiments HPC and LRC were identified as possible binders suitable for wall temperature measurements on TBC material in gas turbine combustors [12]. Before the actual wall temperature measurements were conducted, coatings with both binders were tested in the test rig. After 20 h at flame conditions the coating was inspected, once the combustor had been disassembled. The coating using HPC binder was almost completely ablated, while the LRC coating was still clearly visible (see insert in fig. 5). The background corrected emission spectra shown in fig. 5 were recorded with a spectrometer (AvaSpec, Avantes) behind a long pass filter (GG400, Schott, cutoff wavelength 400 nm) after excitation with a light emitting diode (LED, emission wavelength 365 nm). The spectrum of the LRC coating clearly shows the emission lines of Dy, while the HPC coating shows only very weak Dy emission lines. LRC binder was therefore used for the wall temperature measurements. The peak at 400 nm can be attributed to remaining light from the LED. For the wall temperature measurements the Dy line

Fig. 6. Calibration measurements for YAG:Dy on a coated TBC sample (top) and temperature sensitivity and standard deviation $\sigma(T)$ of the phosphor (bottom).

at 458 nm was used, which is only very weak at room temperature and therefore not visible in fig. 5.

At the combustor an area on the TBC surface of about $5 \times 5 \text{ cm}^2$ was coated. Because calibration measurements were not possible on the original combustor wall, a small sample of coated TBC was used. This way possible influences from the substrate or the coating on the measured signal were captured, in contrast to a pure phosphor powder sample. Compared to a TBC coated steel sample, a pure TBC sample can be heated to much higher temperatures. To obtain this sample a small piece of TBC coated steel substrate (about $4 \times 4 \text{ cm}^2$) was treated with aqua regia (hydrochloric and nitric acid, ratio 1:3) for several hours until the coating dissolved from the steel substrate. This TBC piece was coated with the same phosphor and binder mixture as the surface at the CEC. The layer thickness on the sample was controlled with a coating thickness gauge (TE 1250-0.1FN, Sauter) on a separate steel sample to achieve a thickness of about $20 \mu\text{m}$. Calibration measurements were performed in an optically accessible furnace (LAC, VP 10/16, Boldt Wärmetechnik GmbH). The sample was placed inside the furnace with a reference thermocouple (type B) close to the sample. The decay rate of the phosphorescence is then measured step-wise at different temperatures. Laser setup, detection setup and electronics were identical between calibration and combustor measurements. The Laser energy density on the surface was 0.2 mJ/cm^2 for both cases to avoid systematic errors due to differ-

ent laser energies.

The measured decay rates for temperatures between 1150–1650 K are shown in figure 6. In addition the sensitivity obtained from the polynomial fit to the decay rates is shown. The sensitivity is the normalized derivative of the fitted trace. The temperature sensitive range of this phosphor starts at about 1350 K. In this temperature range the precision is between 0.1–0.5 %, determined from the standard deviation σ of 150 individual laser shots. Additional errors from the calibration procedure (mainly the reference temperature measurement inside the furnace) contribute by 0.5–0.75 % to the total error.

RESULTS AND DISCUSSION

Sample decay traces measured at the CEC test rig are shown in fig. 7a). The used gate scheme for the PMT is indicated with the shaded area. The data was taken from a 1200 shots (80 s) long data set during the first day of the measurement campaign. Gating of the PMT was mainly necessary to remove an intense spike at the beginning of the decay trace. This initial spike could not be suppressed with filters and is therefore not just scattering at the laser wavelength. It has been reported before that Raman scattering and fluorescence from the fiber itself is observed especially in configurations where a single fiber is used for laser and signal delivery [10]. An excitation wavelength of 355 nm was used like in this work. At 365 nm detection wavelength no useful measurements were possible, while at 456 nm (almost identical to the detection wavelength of 458 nm used here) the initial spike was still present, but much smaller due to the larger wavelength shift to the excitation wavelength. The initial spike observed in this work was stronger than the phosphorescence signal and would have caused severe distortion of the decay trace due to saturation of the PMT. The gated PMT is an elegant and simple solution for this problem. An alternative solution could be the use of fiber bundles and spectral filtering inside the probe head, as proposed by Eldridge *et al.* [10]. This is more costly than a single fiber setup and reduces collection efficiency. Also the utilization of blue-shifted phosphorescence by excitation of anti-Stokes luminescence has been demonstrated [11]. This is however not applicable for every phosphor material.

The single-shot decay traces show very strong interferences from flame emissions, probably from CO_2^* , which shows a broadband emission spectrum

Fig. 7. a) Sample decay curves after averaging of 1 – 200 single pulses. The PMT gate is shown as shaded regions at the bottom. b) Obtained temperature and standard deviation for different amounts of averaged single pulses using the same data set.

[14,15]. These emissions made it impossible to evaluate single shot decay rates reliably. After ten averaged laser shots the situation has already significantly improved, and decay traces can be evaluated. As can be seen in fig 7b) a slight systematic shift for less than 100 averaged laser shots is observed. At 100 averaged laser shots the standard deviation is around 1 % (15 K) and does not reduce much with further averaging. This is probably due to actual temperature variations on the wall and not due to errors from the data evaluation. Therefore for further analysis 100 laser shots were averaged. This is a compromise between precision and measurement time (100 laser shots corresponds to 6.7 s measurement time).

Online wall temperatures for the two measurement days are shown in fig. 8. At both days measurements were performed at up to 8 bar. Measurements were performed during test rig heating up, ignition, load variation and finally burner shut down. Typically a series of 900 laser shots was captured for each measurement point shown. Temperatures below 1400 K during test rig heating up are less reliable due to the reduced sensitivity of the phosphor in this temperature region. However, at final test conditions the temperatures rise to about 1500 K where the selected phosphor shows very good sensitivity as can be seen in fig. 6. At the second measurement day the signal level was lower than on the first day, probably due to degradation of the phosphor coating.

During both measurement days several conditions of the burner were tested, to simulate different operating conditions of the gas turbine with different thermal loads. These conditions will be discussed together with the measured cold side temperatures from thermocouples T_{tc} and calculated adiabatic flame temperatures T_{ad} in the following section. Adiabatic flame temperatures were calculated using measured gas flows and temperatures using GRI-Mech 3.0 reaction mechanism [16]. Due to confidentiality T_{tc} and T_{ad} were normalized relative to an arbitrary temperature. Because no measured gas temperatures are available for the investigated conditions, T_{ad} is the best available value to compare relative changes of the gas temperature with measured wall temperatures. In previous lab scale experiments at 8 bar we could show a linear relationship between wall temperature and T_{ad} [12]. T_{ad} and T_{tc} allow only an approximation of the inside wall temperature with limited precision. In figure 9a) temperatures are shown for different test conditions at both measurement days. As expected the thermocouple temperatures on the outside are lower, than the inside wall temperature and the adiabatic flame temperature is higher than the wall temperature. It can be seen, that the general trend of T_{ad} and the measured wall temperature agree well. Especially the lowest temperature for condition 9 is well captured for all three temperatures. However, there are some notable differences, for example between condition 4–7 the adiabatic flame temperature and

Fig. 8. Measured wall temperatures at the CEC at the two measurement days.

Fig. 9. a) Wall temperatures (closed symbols) and normalized temperatures (open symbols) for selected measurement conditions from both measurement days. Lines are drawn for clarity. b) Wall temperature plotted against the normalized adiabatic flame temperature for a selected test series.

inside wall temperature decrease, while the thermocouple temperature shows an opposite trend. This might be explained by the fact, that the thermocouple temperature on the combustor outside also depends on additional factors, like the flow conditions in the flow box. The maximum in T_{ad} was observed at condition 3, while the highest wall temperature was measured for condition 2. This difference might be explained with the rather simple calculation of T_{ad} , that ignores actual flame conditions at the measurement position. Conditions 12 and 16

(marked with circles in fig. 9a) are nominal identical test points. Slight differences between both test conditions are due to deviations in actual gas flows and composition. Both conditions were measured at the same day with a time difference of 1.5 h. It can be seen that wall temperatures measured with thermographic phosphors are also almost identical (1511 K and 1510 K). This shows the good reproducibility of the technique.

For a selected series of test conditions the wall temperatures are plotted against the calculated rel-

ative adiabatic flame temperatures at the measurement location in fig. 9b). A linear relationship between both temperatures can be observed, as expected. However, the measured temperatures at a normalized adiabatic flame temperature of 0.994 and 1.02 seem to be too low. To ensure this is not an artifact from the data evaluation procedure we tested different fit settings (e.g., early and late fitting windows and bi-exponential instead of a mono-exponential fit). This did however not change the obtained temperatures significantly. In future measurement campaigns this could be investigated further.

To improve signal quality and precision some strategies are planned. The limiting factor was the interference from flame emissions, as discussed above. A second PMT could be used to capture only the broadband flame emissions without the phosphorescence. At 410 nm YAG:Dy shows almost no phosphorescence [12], while CO_2^* shows still pronounced emissions [14, 15]. At 410 nm the flame emission spectrum is free from CH^* emissions, like also the phosphorescence spectrum at 458 nm. The measured background signal could be subtracted from the decay trace to remove the unwanted fluctuations. Another approach could involve a high-speed laser to improve the averaging at a given measurement time. At the observed temperatures around 1500 K the decay rates are about 0.1 ms. Therefore a repetition rate of about 1 kHz could be used without significant overlap between consecutive phosphorescence traces.

CONCLUSION

Fiber coupled phosphor thermometry has been successfully applied at a full scale high-pressure gas turbine test rig to measure wall temperatures inside the combustor in real-time. To obtain optical access a modular optical probe was developed. The probe features a modular optical head that allows different front optics to be installed. For laser delivery and signal transmission a single 18 m long large core optical fiber was used. A mobile measurement system was developed, that contains all necessary optics and electronics. The system allows online evaluation of the measured phosphorescence signals. A gated PMT was necessary to shut the PMT off between the laser pulses and to remove a strong spike (probably luminescence generated inside the long fiber) at the beginning of the phosphorescence decay trace. A combination of commercial binder and

YAG:Dy phosphor was used to coat the TBC wall inside the combustor. The durability of the coating was appropriate for the measurement campaign, but could be improved for example by embedding the phosphor into the TBC layer.

During the measurement campaign the capability of the technique could be demonstrated and on-line wall temperatures were measured. The reproducibility of the technique could be shown and temperatures were compared with calculated flame temperatures and thermocouple temperatures on the combustor outside wall. Further campaigns could focus on test conditions where exact knowledge of the inside wall temperature are crucial.

Due to the strong interferences from flame emissions, 100 laser shots had to be averaged to achieve reliable phosphorescence signals. Signal collection could be improved in further investigations to allow single-shot temperature measurements. A strategy could involve a second PMT with a bandpass filter at a different wavelength (e.g. around 410 nm) to capture the flame emissions without the phosphorescence and subtract this signal from the decay trace. This way the measurement precision could be improved.

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REFERENCES

- [1] Kerr, C., and Ivey, P., 2002. "An overview of the measurement errors associated with gas turbine aeroengine pyrometer systems". *Meas. Sci. Technol.*, **13**(6), p. 873.
- [2] Lempereur, C., Andral, R., and Prudhomme, J. Y., 2008. "Surface temperature measurement on engine components by means of irreversible thermal coatings". *Meas. Sci. Technol.*, **19**(10), p. 105501.
- [3] Allison, S. W., and Gillies, G. T., 1997. "Remote thermometry with thermographic phos-

- phors: Instrumentation and applications". *Rev. Sci. Instrum.*, **68**(7), pp. 2615–2650.
- [4] Chambers, M., and Clarke, D., 2009. "Doped Oxides for High-Temperature Luminescence and Lifetime Thermometry". *Annu. Rev. Mater. Res.*, **39**(1), pp. 325–359.
- [5] Aldén, M., Omrane, A., Richter, M., and Särner, G., 2011. "Thermographic phosphors for thermometry: A survey of combustion applications". *Prog. Energ. Comb. Sci.*, **37**(4), pp. 422–461.
- [6] Brübach, J., Pflitsch, C., Dreizler, A., and Atakan, B., 2013. "On surface temperature measurements with thermographic phosphors: A review". *Prog. Energ. Comb. Sci.*, **39**(1), pp. 37 – 60.
- [7] Araguás Rodríguez, S., Jelínek, T., Michálek, J., Yáñez-González, Á., Schulte, F., Pilgrim, C. C., Feist, J. P., and Skinner, S. J., 2017. "Accelerated thermal profiling of Gas turbine components using luminescent thermal history paints". In Proceedings of the 1st Global Power and Propulsion Forum, GPPF 2017.
- [8] Heyes, A. L., Seefeldt, S., and Feist, J. P., 2006. "Two-colour phosphor thermometry for surface temperature measurement". *Opt. Laser Technol.*, **38**, pp. 257–265.
- [9] Fuhrmann, N., Brübach, J., and Dreizler, A., 2013. "Phosphor thermometry: A comparison of the luminescence lifetime and the intensity ratio approach". *Proc. Combust. Inst.*, **34**(2), pp. 3611–3618.
- [10] Eldridge, J. I., Allison, S. W., Jenkins, T. P., Golub, S. L., Hall, C. A., and Walker, D. G., 2016. "Surface temperature measurements from a stator vane doublet in a turbine afterburner flame using a YAG:Tm thermographic phosphor". *Meas. Sci. Technol.*, **27**(12), p. 125205.
- [11] Eldridge, I. J., 2018. "Single fiber temperature probe configuration using anti-Stokes luminescence from Cr:GdAlO₃". *Meas. Sci. Technol.*, **29**(6), p. 065206.
- [12] Nau, P., Yin, Z., Lammel, O., and Meier, W., 2018. "Wall temperature measurements in gas turbine combustors with thermographic phosphors". *J. Eng. Gas Turb. Power*, **141**(4), p. 041021.
- [13] Brübach, J., Janicka, J., and Dreizler, A., 2009. "An algorithm for the characterisation of multi-exponential decay curves". *Opt. Lasers Eng.*, **47**(1), pp. 75 – 79.
- [14] Guethe, F., Guyot, D., Singla, G., Noiray, N., and Schuermans, B., 2012. "Chemiluminescence as diagnostic tool in the development of gas turbines". *Appl. Phys. B*, **107**(3), pp. 619–636.
- [15] Goers, S., Witzel, B., Heinze, J., Stockhausen, G., van Kampen, J., Schulz, C., Willert, C., and Fleing, C., 2014. "Endoscopic Chemiluminescence Measurements as a Robust Experimental Tool in High-Pressure Gas Turbine Combustion Tests". In Proc. ASME Turbo Expo 2014. GT2014-26977.
- [16] Smith, G. P., Golden, D. M., Frenklach, M., Moriarty, N. W., Eiteneer, B., Goldenberg, M., Bowman, C. T., Hanson, R. K., Song, S., William C. Gardiner, J., Lissianski, V. V., and Qin, Z. GRI-Mech 3.0. http://www.me.berkeley.edu/gri_mech/.