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Laser-Induced Phosphorescence for Surface Thermometry in the Afterburner of an Aircraft Engine

H. Seyfried,* M. Richter,† and M. Aldén‡
Lund University, 221 00 Lund, Sweden
and
H. Schmidt§
Volvo Aero Corporation, 461 81 Trollhättan, Sweden

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In the present work, surface thermometry using a method based on the spectroscopy of inorganic luminescent material was applied in the afterburner of a full-size aircraft jet engine. The technique uses laser-induced emission from thermographic phosphors for nonintrusive remote temperature diagnostics in combustion applications with high sensitivity and accuracy. A phosphor material having suitable temperature sensitivity in the expected temperature range was applied to the surface of interest in the engine afterburner. Phosphorescence radiation was generated using the forth harmonic (266 nm) from a pulsed Nd:YAG laser. The resulting signal was detected with a photomultiplier tube and phosphorescence lifetime decay curves were recorded for various engine loads, including operation of the afterburner. By analyzing the phosphorescence decay, temperature data were acquired through implementation of a regression equation extracted from well-defined calibration measurements on the phosphor used. Quantitative temperature data recorded with a repetition rate of 10 Hz are presented. The laser-induced phosphorescence technique for surface thermometry has proven its applicability in the extremely harsh environment prevailing inside and next to a jet engine operating at full load.

Nomenclature

I = intensity
I_0 = initial intensity
t = time
τ = lifetime

I. Introduction

In general, the use of advanced optical diagnostics permits nonintrusive measurements with high spatial and temporal resolution of quantities such as temperature, flame shape, flowfields, species concentrations, etc. [1]. The remote probing capability of optical techniques can be used for in situ measurements in hostile environments such as combustion devices. During the past decades the experimental equipment (in particular, lasers and detectors) has been subject to continuous development. In combination with an intense development of the measurement techniques, laser diagnostics is today an important tool for combustion-related research [1,2]. The work presented in this paper is the result of laser-induced phosphorescence (LIP) for surface thermometry. The LIP technique is based on the spectroscopy of so-called thermographic phosphors from which the laser-induced emission is used for nonintrusive temperature measurements. Early work has demonstrated the potential of the technique in various applications: for example, static and moving surfaces, different temperature ranges [3–5], gas turbines [6–9], and internal combustion engines [10,11]. A thermographic phosphor composed of a carrier material and doped with elements acting as activators is applied to the surface of investigation. Following excitation, the spectral response of the phosphorescence is studied to extract temperatures. For surface thermometry, either the change in lifetime or the change in spectral characteristics can be used for retrieving temperature data. The latter is preferable for 2D measurements, whereas the lifetime method is mainly used for point measurements. Because different phosphors have high temperature sensitivity in different ranges, measurements can be performed over a large temperature range with a high degree of accuracy. A more thorough description of the technique, proven to be an alternative method to thermocouples and infrared pyrometry, can be found in the work by Allison and Gillies [12] and Omrane [13] and references therein.

The purpose of the present study was to apply this remote probing technique to measure surface temperatures in the afterburner of a fighter-jet turbofan engine. The extreme conditions prevailing inside and next to a military aircraft engine present a challenge to most measurement techniques. To use high-precision optical instruments such as lasers in this environment requires special attention. When running the engine with various uses of the afterburner, severe acoustic vibrations will occur inside the test facility and hence effect the diagnostic equipment (e.g., lasers, detectors, and optical components). Absorption of excitation and phosphorescence radiation in the burning jet stream, intense background radiation from the luminous afterburner flame, and a limited optical access are other factors that make measurements challenging in this environment. In the present work, surface thermometry experiments were conducted inside the engine afterburner. Being an essential part of the engine hardware configuration, the afterburner components are exposed to very high temperatures and steep gradients. When in service, those elements are not allowed to be too damaged, because this might deteriorate the function of the afterburner. To avoid damages, the surface temperature at various locations inside the afterburner is a key parameter and accurate measurements are thus of great importance. Because the surface temperature inside the afterburner varies substantially with engine inlet conditions and the afterburner power setting, it is desirable to monitor the temperature for a wide engine-operation range. Analysis methods for prediction of the temperature at different locations inside the afterburner are

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*Ph.D. Student, Division of Combustion Physics, Faculty of Engineering LTH. Member AIAA.
†Associate Professor, Division of Combustion Physics, Faculty of Engineering LTH.
‡Professor, Head of Division, Division of Combustion Physics, Faculty of Engineering LTH.
§M.Sc., Department 6660HS..

complicated due to the combustion itself and the fact that the combustion takes place in a very turbulent environment.

In most industrial applications, thermocouples are used for temperature measurements due to their relatively low cost and high availability. However, a number of uncertainties are associated with the use of thermocouples. In the present application, the use of thermocouples requires an installation of the thermocouple in the area of interest inside the afterburner. This can locally affect the configuration, and the question of whether this influences the measured temperature is an essential issue. Installation of thermocouples requires a complicated routing of the wires, including modification of other hardware components to make it possible to get the wires out of the engine. Furthermore, the assembly of different afterburner components into the engine is difficult and hence expensive and time-consuming. Once the installation is done in the engine, is it very hard to change the configuration and thus difficult to quickly test other hardware configurations. Moreover, when using thermocouples, the measurement location is not easily changed and the lifetime of the thermocouple in this harsh environment is limited.

II. Experimental Apparatus and Techniques

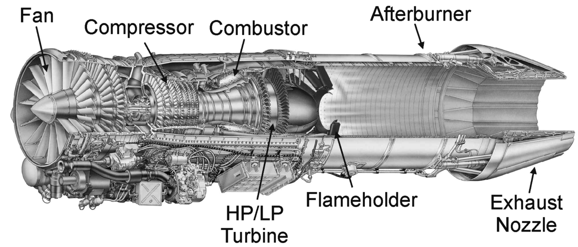
A. Engine Characteristics

The Volvo RM12 engine used in this work is a low-bypass-ratio turbofan engine. It is of twin-spool design and equipped with an afterburner that modulates fully from minimum to maximum augmentation. The engine is based on the General Electric F404 engine and has increased thrust and special features for single-engine safety, including a fan with better foreign object damage and bird-ingestion characteristics. The Volvo RM12 is used in the Swedish multirole combat aircraft JAS 39 Gripen, which has been in service since 1997. The engine is under continuous upgrading, and a full authority digital engine control system and an air-cooled radial afterburner flameholder have been developed. A cross-sectional diagram of the Volvo RM12 engine and some typical engine data are presented in Fig. 1.

B. Experimental Apparatus

An area of approximately 2×2 cm^2 located inside the engine afterburner was coated with the Mg_3FGeO_4:Mn phosphor. The relatively large spot was chosen to ensure a sufficient signal-to-noise ratio in this harsh environment. In other measurement locations with, for example, lower background levels and shorter beam paths, the spatial resolution can be substantially improved. The laser was positioned next to the engine afterburner with the beam output direction almost parallel to the jet flow. The laser beam was directed onto the surface of interest inside the afterburner by a dichroic UV mirror fixed to the exhaust gas tube. Phosphorescence radiation from the measurement area was collected with a lens and focused onto a photomultiplier tube (PMT). A schematic of the experimental arrangement for the temperature measurements is presented in Fig. 2. Thick-walled steel tubes were used to protect the most sensitive equipment (i.e., laser and detector) from acoustic vibrations, turbulent airflow, water sprays, etc. For obvious reasons, it is not possible to have personnel present in the test rig during the measurement. Therefore, remote control is required for most of the measurement apparatus.

Spectral filtering of the phosphorescence signal was performed using an interference filter centered at 657 nm [10 nm full-width at half-maximum (FWHM)] placed in front of the PMT. The output from a PMT is most often in the form of a weak electric current: that is, the PMT is a current generator. This signal can be recorded through direct coupling to the oscilloscope using a high-impedance termination. However, the capacitance of the signal cables will affect the temporal behavior of the measured signal, especially when using long cables. In this application, the correctness of the temporal information, corresponding to the phosphorescence decay time, is of crucial importance. As a further complication, the layout of the test facility required long cables greater than 20 m. The solution to this is



RM12 engine data:	
Total length	4.04 m
Inlet diameter	0.709 m
Dry weight	1055 kg
Bypass ratio	0.31:1
Total compression rate	27.5:1
Performance:	
Thrust	80.5 kN with afterburner 55 kN without afterburner
Airflow	68 kg/s

Fig. 1 A cross-sectional diagram of the RM12 engine and some typical engine data.

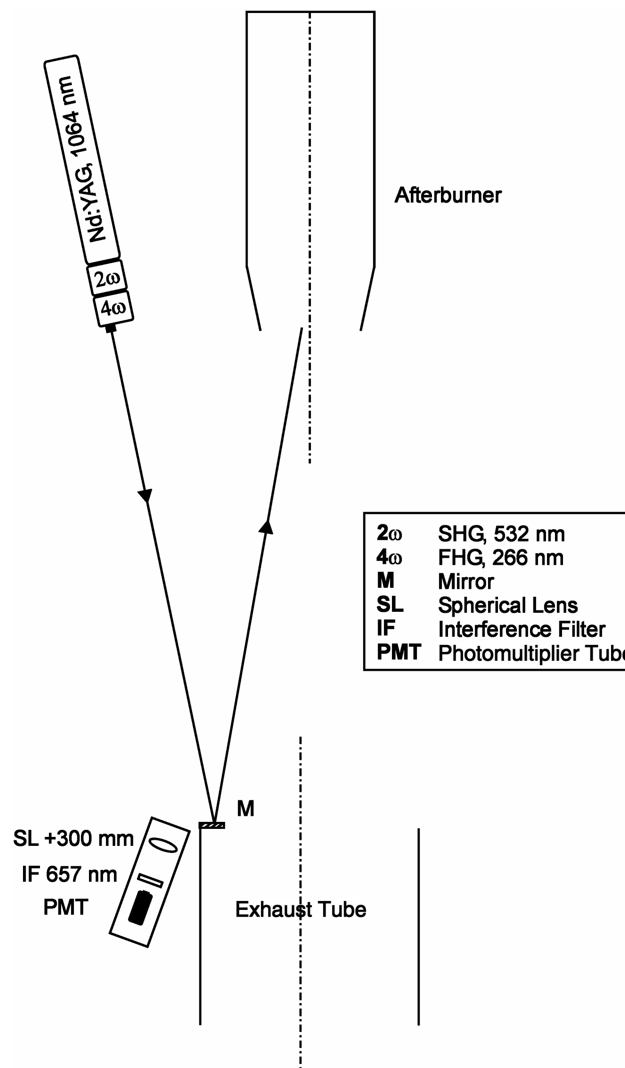


Fig. 2 Schematic of the experimental setup for the temperature measurements.

to use a transimpedance amplifier: that is, an amplifier that converts a current to a voltage. A tailor-made transimpedance amplifier capable of driving a long capacitive cable and with a bandwidth of 1 MHz was used. The bandwidth was chosen with respect to the expected decay times for the phosphors used, which were several microseconds or more, depending on temperature. The generated voltage signals were then sampled using a 1-GHz bandwidth oscilloscope (LeCroy), allowing lifetime decays to be recorded at the repetition rate of the excitation laser (10 Hz).

The laser was firing and the resulting signals from the PMT were recorded at a 10-Hz repetition rate during full-engine test cycles. However, it was not possible to detect any phosphorescence decay curves for two distinct power-level (PL) settings. For the first setting, corresponding to low thrust, the opening of the outlet nozzle was reduced to the extent that the view of the detector was blocked. For the second setting, corresponding to full use of the afterburner, the intense luminous flame introduced a too severe background signal. In addition, the loss of phosphorescence signal could be caused by unburned fuel (JET A-1) in the vicinity of the fuel nozzle absorbing part of the excitation radiation and/or by severe beam steering occurring due to the steep temperature gradients. As can be seen in Fig. 2, both the excitation beam and the corresponding phosphorescence signal have a substantial path length within the flame. In theory, a high temperature could also be causing the lack of signal at the full afterburner load. If this were the case, one would expect a gradual decrease not only in phosphorescence decay time, but also in signal intensity with increasing temperature. Such trends could not be seen, however. Actually, as soon as the fueling of the afterburner was cut off, the phosphorescence signal immediately appeared with a strong intensity. Hence, it was possible to capture the temperature decay of the surface inside the afterburner. Because the temperature was monitored with a 100-ms interval, the first data point recorded after fuel cutoff should indicate the temperature during full-load operation reasonably well.

C. Flame Characteristics

When performing optical diagnostics through a very luminous burning jet stream, as in the present application, it is desirable to be acquainted with the flame spectral characteristics. Because the relatively long lifetimes (up to a few milliseconds at lower temperatures) of the phosphorescence signal implies signal recording with corresponding exposure times, background interference from the burning jet stream can be an issue. This is relevant, especially when the changes in the spectral characteristics are employed for retrieving the temperature.

Flame emission from the burning jet stream was collected from behind through a quartz plate positioned downstream at the end of the exhaust gas tube. A spherical lens, $f = +300$ mm, was used to couple the emitted light to the fiber of a spectrometer (Ocean Optics, USB 2000). Thus, the recorded emission is integrated along the line of sight of the collection optics (i.e., through the entire length of the burning jet stream and into the engine). In Fig. 3, a flame emission spectrum recorded at maximum afterburner load is presented.

The spectrum indicates a broadband distribution with peak intensity in the wavelength region of 600–700 nm. However, emission originating from specific molecular transitions in CH and C_2 molecules can also be distinguished. This radiation has its origin from the deexcitation process of molecular species that were formed in an excited electronic state due to chemical reactions. Furthermore, atomic transitions from sodium and potassium are notable, indicating the presence of trace elements and/or impurities in the fuel composition.

III. Methodology

Laser-induced phosphorescence from thermographic phosphors allows temperatures to be measured with high accuracy in the range between room temperature and 2000 K. An appropriate luminescent phosphor material (in the present work, Mg_3FGeO_4:Mn) is applied on the surface area of investigation using the nonfluorescent binder HPC, found to be suitable for similar applications by Allison et al. [14]. The surface is then illuminated with laser UV radiation for excitation of the phosphorescent material. Following excitation, the subsequent emission due to the relaxation of electrons from the excited state to a lower-energy state can be used for temperature

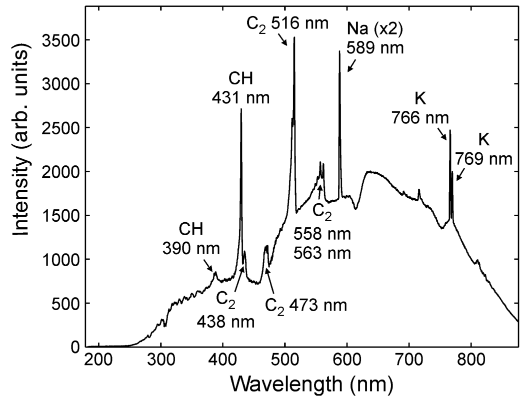


Fig. 3 Flame emission spectrum recorded at maximum afterburner load.

measurements. Two approaches, based on the spectral and temporal behavior, respectively, can be employed when analyzing the phosphorescence emission. The latter, being used in the present work, uses the time-dependent lifetime of the phosphorescence with temperature. A PMT is generally used in combination with an oscilloscope for registration of the phosphorescence decays. The intensity of the measured signal decays exponentially and is thus fitted to a single exponential function. This mathematical operation allows the lifetime to be calculated for each of the measured decay curves. The lifetimes are then converted to temperatures by means of calibration data, measured under temperature-controlled conditions. In practical applications, an interference filter is normally used to isolate a suitable wavelength region and to increase the signal-to-background ratio. The main advantage with the lifetime method compared with the spectral method, mostly used for 2D measurements, is a less pronounced influence from background radiation. This is the case because the spectral method relies on the intensity ratio between two different wavelength regions; hence, any unknown background signal would alter the ratio and thereby introduce a false temperature reading. In general, the precision of the lifetime method is less than 1%, according to a study by Feist et al. [9]. In harsh environments such as the one prevailing in the presented study, a quantitative error analysis is far from trivial. However, parameters such as the varying temperature sensitivity of the phosphor and the weak signal-to-noise ratio caused by the luminescent flame in combination with signal absorption are expected to reduce the practical precision.

The spectral distribution of the phosphorescence from Mg:Mn-based phosphors when excited with UV laser radiation has been reported by Kemeny and Haake [15], Cates et al. [16], and Omrane et al. [17]. The emission spectrum contains two emission bands, both in the red spectral region around 631 and 657 nm, respectively, and corresponds to transitions from the split excited state to the ground state. The spectrum also reveals individual peaks within the two bands. At high temperature, the nonradiative deexcitation rate dominated by thermal relaxation (transfer of energy into lattice vibrations) increases. This nonradiative deexcitation rate is strongly coupled to the temperature, resulting in a decrease of emission efficiency and a shorter emission decay time at high temperatures.

In Fig. 4a, emission decay curves for the Mg_3FGeO_4:Mn phosphor is presented. The signals are extracted from measurements inside the afterburner and correspond to three different temperatures. Detection was made using an interference filter centered at 657 nm (10-nm FWHM) to isolate the 657-nm emission line. As the temperature increases, the signal intensity decay gets shorter. Temperature data can thus be acquired by calculating the phosphorescence lifetime from the intensity decay curve and comparing the value to a well-defined calibration measurement. To obtain the lifetime, a single exponential function is fitted to the measured decay signal, as illustrated in Fig. 4b.

Calibration data were acquired by using thermocouples as reference and a temperature-adjustable oven. A sample coated with the thermographic phosphor Mg_3FGeO_4:Mn was placed inside the

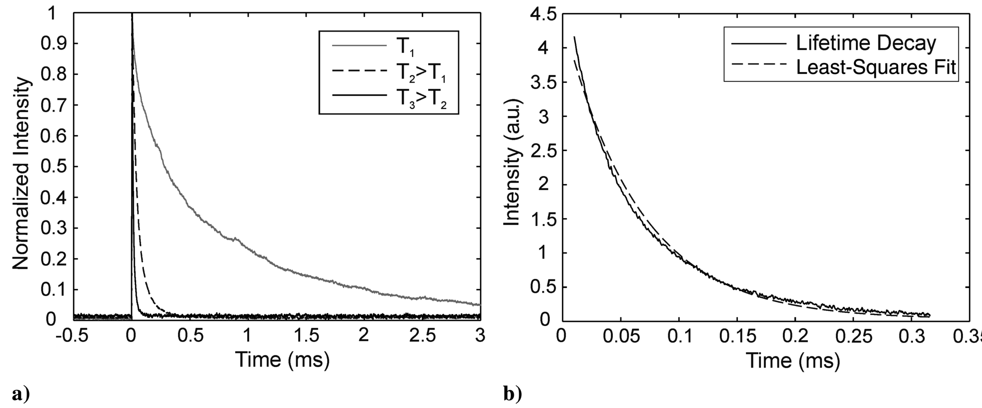


Fig. 4 Plots of the a) phosphorescence decay of the Mg_3FGeO_4:Mn phosphor at different temperatures detected using an interference filter centered at 657 nm (10-nm FWHM) and b) least-squares fit applied to the lifetime decay.

oven and in contact with the thermocouples. As in the main thermometry experiments onsite at Volvo Aero Corporation, the phosphorescent material was excited with UV laser radiation at 266 nm from a pulsed Nd:YAG laser (Quantel, Brilliant B). Following deexcitation, the phosphorescence signal from the sample was spectrally filtered by means of an interference filter centered at 657 nm (10-nm FWHM) and focused onto a PMT. To avoid systematic errors, the exact same setup of experimental equipment was used for the calibration measurements as for the afterburner measurements at Volvo Aero Corporation. The intensity lifetime decays were subsequently monitored and stored using a broad bandwidth (1-GHz) oscilloscope (LeCroy). Calibration data were measured over a temperature range corresponding to the sensitivity of the phosphoric material. To avoid systematic errors in the method when scanning the temperature, data were acquired when ramping the oven from cold to hot and then repeated when going from hot to cold. The temperature was gradually changed in steps of 5 deg from room temperature up to 700°C. In the present calibration measurement, the mean values from two thermocouples (K-type) were used and five decay curves were stored for each temperature. Data were recorded when the thermocouples indicated stable conditions. When processing the data, the lifetime of the intensity decay was calculated by assuming an exponential decay of the intensity according to

$$I(t) = I_0 \cdot e^{-\frac{t}{\tau}} \tag{1}$$

where τ is the lifetime. As illustrated in Fig. 4b, the least-squares method was used to fit a function to the measured data and hence to calculate the lifetime. In Fig. 5, the lifetime decay dependence on temperature extracted from calibration data is presented.

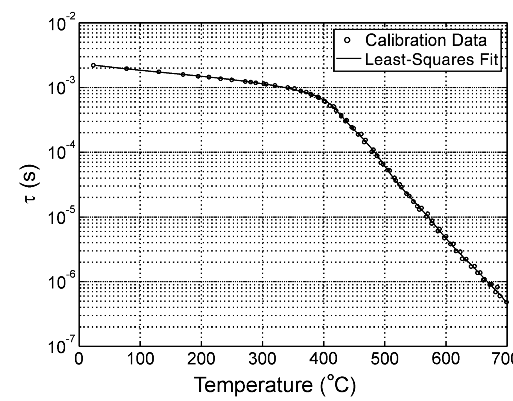


Fig. 5 Phosphorescence lifetime as a function of temperature for the Mg_3FGeO_4:Mn phosphor; detection through an interference filter centered at 657 nm (10-nm FWHM).

IV. Results and Discussion

Temperature data were measured for different engine running conditions, including various use of the afterburner. The engine operational range was automatically adjusted according to programmed test cycles. Measurements were performed for two different test cycles, referred to as cycle A and cycle B, respectively,

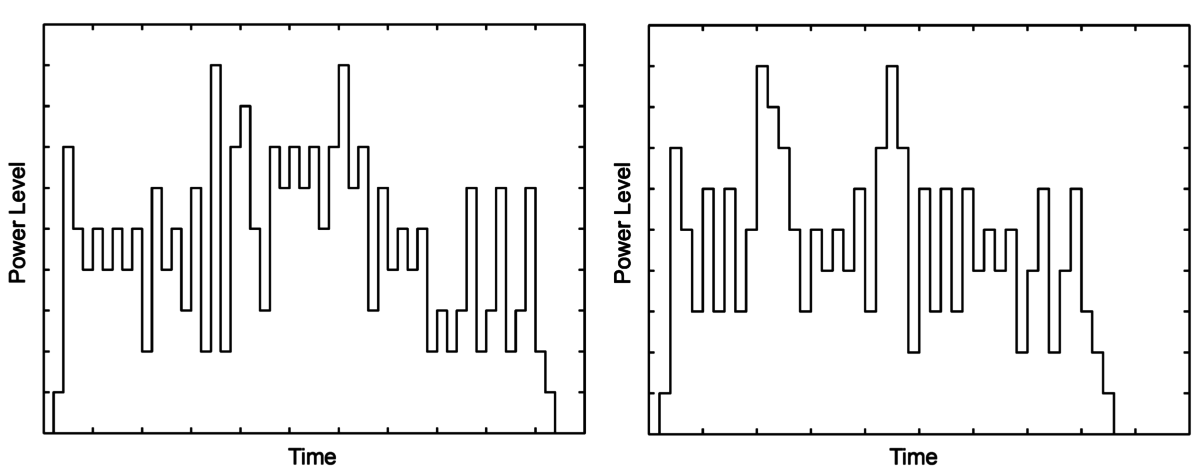


Fig. 6 Power level versus time for two different engine test cycles: a) cycle A and b) cycle B; cycles are just schematically presented.

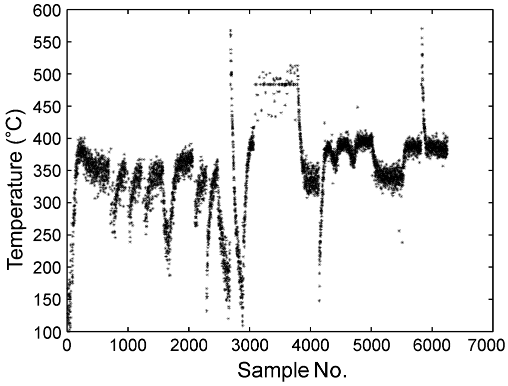


Fig. 7 Surface temperature data measured inside the engine afterburner for test cycle A.

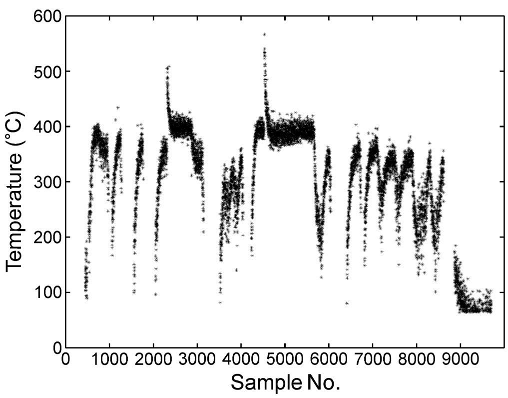


Fig. 8 Surface temperature data measured inside the engine afterburner for test cycle B.

and are presented in Fig. 6. The cycles are just schematically presented; for example, the time duration for a specific load is not stated in detail. However, the transient behaviors when varying the engine load are seen clearly in the figures.

In Figs. 7 and 8, temperature values are plotted for the two test cycles studied. In the figures, data are not presented for the entire test cycles.

In the figures, each sample corresponds to a temperature calculated from a single phosphorescence intensity decay. As described in the experimental discussion, data acquisition was possible for all engine loads except for a specific low-load condition and for maximum afterburner load. Moreover, it is clearly shown that changing the engine load implies a change in temperature almost momentarily. The measured surface temperature on the area inside the afterburner varies in the range 100–570°C when operating the engine according to the test cycles. At maximum load without the use of the

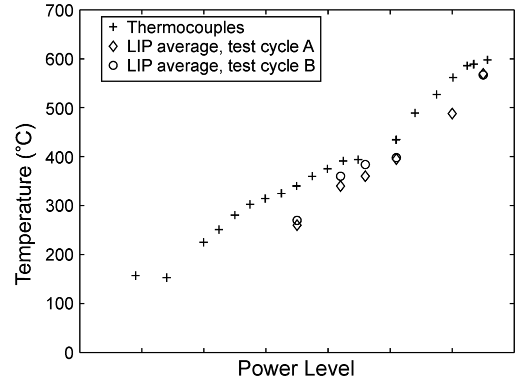


Fig. 10 Surface temperature measurements conducted inside the afterburner; results using the LIP technique are plotted together with previously made thermocouple measurements.

afterburner, the surface temperature reaches approximately 400°C, whereas the temperature captured immediately after an afterburner shutdown from full load is about 570°C. In Fig. 9, temperature data are presented for test cycle A. In Fig. 9a, the temperature is plotted for a load transient when changing the engine load from idling to maximum load without the afterburner. In Fig. 9b, the cooling process from high afterburner load down to almost engine idling is presented in terms of temperature data. As seen in these figures, the temporal resolution of the LIP technique also allows temperatures to be measured during rapid load transients.

Surface temperature measurements have previously been made inside the afterburner using thermocouples. Results from those measurements correspond well with the temperature data presented in this paper (see Fig. 10). The thermocouple measurements were made in a similar location, the only difference being a change in the angular position of the measurement location in the afterburner.

The results reveal temperatures of approximately 597 and 434°C for maximum load with and without the afterburner, respectively. Compared with the temperatures measured with the LIP technique, the thermocouple values are slightly higher: 4.5 and 8% at maximum load with and without the afterburner, respectively. As mentioned earlier, the phosphorescence could not be captured at full afterburner load. Instead, the first reading occurs immediately after cutting off the afterburner. Because the temperature is probed every 100 ms, the first reading should not be too far from the temperature prevailing at full load. This could be an explanation for the slight difference at maximum afterburner load. Another possible explanation for getting a higher temperature when measuring with thermocouples in the afterburner is the occurrence of catalytic reactions on the thermocouple surface, especially in fuel-rich environments.

V. Conclusions

Nonintrusive laser diagnostics were applied for remote probing of surface temperatures in the afterburner of an aircraft jet engine. The

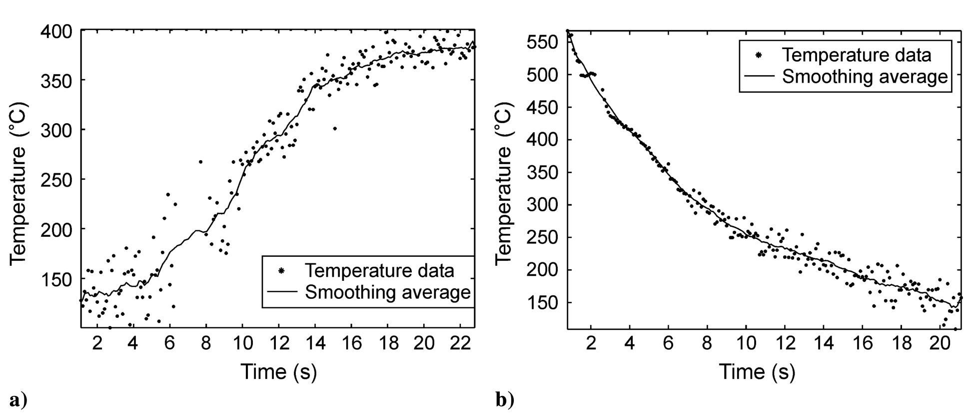


Fig. 9 Surface temperature data measured inside the engine afterburner for test cycle A: a) heating process when going from engine idling to maximum load without the afterburner and b) cooling process when going from maximum load with the afterburner to almost engine idling.

temporal response (i.e., the lifetime of the laser-induced phosphorescence from thermographic phosphors) was used for assessing temperature data. The technique has demonstrated its applicability in the extreme harsh environment prevailing inside and next to an aircraft engine. Despite high levels of background radiation and sonic surroundings with sound effects of several kW/m^2, quantitative temperature data could be obtained for a wide engine-operation range. It was observed that a change in engine load almost momentarily implied a change in temperature. The sampling rate of ten measurements per second was sufficient for resolving these temperature variations under the engine load transients. Optical probing techniques such as the thermographic phosphor technique presented in this paper prove to have several advantages compared with conventional thermocouples for real industrial applications. For example, measuring on different hardware configurations involves fewer difficulties, because the extensive installation and preparation process is not needed. In addition, this implies a much faster and more convenient change in measurement location.

Acknowledgments

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J. Gore
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