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EVALUATING THERMOGRAPHIC PHOSPHORS IN AN OPERATING TURBINE ENGINE

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ABSTRACT

The results of a field test in a commercial turbine engine showed that we can remotely measure the temperature of engine components in operating engines using thermographic phosphors. The remote-measurement method exploits the temperature dependence of the characteristic decay time of the laser-induced fluorescence of thermographic phosphors. This paper summarizes recent work leading up to and including a successful test of the thermographic-phosphor method in an operating turbine engine.

INTRODUCTION

Over the past several years, we have developed a method of remote temperature measurement that uses thermographic phosphors (TPs). We apply the TP to a surface, excite the TP with uv light (whereupon it emits fluorescence in a spectrum of narrow lines whose characteristics are temperature dependent) and determine the surface temperature by measuring either the characteristic decay time of the laser-induced fluorescence (LIF) or the relative amplitudes of the emission lines.

We have used the method on rotating machinery, such as gas centrifuges (Cates *et al.* 1984) and developmental motors (Allison *et al.* 1988), in which the operating temperatures were near ambient. The method has been used to measure the temperature of the stationary surface of a variable-area ejector bathed in the high blackbody background from the augmentor flame of an operating turbine engine (Allison *et al.* 1987). We have recently been adapting the method to measure the surface temperature of components, such as stator vanes and turbine blades, in operating turbine engines (Noel *et al.* 1988). During this development, we studied the TP characteristics and their calibration, bonding methods, instrumentation development,

and methods of data analysis (Noel *et al.* 1987). We also did a number of tests (Noel *et al.* 1989) that evaluated various aspects of the TPs' performance in high-temperature environments that simulate various aspects of an engine.

In this paper, we discuss the results of a test of the TP method in an operating turbine engine.

The purpose of the test was to demonstrate the feasibility of the method in an operating turbine engine. The main technical questions to be answered included the following:

1. Will the TP coatings survive in an engine environment?
2. Can an engine pyrometry probe be modified so that the TP coatings can be illuminated by uv and the LIF viewed by the probe optics?
3. Is it possible to detect the LIF from first-stage stator vanes in the presence of the large blackbody background from the burner?
4. Can the LIF signals be seen with a high-enough signal-to-noise ratio (SNR) to extract the temperature data?

THE EXPERIMENT PLAN

We tested the method in a Pratt & Whitney (P&W) PW2037 commercial engine at a P&W test stand in East Hartford, CT. We were able to use a pyrometer port located such that the pyrometer probe fits in a groove machined into one of the first-stage vanes on its downstream side. The vane is made of superalloy coated with a passivation layer.

Previous experience showed that, for stationary or periodically rotating structures, the LIF decay-time approach gave superior results compared with the approach using the ratio of emission-line amplitudes. We chose that method for this test.

Our initial choice of TP was europium-doped yttrium oxide, $\text{Y}_2\text{O}_3\text{:Eu}$; the 611-nm emission line from this TP is bright, its LIF decay times in the operating-temperature range of the engine fall well within the capabilities of the instrumentation, and it is the TP that we have most thoroughly studied and characterized. The 611-nm line of $\text{Y}_2\text{O}_3\text{:Eu}$ is usable in the range from 650°C to > 1200°C.

Earlier tests suggested that the TP should be electron-beam-deposited on the vanes, so that was done. In-laboratory evaluation of the virgin brightness of the TP-coated vane showed poor results; the brightness was less than 0.7% as bright as a reference sample of $\text{Y}_2\text{O}_3\text{:Eu}$ powder. This situation was complicated by the fact that, during the electric-discharge machining of the pyrometer hole in the vanes, the passivation layer was removed in a region in and around the hole, where we planned to view with our probe. Our previous experience had shown that TPs bonded to nonpassivated areas either did not bond well or tended to come off after exposure to an oxidizing atmosphere. This occurs because the thin coating of TP is porous to oxygen, the metal oxidizes, and the oxide spalls when the metal cools, taking the TP with it. Figure 1 is a photograph of the vanes taken before the test. The figure shows the machined probe hole and the $\text{Y}_2\text{O}_3\text{:Eu}$ coating, which emits yellow-orange LIF because it is illuminated by a uv lamp. The passivation layer is missing under the TP in the region adjacent to the hole. This fact made it necessary for us to view the region farther from the hole, at a distance of about 2 cm from the face of the probe.

Because of concerns about phosphor spalling and dimness of the electron-beamed $\text{Y}_2\text{O}_3\text{:Eu}$, we added three strips of TP mixed with a Sperex SP-115 inorganic high-temperature binder on top of the electron-beamed coating. The strips contained three different phosphors: $\text{Y}_2\text{O}_3\text{:Eu}$; europium-doped yttrium vanadate, $\text{YVO}_4\text{:Eu}$ (a TP with a bright emission line at 618 nm that shows promise for high-temperature applications, but which has not been as thoroughly characterized as $\text{Y}_2\text{O}_3\text{:Eu}$); and europium-doped scandium phosphate, $\text{ScPO}_4\text{:Eu}$ (which, in theory, should be usable at higher temperatures than either $\text{Y}_2\text{O}_3\text{:Eu}$ or $\text{YVO}_4\text{:Eu}$, but which is still in the developmental stage). The $\text{ScPO}_4\text{:Eu}$ intensity turned out to be so low that, when the deposits were inadvertently removed in a degreasing operation, the $\text{ScPO}_4\text{:Eu}$ was not replaced.

INSTRUMENTATION

The LIF-decay-time method requires a pulsed uv source having a pulse duration short relative to the decay time. In those experiments where ample SNR is available, it is possible to use a small nitrogen laser. In the present experiment, with long lengths of fiber optics, small-diameter probe optics, a relatively poor optical geometry, high blackbody background, and rather dim TPs, we chose to use a high-power Nd:YAG laser tripled to emit at 355 nm. The laser was set up in the control room adjacent to the test cell. The experiment setup is shown in Fig. 2. The uv laser light was coupled into a 600- μm -diam uv-grade glass-on-glass fiber-optic cable and launched into the probe through a beam-splitting apparatus. The probe also contained a 600- μm -diam uv-grade fiber. The probe optics focused the uv light on the TP-coated vane. The LIF return light was gathered by the same optics and fiber, returned to the beam-splitting apparatus, coupled into a 1000- μm -diam plastic-clad-silica fiber and sent to the data-gathering station, which was situated in another part of the control room. The LIF passed through a fast optical shutter before being detected by a photomultiplier tube (PMT). The shutter reduced the amount of blackbody background seen by the PMT during the time when no LIF signal was present. The PMT output was analyzed by a Tektronix 7854 waveform-processing oscilloscope that was preprogrammed to accommodate the data.

The laser output was sampled by a photodetector; its output triggered the oscilloscope. A pulse generator provided master timing. Its output was delayed and buffered to trigger the laser; it also controlled the fast optical shutter.

The optical configuration, Fig. 3, shows the details of the beam-splitter apparatus. The path labeled (1) is the uv into the assembly from the laser, via a high-uv-reflectivity mirror. The dichroic mirror reflects most of the uv into the path labeled (2). The return signal from the probe contains both LIF and substantial reflected uv. On the return path, the dichroic mirror accepts the LIF, but rejects most of the uv. The narrowband filters were selected to pass only the 610-nm line of $\text{Y}_2\text{O}_3\text{:Eu}$ and the 618-nm line of $\text{YVO}_4\text{:Eu}$. These filters rejected most of the remaining uv light.

The probe went through several revisions *en route* to its final form, which is shown in Fig. 4. This is a simpler configuration than the one described in in Noel *et al.* (1989) and, despite the reduced overall optical-system efficiency, it was more convenient for this experiment.

RESULTS AND DISCUSSION

The various components were set up before the experiment

in our laboratories for evaluation, calibration, and other pretesting. All the various pieces were then disassembled, moved to P&W, and reassembled.

The electron-beam-deposited $Y_2O_3:Eu$ gave signals too small to be usable during the testing. Because the signals were even smaller than expected, we used a borescope to examine the vanes during periods when the engine was not running. The observations allowed us to get a qualitative feel for the rate of abrasion of the various TP coatings. The TP strips attached with the Sperex binder survived long enough (through about 15 h of engine running) to give useful data. Another factor that contributed to the low signals was the laser excitation. At 355 nm, the excitation efficiency was much lower than at the more desirable resonance excitations at 467 or 538 nm (for the $Y_2O_3:Eu$). These latter excitation wavelengths, which can be produced with a dye laser, are also better propagated by fiber optics. In terms of SNR, the $YVO_4:Eu$ gave the best signals throughout the test. We therefore concentrated our efforts on observing signals from $YVO_4:Eu$.

The blackbody effects, which cause charge starvation when the PMT views the scene continuously, were mitigated well by the mechanical shutter up to the maximum temperatures observed, about 700°C.

Figure 5 is an overlay of several oscilloscope traces that illustrate the various components of the signal. The uppermost trace was obtained by blocking path (1) in Fig. 3; it shows only the electronic noise, which includes a few-hundred-microvolt excursion at the time the laser fires. The next lower trace was obtained by blocking path (2) of Fig. 3. It shows that, despite the precautions taken to exclude any laser light from the PMT, a large amount remains. The next trace was obtained by viewing a time region when there is no LIF, but there is blackbody background. The background causes a shift in the dc level, as expected, but the signal is well within the dynamic range of the PMT, therefore, the signal neither saturates nor decreases the gain because of charge starvation. The lowermost trace is of the total composite signal. We extract the TP's decay time from such signals by painstakingly removing the background and finding the slope of a straight-line fit to the logarithm of the decay curve. The consistently repeatable results over a wide range of temperatures, geometries, and other parameters verify the utility of this simple approach.

The inset of Fig. 6 shows the worst-case data during this experiment: taken at the highest temperature, the blackbody background is largest and the signal is the smallest. The logarithm can be fit to a reasonable straight line and, as discussed below, the results are acceptable. We did not

treat these data to any statistical analysis to find the error bars because we considered such analysis to be outside the scope of the experiment.

Although we did this experiment to evaluate the TP method in an operating engine and not with the intention of acquiring data, we did acquire some data. The results are shown in Fig. 7. Our data are plotted here as a function of engine rpm from idle at about 7500 rpm, to 9643, 9864, 9885, 10 093, 10 225, and 10 568 rpm. Also plotted are the thermocouple data acquired by P&W personnel. The agreement is remarkably good. We conclude that this first test showed the feasibility of using the TP method in operating turbine engines.

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Figure Captions

Fig. 1. Photograph of first-stage stator vanes for Pratt & Whitney PW2037 engine. One vane is coated with thermographic phosphor (TP) applied by electron-beam deposition. The vane assembly contains an electro-machined hole for insertion of either a pyrometer probe or the TP probe, which used a pyrometer-probe housing.

Fig. 2. Experiment setup. The YAG laser excites the TP on the vanes by way of the fiber optics to the probe. The return signal is detected by a photomultiplier tube (PMT) and analyzed in the waveform-processing oscilloscope.

Fig. 3. The optical configuration in detail, showing the beam-splitter apparatus.

Fig. 4. Cross-sectional view of the probe assembly.

Fig. 5. Reproduction of multiple oscilloscope traces, showing the various components of the signal.

Fig. 6. Reproductions of oscilloscope traces of raw data (inset) and logarithm of corrected data for the highest temperature (672°C) and highest engine rpm (10 568) during the experiment.

Fig. 7. Temperature vs engine-speed data obtained using TPs and plotted on same scale as thermocouple data.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7