Proposed Laser-Induced Fluorescence Method for Remote Thermometry in Turbine Engines

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Introduction

RESEARCH is under way to measure the temperature of surfaces within operating turbine engines. To supply these measurements, which are necessary for some Air Force programs, current efforts are concentrating on the first-stage rotor blades and stator vanes.

These components, positioned just behind the burner, are the most difficult parts of a turbine to measure because they are the hottest and because the leading surfaces of the first-stage vanes reflect intense background blackbody radiation from the burning fuel.

Currently, the two principal temperature-diagnostic tools are pyrometers and thermocouples. "Contact" sensors, such as thermocouples, require leads that connect them to data-recording instruments, while optical sensors, such as pyrometers, are "remote" (noncontact) electric thermometers. Both thermocouples and pyrometers exhibit limitations in turbine-engine applications.

Protruding surface-mounted wire thermocouples, which disturb the airflow and heat-transfer characteristics, perturb the temperature at the point being measured. Cutting trenches to flush-mount them changes the structural properties and also perturbs the temperature. Thin-film thermocouples are so small and flat that their influence on temperature is negligible, but they do not adhere well under operating conditions. They also erode and oxidize and are expensive to install.

Because they lack a way of scanning, pyrometers can look at only one point in any given experiment geometry and are therefore not suitable for measuring static surfaces. In addition, pyrometers give erroneous readings in the presence of intense background radiation, and their low-temperature limit of about 700°C makes them useful only in hot regions of engines.

Both gas centrifuges and turbine engines have hostile internal environments when operating. For our purposes, the principal difference is that the engine runs at high temperatures, while the centrifuge does not. A method recently developed for remotely measuring temperatures in operating gas centrifuges[1,2] may be adaptable to similar measurements in operating turbine engines. The method is based on analyzing the laser-induced fluorescence (LIF) from a thin layer of phosphor bonded to the surface to be measured. The thin layers do not perturb the temperature. The phosphors are relatively inexpensive, chemically stable, durable metal oxides. Thus, they should not exhibit the problems of thermocouples. The method also does not have the limitations of pyrometers. It can be used on either stationary or rotating surfaces. The portion of the fluorescence we use occurs over a short duty cycle and in a narrow spectral bandwidth, so that most of the energy from blackbody radiation is rejected. By appropriate choice of phosphors and emission wavelengths, we can measure the entire range of temperatures occurring in contemporary turbine engines.

This Note presents 1) preliminary data on the LIF from several phosphors over a broad temperature range and 2) qualitative results from preliminary tests of candidate phosphor-bonding methods.

Basis of the Laser-Induced Fluorescence Method

Certain materials called thermographic phosphors exhibit unique characteristics following uv excitation. The particular thermographic phosphors we are studying are rare-earth doped oxides and oxysulfides having the chemical formula M_2O_3:D or M_2O_2S:D, where M is a group-III metal and D is the dopant. So far, we have investigated yttrium and lanthanum compounds in which the dopants are the lanthanide rare earths Eu, Gd, and Tb. These phosphors emit fluorescence from atomic levels characteristic of the dopant. Two properties of the fluorescence-emission spectral lines are temperature-dependent: 1) the relative and absolute intensities of the lines and 2) the characteristic decay time, following pulsed excitation, of selected lines. The temperature dependence is caused by competition between radiative and nonradiative decay paths that are available to the transition electrons.[3] Temperature dependence of the intensity of the spectral lines is illustrated in Fig. 1, which shows part of the emission spectrum of Y_2O_3: Gd over the temperature range 48-465°C. The lines near 418 nm pass through an intensity maximum near 105°C. The line at 549 nm, which peaks near 160°C, varies over the entire temperature range. It is evident that the relative intensities can be used to indicate the phosphor's temperature. This basic approach can use either continuous wave (cw) or pulsed excitation. (A commercially available thermometry system that employs cw excitation is the model 1000A Fluoroptic Thermometer, made by Luxtron, Mountain View, California.)

In the method described here, the phosphor is excited by a short-duration pulse of uv light (e.g., a uv laser used at a low average-power level that should not produce any surface pitting or localized heating). We then measure the temperature dependence of the characteristic decay time of the emission lines, which are well-behaved functions of temperature over at least part of their range. In this remote method, which is similar to that reported by McCormack,[4] the only mechanical attachment to the surface being measured is a thin layer of phosphor or phosphor-plus-binder; no electrical connections are necessary. The degree of remoteness is limited only by the available signal-to-noise ratio (SNR). Two features greatly improve the SNR. First, the low repetition rate of the pulsed uv laser and decay times ranging from 300 ns to 1 ms gives a small duty cycle, which rejects much of the energy from steady-state sources. (At a pulse rate of 10 pps, the duty cycle is about 10^{-7} to 3×10^{-2}.) Second, using a narrowband (typically 10-nm) optical filter to select the desired spectral line eliminates much of the broadband energy while rejecting any small background fluorescence caused by the laser. These background-rejection features will be especially useful in measuring the temperature of the first-stage vanes in turbine

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engines. Another important feature is that, because the excitation is pulsed, timing and synchronization strobing can be used to map out the temperature distribution axially or radially on rotating surfaces. Obviously, the method can also be used on stationary surfaces.

This technique can be sucessfully applied to operating turbine engines if certain conditions are met: 1) we must find a phosphor (or phosphors) whose LIF is usable at the engine's operating temperatures, 2) the phosphor must be chemically nonreactive and stable over multiple temperature cycles, and 3) the phosphor must be so thoroughly bonded to the engine components that it will adhere through the temperature cycles and high blade velocities of the erosive turbine environment.

LIF Experiments

A. Experimental Method

Several approximately equivalent experiments were set up to measure the characteristic decay time-vs-temperature curves for thermographic phosphors. Each included a variable-temperature oven containing the phosphor, a pulsed laser and optical fiber for excitation, another optical fiber to pick up the fluorescence signal, either an optical bandpass filter or a monochromator to select the spectral line, a photomultiplier tube (PMT) to detect the signal, and a data-analysis system for calculating and storing the decay time of the LIF. We used a N_2 laser with 30-kW peak power and 3-ns FWHM pulse duration, 1-mm-diam core plastic-clad silica optical fibers, and RCA 2020 PMTs with their voltage dividers optimized for linearity and minimum pulse droop. Although each phosphor has several resonant wavelengths at which it is excited most efficiently, we used the 337.1-nm excitation for the relatively uncomplicated experiments reported here.

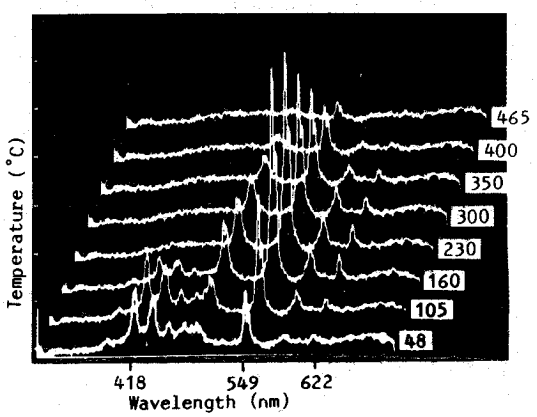

Fig. 1 Variation with temperature of a portion of the emission spectrum of Y_2O_3:Gd. The data were taken with a PAR optical multichannel analyzer

In the experiment setup shown in Fig. 2, the modified Marshall oven has a cylindrical chamber with a horizontal axis of symmetry. A well in the ceramic holder contains the phosphor, while the refractory crucible over the holder supports the quartz lens when it is inverted and its bottom is removed. The temperature of the phosphor is obtained by recording the signal from the thermocouple. Laser radiation brought into the oven by an optical fiber excites the LIF from the phosphor. The LIF is gathered by a second optical fiber and passed through the optical bandpass filter to select the desired emission line. A tandem uv filter rejects scattered light from the laser. A transient recorder gathers the LIF data. A beam splitter uses part of the laser pulse as a stop pulse for a transient recorder. A DEC LSI-11/23 microcomputer averages a sufficient number (typically 100) of LIF pulses to improve the SNR to an acceptable level, smooths the result, subtracts a stored background, takes the logarithm of that result, and calculates the time constant. Data storage is on a floppy disk. The data discussed in the next section were, with one exception, taken with this setup. The data on the 537-nm line of La_2O_2S:Eu were taken and analyzed with a Biomation transient recorder and a Tektronix 7854 waveform-processing oscilloscope instead of the Lecroy recorder and the computer.

B. Results and Discussion

We studied the LIF-vs-temperature characteristics of several phosphors, including La_2O_2S:Eu, Y_2O_2S:Tb, and Y_2O_3:Eu. The best data are summarized in Fig. 3, where the plotted points are the values obtained at each oven temperature by the averaging method described above. Each decay curve shows a usable temperature range for a given emission line and phosphor. In every case, above a cut-on temperature, the data are monotonic and nearly linear on a semilog plot. For example, the 612-nm line of Y_2O_3:Eu is usable above 550°C. Clearly, the monotonic portions can be used as calibration curves to obtain the temperature by measuring the decay time. One can cover at least the 20–930°C range with the phosphors and lines that have been studied. Because of the oven's temperature limit, we have not yet studied phosphors above 930°C. However, by extrapolating from SNR and decay times, it appears possible to achieve at least 1200°C with the 612-nm line of Y_2O_3:Eu. This phosphor exhibits fluorescence up to its fusion point,[5] but we have not determined which spectral lines are responsible for this emission.

The reason for data-averaging is that it allows us to extract the signal from the noise, which is due almost entirely to the PMT. When averaging is followed by judicious smoothing, the PMT's noise is virtually eliminated and the time-constant extraction is subject only to the residual systematic error. Because the magnitude of error has not yet been determined, no error bars are shown, but the magnitude can be estimated by observing the scatter in the data about the fitted curve. The scatter is a function of many parameters, including the

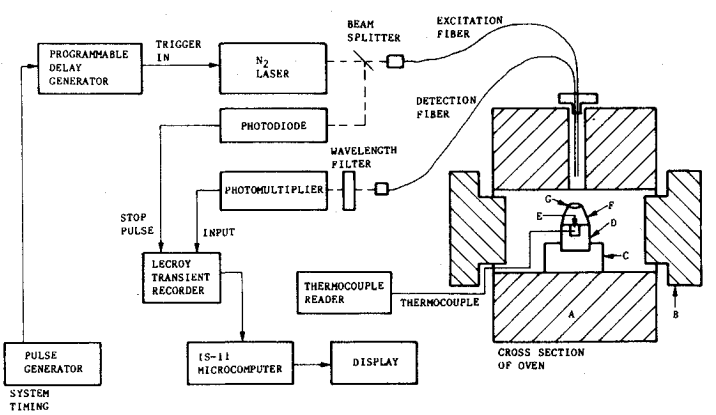

Fig. 2 Experimental setup for obtaining emission-like characteristic decay-time vs temperature data. A is the oven assembly; B, insulating-brick end plug; C, insulating-brick sample support; D, ceramic sample holder; E, phosphor well; F, refractory crucible; G, quartz lens.

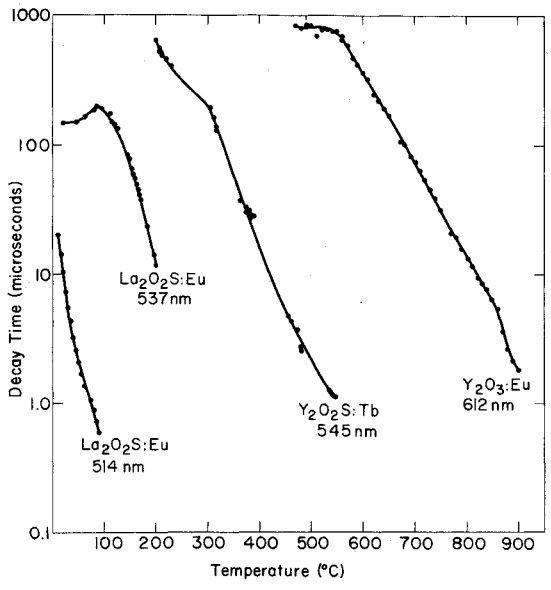

Fig. 3 Characteristic decay time vs temperature for several phosphor emission lines.

number of averages taken at each temperature, the stability of the oven, the noise and gain stability of the photomultiplier tube, the extent of nonoptimization of the optics and geometry of the experiment setup, digitizing errors, and various other systematic errors. We are currently trying to determine the residual systematic error and expect it will prove to be well under 10%. However, the measured decay time is such a strong function of the temperature that even a 10% error in the decay-time measurement results in only about 0.5% uncertainty in the temperature. In the initial experiments, we made only a limited effort to minimize the effect of these parameters on the precision or accuracy of the measurements. However, in an experiment carefully done at room temperature in an operating centrifuge, it was possible to determine the rotor-wall temperature within a minimum resolvable temperature differential of 0.3°C.

The trend of the data points relative to the solid lines representing the curve fit shows that, neglecting random scatter, the data from Y_2O_2S:Tb and Y_2O_3:Eu exhibit what appears to be a periodic variation about the curve. This is especially evident in Y_2O_3:Eu, where the data tend to fall below the curve at the beginning of a period and on or above the curve at the end. The periodic variation is caused by fixing the length of the "window," or location of the two points on the decay curve between which the time constant is calculated. The variation occurs when the decay curve is not a simple exponential and can be eliminated by programming the computer or oscilloscope such that the two points defining the window are constant fractions of the peak amplitude. When this improved method was used to acquire the 537-nm La_2O_2S:Eu data, the two window points were chosen at 0.9 and 1/e times the peak fluorescence amplitude, and an improved curve resulted.

Phosphor-Bonding Experiments

A. Selection Considerations

Gaseous erosion at high gas velocities, large thermal gradients on the substrate-phosphor transition, deposits of unburned hydrocarbons that partly occlude the phosphors, and chemical reactions can occur in the hostile environment inside an operating engine. Any successful technique for bonding a phosphor to a substrate (a surface whose temperature is to be measured) has to accommodate many parameters, including the required temperature range, the number and duration of temperature cycles, the physical and chemical environment, the characteristics of the substrate, the thickness of the phosphor coating, the degree of matching of thermal-expansion coefficients, and whether the phosphor can be applied in the laboratory or must be applied on-site.

Because a phosphor-binder combination has lower thermal conductivity than the substrate, it must be thin enough to make negligible any temperature differential between the phosphor and substrate—unless we can find a way to account for the temperature differential.

B. Surface Preparation

Abrasive-blast cleaning conditions the surface by providing a tooth that permits a strong mechanical bond between the coating and the substrate. All our samples were abrasively blast-cleaned and then ultrasonically cleaned before the phosphor-binder mixture was applied. The abrasive cleaning was done with 50- to-80 grit sand, 150- and 220-grit silicon carbide, 400-grit Al_2O_3 and, in some instances, 100- and 200-grit grinding wheels.

C. Bonding Phosphors to Surfaces

We considered more than a dozen techniques for applying and bonding phosphors to substrates and tested four of these. In three of the methods, the phosphor was mixed with a binder and the mixture was applied to the surface; in the fourth method, the phosphor was sputtered onto the surface. (Other methods, including plasma spraying, flame spraying, electrostatic spraying, and electron-beam deposition, are currently being studied.) In our tests, the lanthanum compounds were applied to aluminum and sheet-iron plates. Yttrium compounds were applied to high-temperature nickel-alloy plates and rods and to superalloy turbine blades.

1) Phosphor with a binder of sodium and potassium silicates was sprayed onto the substrates and cured first at room temperature, then in an oven with no air motion. The materials are difficult to outgas completely; bubbles tend to form on the surface with curing. The product also absorbs CO_2, and its expansion coefficient is not compatible with all substrates. Nevertheless, samples were successfully tested for durability to >1040°C.

2) Phosphor bound with a silicone resin-silicate-organic solvent mixture (a proprietary formula from Sperex Corporation) was sprayed on and underwent a prescribed curing procedure. The mixture is easy to apply and economical. It is flexible, so that expansion-coefficient matching is not necessary. However, it has low thermal conductivity. Any temperature differential between the measured surface and the substrate can be minimized by using a sufficiently thin film. Curing this material on large assemblies may be difficult because the substrate must be heated to 540°C for 30 min for maximum durability. Properly cured, thin (2- to 2.5-mil) layers have withstood 640° C thin, low-density layers withstand 1040°C, cold-water quenching, and flexing.

3) Phosphor with a water-reacting powdered-refractory binder is easy to apply and adheres well, but the relatively thick (>5-mil) coating may make it subject to erosion in the presence of high-velocity hot-gas streams. Samples have withstood temperature to 1040°C.

4) Sputtering is expensive and slow, but it can apply a smooth, thin layer of phosphor. The resulting surface is quite hard and may have a thermal-expansion coefficient matching that of the passivating oxides on superalloys. A test of a sputtered surface showed no appreciable fluorescence from a 1-μ phosphor thickness. Investigation revealed that the mold used to hot-press the yttrium oxide sputtering source was contaminated with carbon atoms from the mold used to hot-press it. Apparently, the carbon atoms kill the luminescence. After bakeout at 870°C for 4 h, luminescence was observed; it was relatively faint, presumably because of the small phosphor thickness.

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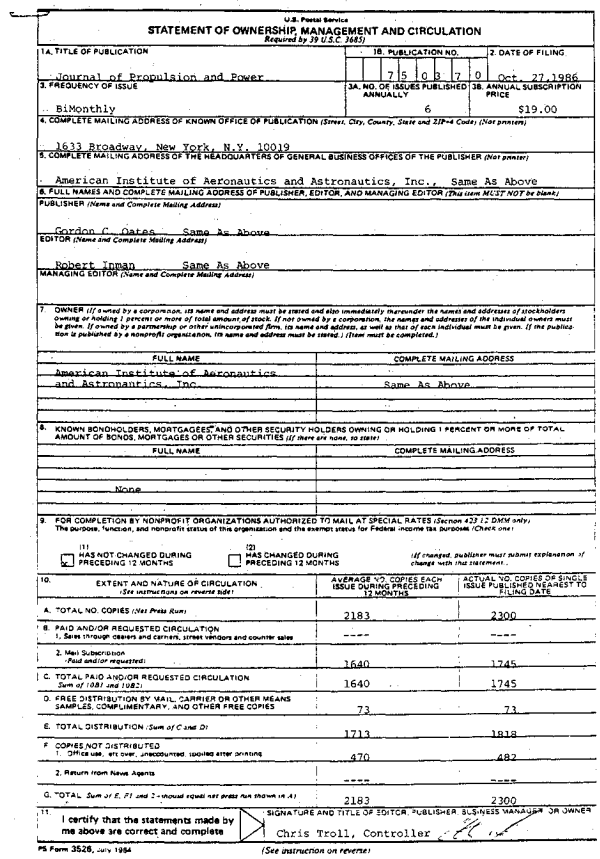

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