Phosphor Thermometry in an Operating Turbine Engine

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It is well known that phosphor thermometry may be used in environments characterized by high brightness from blackbody background or combustion flames. The present work describes measurements performed inside an operating turbine engine. For this application, two thermographic phosphors were chosen to cover the expected temperature range. The first, Yttrium Oxide doped with Europium (Y_2O_3:Eu) has received much attention as a temperature-indicating material for higher temperature ranges. The second, Yttrium Vandidate doped with Thulium (YVO_4:Tm) is relatively new, and was chosen for several reasons. First, it exhibits a bright emission line at 475 nm, which is much bluer than Y_2O_3:Eu line at 611 nm. Blackbody emission will have less effect on the detection of blue emission as opposed to the red. Second, YVO_4:Tm also exhibits temperature dependence from at 100 ^oC to above 900 ^oC in the range not covered by Y_2O_3:Eu. This testing proved that temperature measurements are possible in this environment, given proper selection of the emission wavelength and temperature range.

I. Introduction

The basic principle of thermal phosphors is well established, and researchers at Oak Ridge National Laboratory (ORNL) have demonstrated several useful applications[1-6]. The method relies on measuring the rate of decay of the fluorescent response of an inorganic phosphor as a function of temperature. Having calibrated the phosphor over the temperature range of interest, a small surface deposit of phosphor is excited with a pulsed laser and the fluorescent decay is measured (typically in less than 1 ms) to calculate the temperature of the substrate. In some instances, (e.g., in a continuous steel galvanneal process) a simple puff of powder onto the surface provides an adequate fluorescent signal.

Often temperature measurements are made using thermocouples or optical pyrometry. However, in situations where rapid motion or reciprocating equipment is present at high temperatures, it is best to use other techniques. For certain phosphor coatings, the prompt fluorescence decay time (τ) varies as a function of temperature and is defined by:

$$I = I_0 \exp\left\{-\frac{t}{\tau}\right\}, \tag{1}$$

where:

I = Fluorescence light intensity (arbitrary units),
I_0 = Initial fluorescence light intensity (arbitrary units),

t = Time since cessation of excitation source (s), and
τ = Prompt fluorescence decay time (s) [ref. 9].

The time needed to reduce the light intensity to e^{-1} (36.8%) of its original value is defined as the prompt fluorescence decay time (τ). By measuring the decay time as a function of temperature, the phosphor can be calibrated. In the present research, this required two calibrations to be made.

II. Material Selection and Application

Phosphor thermometry relies on two critical selections: 1) phosphor; and 2) surface adhesion. In this application, the complexity required extended laboratory evaluation of the materials[7]. The solutions selected required not only multiple phosphors but also two different coating techniques.

A. Phosphor Selection

In order to cover the temperature range of interest (room temperature to turbine operating temperature), two phosphors were selected. Y_2O_3:Eu was selected for the high-temperature range (>600 ^oC). Y_2O_3:Eu is a well proven high-temperature phosphor, but it has one major drawback. The temperature sensitive emission line is at 611 nm, which is a red color. Unfortunately, this emission line is close to the flame color in the gas turbine. Special instrumentation will be required to limit the exposure of the light detector and discern the phosphor emission from the flame. YVO_4:Tm was chosen to measure the lower temperature (<600 ^oC) range for a variety of reasons. First, it exhibits a bright emission line at 475 nm, which is much bluer than Y_2O_3:Eu line at 611 nm as shown in Figure 1. Blackbody emission will have less effect on the detection of blue emission as opposed to red. Second, YVO_4:Tm also exhibits temperature dependence from at 100 ^oC to above 600 ^oC in the range not covered by Y_2O_3:Eu.

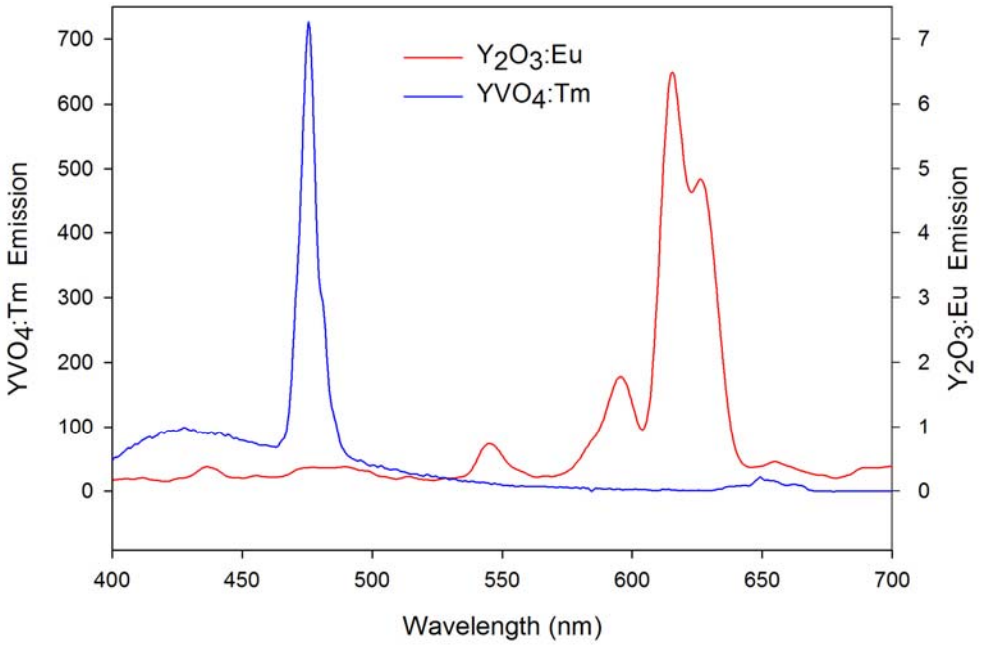

Figure 1 Emission spectra of selected temperature sensitive phosphors.

B. Coating Method

There are a variety of methods for applying phosphor coatings to test surfaces. These methods can range from surface rubbing or painting to more advanced processes such as: RF sputtering, laser ablation, e-beam deposition, and plasma spray. Considering the nature of the test environment, rubbing phosphor on the surface obviously would not work. Inorganic binders have shown great advances over the past five years for high

temperature sensitive paints[5-11]. However; it was felt that the difference in the thermal expansion of the base material and paint would cause the coating to fail prematurely. This left one of the more complex coating application techniques. From previous experience it was known that laser ablation and e-beam deposition created highly durable coating. The drawback of these techniques is that the coating process causes damage to the phosphor, which reduces emission. This damage can be corrected by placing the part in a high-temperature furnace and annealing the coating[12]. In the end, the selection was made based on availability, initial test samples were fabricated by plasma spraying the Y_2O_3:Eu phosphor over a metal substrate. The YVO4:Tm phosphor was painted over the plasma sprayed coating. Since the phosphors have similar coefficients of thermal expansion, the painted overcoat was able to adhere to the surface. A photograph of a test coupon is shown in Figure 2. The YVO_4:Tm is on the right side and varies in thickness from left to right. The Y_2O_3:Eu is one the right side of the sample.

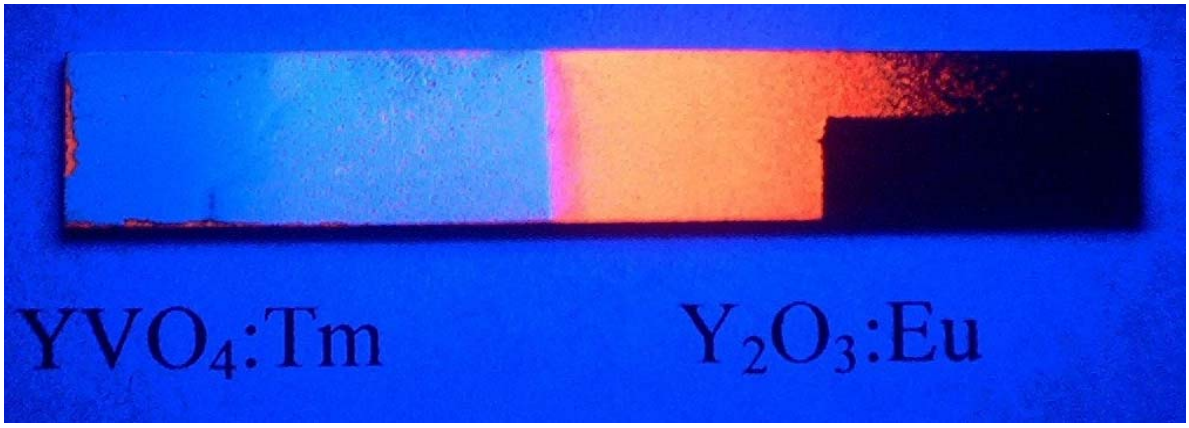

Figure 2 Example of coated samples illuminated under UV lamp.

III. Experimental Procedure

For this series of experiments, the phosphor combination was applied to a stator vane located just past the combustor of turbine. This location increased the difficulty of the measurement. Since the sample was so close to the fireball, there is a large blackbody background, which has a tendency to saturate the light detector. To counter act this, several special optics arrangements and electronic timing were necessary as shown in Figure 3. A Lamda Physik ximer laser (λ=308 nm) was coupled into one leg of a fiber-optic probe to excite the phosphor. The excitation light then strikes the surface of the phosphor, and causes it to emit. The emitted light is then collected by the second leg of the fiber optic probe and transmitted back to the control room. Once back in the control room, the emitted light was directed through an optical shutter to reduce the exposure time of the Hamamatsu R1104 Cooled photomultiplier tube (PMT). Once through the shutter the light is collected by a two inch focal length lens. The light is then sent through a 308 nm 90^o dichroric mirror and a UV blocking filter to remove reflected excitation light. The light is then sent through an Acton Research Corporation Spectrapro 275 monochromator so that only light near the emission wavelength is sent to the PMT. The voltage signal from the PMT is then sent through a variable impedance box to match the impedance of the PMT and prevent saturating the signal of the oscilloscope. A critical part of this test was the timing of the laser and the shutter. To perform this, a DEI PDG 2510 function generator was used to trigger the oscilloscopes, the laser and the shutter. The shutter and the oscilloscopes were both triggered the first channel of the function generator. The second channel was delayed relative to the first and used to trigger the laser. This allowed the timing of the laser firing to coincide the time the shutter was open. This could also be adjusted so that the entire phosphor emission could be captured. Two oscilloscopes and two data collection systems were used to provide a redundant data stream and maximize the probability of success.

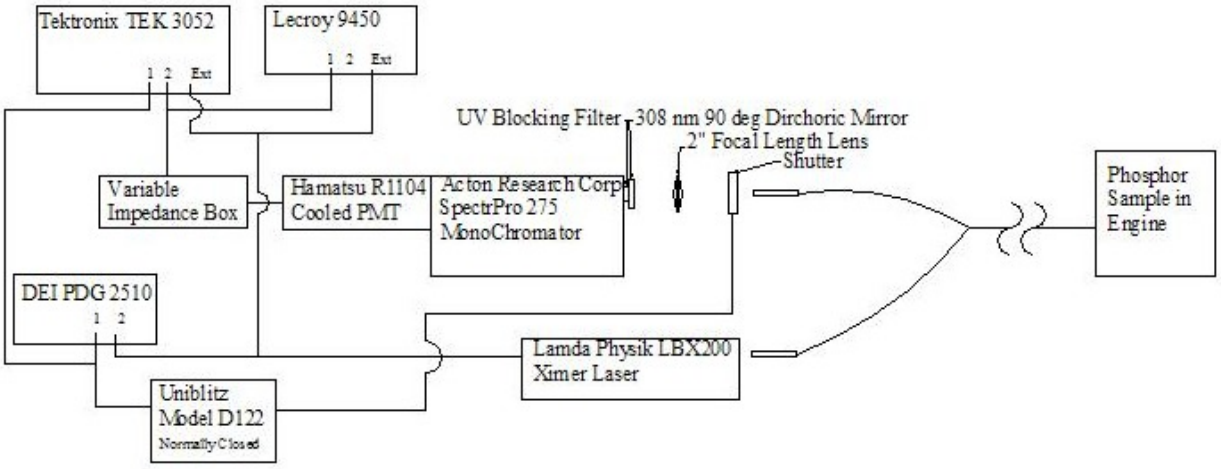

Figure 3 Experimental arrangement.

IV. Results

The application of jet engine vane temperature measurement is difficult because of the many restrictions such as: large blackbody background; desire to minimize the effect on flow; and remote accessibility. For these same reasons, phosphor thermometry is an attractive option. The technique is minimally restricted by blackbody background. Since only thin coatings of phosphor are required; there is not interruption in the flow through the turbine. Through the use of fiber optics the measurements can be made remotely.

For the present application, two phosphors were selected YVO_4:Tm and Y_2O_3:Eu to cover the expected temperature range. The YVO4:Tm phosphor was selected for temperatures up to 1000 ^oC such as are seen during start up and cool down. Since the emission of this phosphor is in the blue; the background combustion emission has less effect on the captured signal. The difficulty with YVO4:Tm is that the decay signature has a dual exponential decay as seen in Figure 4.

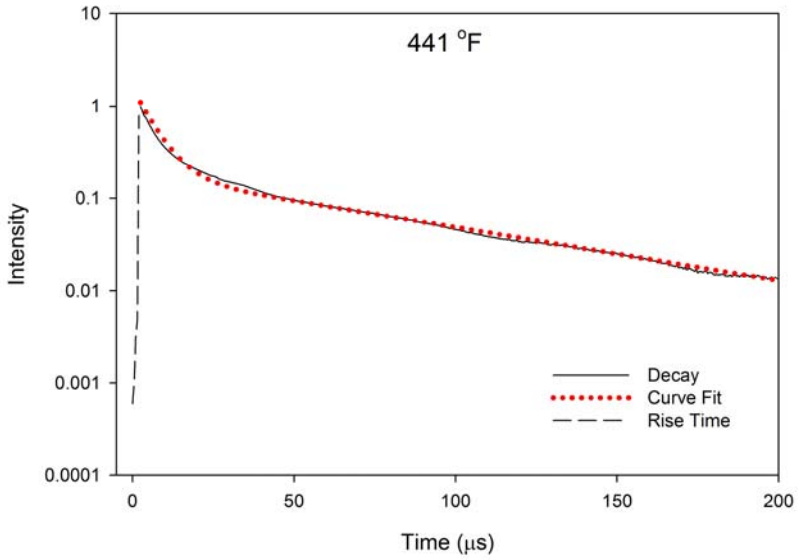

Figure 4 Typical decay signature of YVO_4:Tm.

Because of the dual exponential nature of the emission it is difficult to fit the curve in real time and requires post processing to calculate the temperatures. A typical decay time calibration curve for YVO4:Tm is shown in Figure 5. An alternate calibration option for this phosphor is a comparison of the intensity at a set time. Figure 6 shows intensity calibrations for times of 0, 50 and 100 microseconds. These calibration curves have similar shapes but are offset from one another.

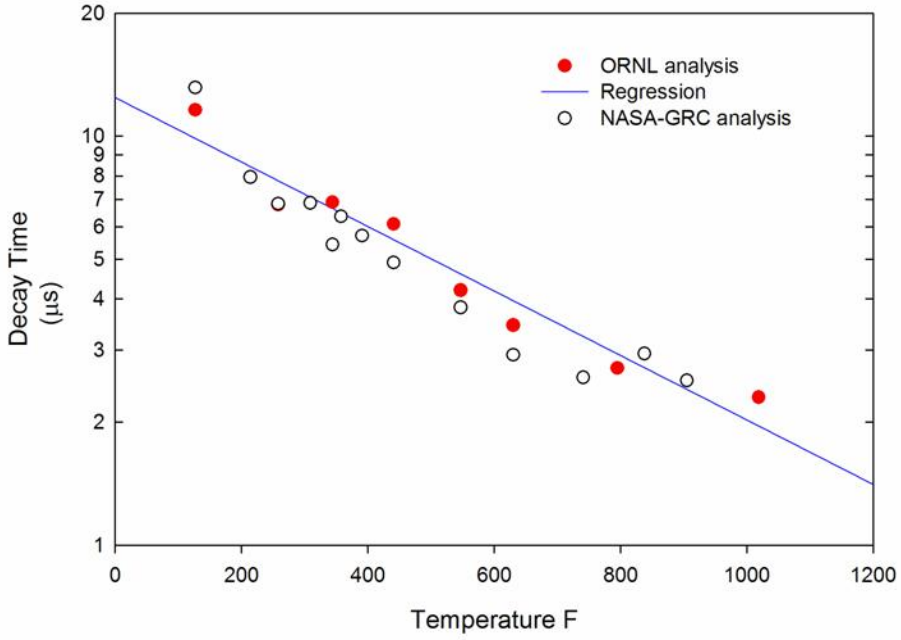

Figure 5 Temperature calibration decay time method.

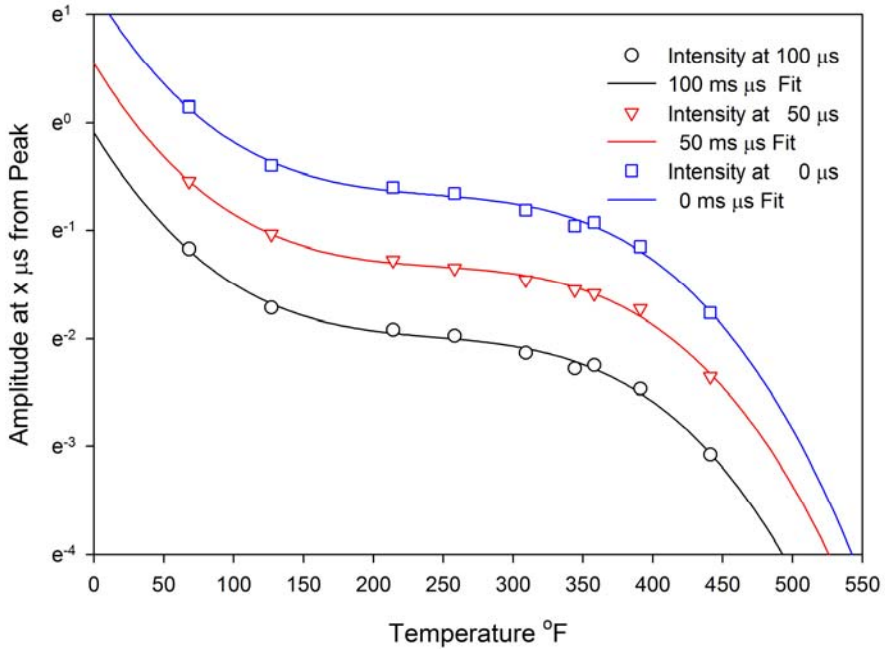

Figure 6 Temperature calibration intensity method.

Taking the two calibration techniques into consideration, captured decay signatures were analyzed and plotted versus a correlation thermocouple. This data is shown in Figure 7 with hollow black circles representing the thermal couple data, decay time temperature calculations represented by hollow blue squares and intensity based temperature calculations represented by solid blue triangles. Once the data was normalized to the initial thermocouple data point; the phosphor measurements closely follow the thermocouple measurements. This shows that the phosphor thermometry technique can be utilized over a limited range for this application. It is possible that a different phosphor could be found with a wider temperature range and emission wavelength in the blue region and the measurements could be extended.

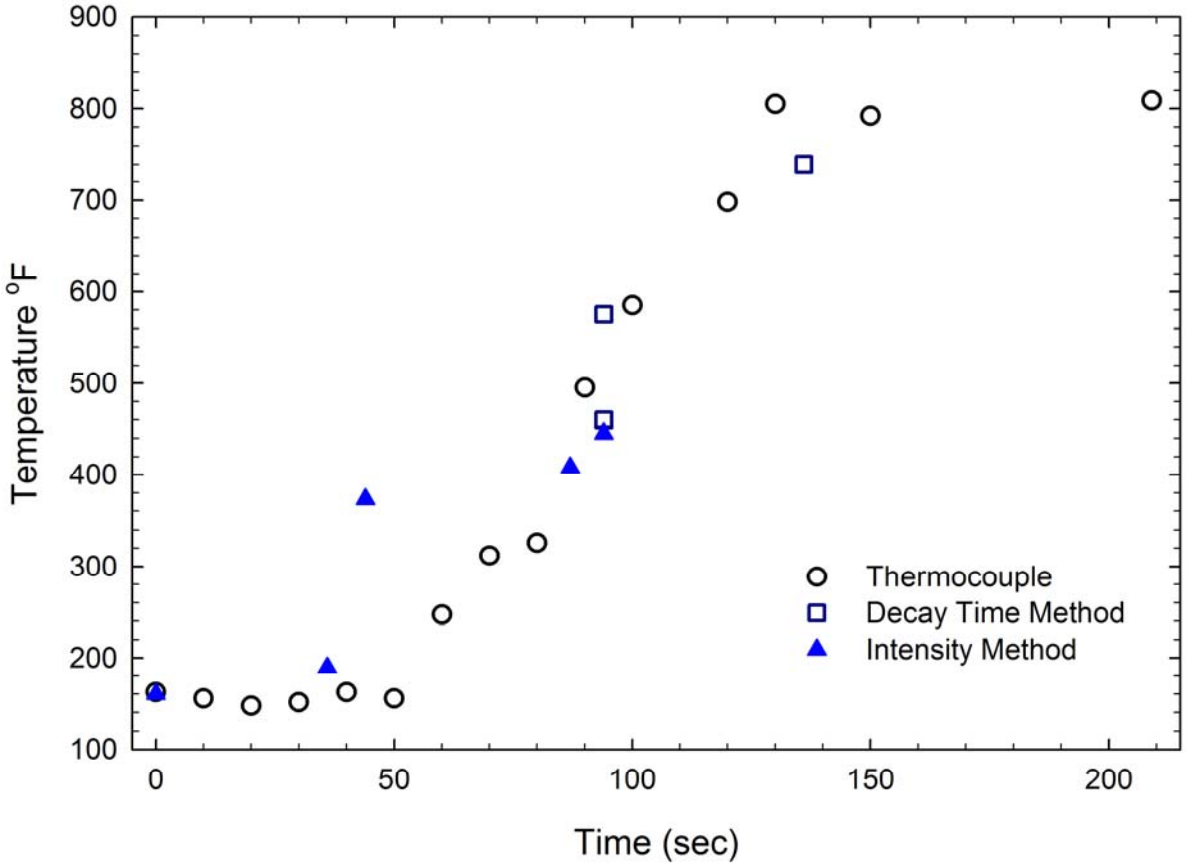

Figure 7 Phosphor temperature measurements during engine startup.

V. Conclusions

In the course of testing, YVO_4:Tm was found to be very sensitive to the temperature changes seen during engine start up and cool down. At the higher operating temperatures, the response of the YVO_4:Tm was very weak and difficult to discern. At these temperatures, the Y_2O_3:Eu undercoating was also difficult to distinguish through the YVO_4:Tm coating and the blackbody background. This testing proved that temperature measurements are possible in this environment, given proper selection of the emission wavelength and temperature range. Further research is necessary to extend the temperature range of the measurement technique in this application.

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