ABSTRACT

This paper describes a novel, non-intrusive thermal imaging system based on the fluorescence properties of an europium-doped lanthanum oxysulfide (Eu\(^{3+}\)-La\(_2\)O\(_2\)S) thermographic phosphor. In this system the phosphor coating on a test surface is excited by a pulsed Nd:YAG laser. The resulting fluorescent emission of the temperature-sensitive 512 nm transition, along with that of the relatively temperature independent 620 nm transition, is acquired using an image-intensified charged coupled device (ICCD) camera. The ratio of the 512- and 620-nm emissions, integrated over a set gating period, is then correlated with temperature. Quality data obtained from a calibration procedure have demonstrated that the present approach can be more advantageous than many existing thermal imaging techniques. The system has been specifically designed to provide two-dimensional temperature measurements with high accuracy and exceptional spatial resolution. Because of the extremely short fluorescent lifetimes of various thermographic phosphors (~µs), applicability of the technique to fast-moving or rotating surfaces is very promising.

INTRODUCTION

The conventional method for temperature measurement in heat transfer research often relies on the use of electrically-resistant sensors such as thermocouples. While such devices offer good accuracy, their usage for surface temperature measurement does present certain difficulties. Owing to the discrete nature of temperature measurement, thermocouples may be ill suited for the study of local convective heat transfer in complex flow fields such as those that occur in an axially cooled rotor-stator disk cavity. In such experiments it may not be feasible to instrument the surface of the rotor or stator with the large number of thermocouples necessary to provide an accurate mapping of local variations in heat transfer. Finally, installation of thermocouples on rotating surfaces such as a turbine disk present severe technical difficulties. Great care must be exercised in thermocouple installation to ensure that the thermocouples or their leads do not affect the flow, and thus the heat transfer, within the disk cavity. An additional concern in turbine instrumentation is the need to use slip ring assemblies, which permit intermittent contact between rotating thermocouple leads and stationary data acquisition system leads. The movement of these contacts introduces noise in the output signal.

With recent advances in digital video technology and improvements in the processing capabilities of personal computers, non-intrusive optical temperature measurement techniques such as infrared imaging or liquid crystal thermography have become attractive alternatives to thermocouple instrumentation. Each of these techniques, however, present certain limitations that prevent their general use. While infrared imaging is a viable technique for use in high temperature environments, room temperature measurement is difficult due to the inability to accurately screen background radiation. The chief disadvantage of liquid crystal thermography is the limited temperature measurement range, which is from -25 C to 250 C. Furthermore, because this technique relies on the measurement of reflected light, results are sensitive to both illumination intensity and viewing angle. A thermal imaging technique that overcomes these limitations is a technique based on the temperature-sensitive properties of rare-earth ion doped phosphors (i.e., thermographic phosphors). With the choice of an appropriate thermographic phosphor, this technique can be used over a broad temperature range, from cryogenic temperatures to the high temperatures associated with combustion. In addition, measurements can be made to be independent of viewing angle.

Laser-induced fluorescence (LIF) was first employed as an advanced optical diagnostic technique in combustion research for species measurements (Dyer and Crosley, 1982) and later for flame temperature measurements (Cattolica and Stephenson, 1984). In one of the first efforts to use such a technique for surface temperature measurement, the fluorescence lifetime of an emission line of a rare-earth ion-doped phosphor (i.e., thermographic phosphor) was correlated to temperature (Cates, et. al., 1985). While this technique has been successfully employed to provide point temperature measurements in an operating turbine engine (Noel et. al., 1990), it is not an amenable approach for two-dimensional imaging because the decay time of most phosphors is so rapid that it not possible to obtain the images necessary to compute decay times. The feasibility of two-dimensional thermal imaging was demonstrated in a study in which the surface temperature of combusting rocket propellant was measured (Goss et. al., 1989). By seeding the rocket propellant with thermographic phosphor crystals, surface temperatures over the range of 300 to 1500 K were measured with an accuracy of approximately 3 percent.

In this study an LIF thermal imaging system, capable of accurate, two-dimensional surface temperature measurement, has been developed and demonstrated for use in general heat transfer...
dependent. Nonradiative relaxation between different energy
decay time. Secondly, thermal expansion of the crystal lattice as
temperature will increase crystal lattice vibration, resulting in
earth ion doped phosphor in several ways. First, an increase in
form of heat by increased vibratory atomic motion (phonons).
excitation energy in nonradiative quenching is dissipated in the
spectral emission lines. A third effect is the increase in the
phosphor temperature is increased may cause a frequency shift of
fluctuations in the crystal electric field. In turn, electric field
levels occurs by the emission of a photon whose wavelength is
energy level occurs as a result of the absorption of a photon with an
energy equivalent to
\[ \Delta E = h \nu \]
where \( \Delta E \) is the energy difference between the excited- and
ground-state levels in ergs, \( h \) is Planck's constant \((6.62 \times 10^{-27} \text{ erg sec})\) and \( \nu \) is the frequency of the excitation source in cycles per
sec. In order to minimize its potential energy, the excited electron
seeks to return to the lower energy ground state by releasing its
excess energy via radiative and/or nonradiative quenching. In
radiative quenching a discrete electronic transition between energy
levels occurs by the emission of a photon whose wavelength is
dependent on energy level spacing (i.e., \( \Delta E/h \)). In contrast, excitation energy in nonradiative quenching is dissipated in the
form of heat by increased vibratory atomic motion (phonons).

Changes in temperature can affect the fluorescence of a rare-
earth ion doped phosphor in several ways. First, an increase in
temperature will increase crystal lattice vibration, resulting in
fluctuations in the crystal electric field. In turn, electric field
variations near the rare-earth ion will broaden the line width of
radiative transitions. An increase in crystal vibratory motion will
also increase nonradiative relaxation, reducing the fluorescence
decay time. Secondly, thermal expansion of the crystal lattice as
phosphor temperature is increased may cause a frequency shift of the
spectral emission lines. A third effect is the increase in the
population of upper energy levels with temperature according to
Boltzmann's law, \( \exp(-\Delta E/kT) \). In general, radiative transitions
associated with a particular energy level increase with population,
causin a greater fluorescence intensity. However, increasing
phosphor temperature may favor certain relaxation transitions over
others, so the intensity of certain emission lines may decrease with
temperature rather than increase. Of these effects, the ones that are
of most interest in terms of optical temperature measurement are
those affecting the lifetime and intensity of radiative emissions.

While the emission lifetime, or fluorescence decay time, of a
phosphor is a function of both the radiative and nonradiative
relaxation rates, only the nonradiative rate is temperature
dependent. Nonradiative relaxation between different energy
levels occurs by phonon emissions that conserve transition energy. These multiphonon processes are a result of the interaction of the
rare-earth ion and the fluctuating crystalline electric field. Crystal
lattice or molecular group vibrations, which vary according to
temperature, cause oscillations in the electric field at the ion site.
These lattice vibrations are quantized as phonons, whose excitation
energies are a function of the masses of the constituent ions and the
atomic binding forces. The temperature dependence of the
emission lifetime; therefore, is a function of the number of phonons necessary to conserve the transition energy. The emission-lifetime temperature dependence is more significant for
higher-order phonon processes.

The second fluorescence phenomenon of importance in
optical temperature measurement is the variation in emission intensity with temperature. For the temperature-sensitive 512 nm
emission line of \( \text{La}_2\text{O}_3\text{S}:\text{Eu}^{3+} \), charge transfer state (CTS)
resonance transitions (Fonger and Struck, 1969) cause fluorescence
intensity to decrease as the temperature rises. Although the upper
energy level populations increase with temperature, the higher
individual temperature of these excited electrons causes quenching
via the CTS to be preferable to the 512 nm radiative transition.
The CTS rapidly thermalizes excitation energy so that the excited
electron can be fed to a lower ion energy level near the CTS
minimum energy level.

By exploiting the temperature sensitivity of both the
fluorescence intensity and lifetime of the europium-doped lanthanum oxysulfide 512 nm emission triplet, it is possible to
obtain accurate two-dimensional surface temperature measurements with exceptional spatial resolution. The 512 nm
fluorescent emission, when integrated over 40 \( \mu \text{s} \) after pulsed excitation, which is a considerably greater time frame than its
lifetime of a few microseconds, decreases by a factor of 8 as
temperature is increased from 20 \( \degree \text{C} \) (68 \( \degree \text{OF} \)) to 60 \( \degree \text{C} \) (140 \( \degree \text{OF} \)). In
contrast, under continuous illumination the emission intensity over
this temperature range only varies by a factor of 2.5. Consequently, measurement of integrated intensity during
fluorescence decay provides for greater temperature resolution than
measurement of either continuous emission intensities or decay
times alone.

**EXPERIMENTAL APPARATUS AND PROCEDURE**

The primary components of the LIF thermal imaging, shown
schematically in Figure 1, are the neodymium-doped yttrium aluminum garnet (Nd:YAG) pulsed laser and the image-intensified
crystal charge coupled device (ICCD) camera. To permit measurement of the integrated fluorescent emission over a narrow wavelength
range during fluorescence decay, it is necessary to use a pulsed
excitation source and an image detector capable of low-light level
operation at gating speeds as rapid as a few microseconds. The
timing and duration of the image-intensifier gate, or electronic
shutter, on the ICCD camera is precisely coordinated with the laser
pulse by a pulse generator. A 486 processor-based personal
computer provides overall system control and image data storage,
as well as image post-processing necessary to calculate surface
temperatures.

To employ the LIF technique for temperature measurement, a
phosphor coating must be applied to the test surface. This coating
must be dense enough to provide a strong, uniform fluorescence
signal, but it should not be so thick as to appreciably affect local
surface heat transfer. Furthermore, if the phosphor is applied using a binder such as an epoxy or silicone resin, the binder must be
chosen to ensure that it does not fluoresce at the wavelengths of
interest. For this experiment, europium-doped lanthanum oxysulfide crystals with a nominal grain size of 7 microns were
applied using a settling technique commonly employed in the
construction of cathode ray tubes. In this technique phosphor is
suspended in a fluid and allowed to settle onto the test surface. It
was determined that a phosphor coating density of 10 mg/cm
which is equivalent to a coating thickness of 100 microns, was
necessary to obtain a fluorescence uniformity of ± 5 percent. Since the resulting phosphor coating using this technique is extremely fragile, a thin silicone overcoat was applied to protect the surface.

During temperature measurement, the phosphor coating on the test surface is excited by the 355 nm tripled output of the Nd:YAG laser. Although individual laser pulses can be coordinated with ICCD image acquisition, the laser is allowed to operate at its optimum frequency of 10 Hz in order to minimize pulse-to-pulse energy deviations. Approximately 80 mJ of excitation energy over a beam diameter of 6.4 mm (0.25 inch) are provided during each 8-ns laser pulse. To permit temperature measurement over a more substantial target area, the laser output beam is passed through a -100 mm focal length plano-cylindrical lens, providing a 6.4 mm (0.25 inch) by 76 mm (3.0 inch) beam for illumination of the test surface.

Coordination of image acquisition with the laser pulse is accomplished via the laser Q-switch advance synchronization signal. This signal, which is adjusted to occur 500 ns before the laser pulse, serves as the input trigger for the pulse generator. Upon receipt of the trigger, the pulse generator provides a gate pulse that activates the ICCD image-intensifier. The width of this pulse determines the gating or 'shutter' speed of the camera, and for the bulk of tests was adjusted to provide either a 35 or 40 µs gate. This gating ensures intensity integration over a period of time greater than the fluorescence lifetime of the 512 nm emission, which varies from approximately 10 µs at 20 °C to 1 µs at 60 °C (Cates, et al., 1985).

As illustrated in Figure 2 the fluorescence signal from the test surface is collected by a 150 mm enlarger lens and split into two equal length optical paths that are focused side-by-side onto the image detector. One optical path passes through a 510 nm narrow bandpass interference filter, while the other is directed through a 620 nm bandpass filter and a neutral density filter. The neutral density filter is required to reduce the intensity of the 620 nm fluorescence signal to a level comparable to that of the 512 nm signal, because the intensity and lifetime of the 620 nm emission is considerably greater than that of the 512 nm triplet. Because of the weak emission intensity of the 512 nm triplet, integrated fluorescent emissions are accumulated over several laser pulses to increase the system signal-to-noise ratio. When the specified number of laser pulses comprising a single exposure can be obtained, the camera controller disables image intensifier gating and stores the raw digital image data to a disk file for later analysis.

The simultaneous acquisition of fluorescent images at two distinct emission wavelengths is performed because intensity differences over the test surface occur as a result of spatial variations in the density of the phosphor coating and laser excitation energy. For three-dimensional surfaces variations in viewing angle caused by surface curvature may also affect spatial emission intensities. As previously noted, fluorescence intensity spatial deviations due to variations in the phosphor coating density on the test surfaces employed in this study are approximately ± 5 percent. Intensity differences due to energy level variations of the expanded laser beam output can be discerned by visual observation; therefore, these variations are more pronounced than those associated with the uniformity of the phosphor coating. The influence of these factors when correlating measured emission intensity values to temperature, however, can be eliminated by ratioing the intensity of two distinct emission lines. While the absolute value of the intensity of each emission line at any given location on the surface is affected by the density of the phosphor, the excitation energy level and the viewing angle, the effect on the intensity ratio is minimal and can be corrected.

Prior to collecting fluorescent images for analysis, the proper pixel-to-pixel correspondence between the two images projected onto the CCD and the spatial intensity response of the camera must be established. To ensure proper alignment of the two images when performing individual pixel intensity ratio calculations, a thin black cross on a white background was imaged. The pixel location of the center of the cross for each of the images projected onto the CCD was calculated by identifying the edges of each arm of the cross. The criterion for identifying an edge was the pronounced increase in intensity between a pixel on the cross edge and its neighbor in the white region surrounding the cross. Once the image centers are established, flat field image correction data can be collected. Variations in the phosphor coating of the ICCD camera photocathode, which converts photons into electrons that are in turn multiplied by the image intensifier, cause differences in pixel-to-pixel intensity values. To correct for these intensity response variations of the camera, a uniformly illuminated white surface is imaged. For each of the images focused on the detector, a correction array is obtained by dividing individual pixel intensity values by the average intensity of the image.

Post-acquisition analysis of fluorescent images is performed using a program in which the user specifies discrete points on the target surface at which local temperatures are to be calculated. The number of pixels to be used to calculate the intensity ratio at these points are also specified in terms of the size of the calculation area (e.g., a 10 by 10 pixel area). After these data are input, the flat field correction is applied to the raw image data and the first frame of the image is used to calculate a surface correction array to account for spatial intensity variations caused by differences in phosphor density and laser excitation energy. These corrections are then applied to all succeeding frames of data. Intensity ratio values are calculated for each pixel within the calculation area and then averaged. The intensity ratio at each point can then be converted to a temperature using a calibration curve established by data obtained using an isothermal bath to heat a phosphor-coated copper test specimen.

RESULTS AND DISCUSSION

A calibration curve for europium-doped lanthanum oxy sulfide was established using the apparatus shown in Figure 3. In this setup the front surface of a 25 mm (1 inch) x 25 mm (1 inch) x 12.7 mm (0.5 inch) copper block is coated with the phosphor, and its back surface is immersed in water. The water
temperature can be adjusted and is controlled to within 0.1 C (0.06 
°F) by a circulating isothermal bath. Fluorescent image data are 
gathered for at eight temperatures in the range of 18.9 C (66 °F) to 
60 C (140 °F). At each temperature ten image frames, each 
recording the integrated fluorescence intensity over 20 laser pulses, 
are collected. The intensifier gate, or signal integration period, for 
each pulse is 40 µs. Calculated average values of the 510 nm to 
620 nm intensity ratios for the ten image frames collected at each 
temperature examined are presented in Table 1, along with 
pertinent statistical data.

<table>
<thead>
<tr>
<th>Temperature C (°F)</th>
<th>Average Ratio</th>
<th>Std Deviation of Ratio</th>
<th>Greatest Deviation from Average Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.9 (66.0)</td>
<td>1.331</td>
<td>0.015 (0.38 OF)</td>
<td>0.016 (0.46 OF)</td>
</tr>
<tr>
<td>25.3 (77.5)</td>
<td>0.928</td>
<td>0.013 (0.42 OF)</td>
<td>0.020 (0.66 OF)</td>
</tr>
<tr>
<td>30.1 (86.2)</td>
<td>0.692</td>
<td>0.006 (0.26 OF)</td>
<td>0.009 (0.37 OF)</td>
</tr>
<tr>
<td>35.4 (95.7)</td>
<td>0.505</td>
<td>0.004 (0.21 OF)</td>
<td>0.007 (0.44 OF)</td>
</tr>
<tr>
<td>40.1 (104.2)</td>
<td>0.384</td>
<td>0.003 (0.25 OF)</td>
<td>0.005 (0.45 OF)</td>
</tr>
<tr>
<td>45.0 (113.0)</td>
<td>0.255</td>
<td>0.005 (0.60 OF)</td>
<td>0.008 (0.94 OF)</td>
</tr>
<tr>
<td>50.1 (122.2)</td>
<td>0.232</td>
<td>0.002 (0.41 OF)</td>
<td>0.004 (0.70 OF)</td>
</tr>
<tr>
<td>60.0 (140.0)</td>
<td>0.149</td>
<td>0.003 (0.86 OF)</td>
<td>0.003 (0.95 OF)</td>
</tr>
</tbody>
</table>

An 11 x 11 pixel array, equivalent to a 1.6 mm (0.0625 inch) 
square area on the copper block surface, was used to calculate the 
ratio data presented in the table above. For an individual frame of 
data, the calculated ratio is accurate within 0.95 OF across the 
entire temperature range examined. Individual frame intensity 
ratio data becomes less accurate as temperature is increased 
because the integrated intensity of the 510 nm emission drops 
substantially, resulting in a decrease in the signal-to-noise ratio.

As illustrated in Figure 4, variation of the integration time 
(i.e., the duration of the image intensifier gate) has a significant 
effect on calibration curve. Although reduction of the intensifier 
gate increases the intensity ratio gradient at lower temperatures, the 
reduced integrated intensity tends to decrease measurement 
accuracy, especially at higher temperatures. A quantitative 
assessment of the impact of gating duration on measurement 
accuracy can be seen by comparing the calibration results of Table 
1 with those presented in Table 2.

The greatest portion of the frame-to-frame deviation in the 
calculated intensity ratio is related to electron shot noise. Since the 
image intensifier multiplies each incoming photon to produce as 
amany as 100,000 electrons, small variations due to shot noise are 
multiplied. The most effective means of reducing the effects of 
short noise are to average data over a greater number of frames. To 
illustrate the benefit of frame averaging, two independent 
calibrations using a 35 µsec intensifier gate were performed on 
different days. Comparing the results of these calibrations reveals 
that the individual frame-to-frame uncertainty for the frames from 
both calibrations is similar, but the deviation between the intensity

<table>
<thead>
<tr>
<th>Temperature C (°F)</th>
<th>Average Ratio 1</th>
<th>Average Ratio 2</th>
<th>Ratio Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.0 (66.2)</td>
<td>1.691</td>
<td>1.688</td>
<td>0.003 (0.06 OF)</td>
</tr>
<tr>
<td>25.1 (77.2)</td>
<td>1.188</td>
<td>1.186</td>
<td>0.002 (0.05 OF)</td>
</tr>
<tr>
<td>30.0 (86.0)</td>
<td>0.871</td>
<td>0.874</td>
<td>0.003 (0.10 OF)</td>
</tr>
<tr>
<td>35.0 (95.0)</td>
<td>0.642</td>
<td>0.646</td>
<td>0.004 (0.20 OF)</td>
</tr>
<tr>
<td>40.0 (104.0)</td>
<td>0.480</td>
<td>0.484</td>
<td>0.004 (0.28 OF)</td>
</tr>
<tr>
<td>45.0 (113.0)</td>
<td>0.365</td>
<td>0.366</td>
<td>0.001 (0.09 OF)</td>
</tr>
<tr>
<td>50.0 (122.0)</td>
<td>0.283</td>
<td>0.285</td>
<td>0.002 (0.25 OF)</td>
</tr>
<tr>
<td>60.0 (140.0)</td>
<td>0.176</td>
<td>0.176</td>
<td>0.002 (0.87 OF)</td>
</tr>
</tbody>
</table>

To demonstrate the feasibility of utilizing this technique for 
temperature measurement on moving surfaces, a series of 8 
fluorescence image data sets from the surface of a 127 mm (5 inch) 
quartz disk rotating at 1000 rpm were obtained. Image data were 
collected near the radial midpoint of the disk, so the linear velocity 
was approximately 3.3 m/sec (1 f/sec). Each of the 10 frames in a 
data set represent the accumulated fluorescent emissions for 40 µs 
after surface excitation over 15 laser pulses. The average 520 to-
610 intensity ratio for all 80 frames is 1.887. This intensity ratio at 
room temperature differs from the data presented above because 
the phosphor surface was viewed from the back side of the disk 
and the quartz preferentially absorbs more of the 620 nm emission 
than the 510 nm emission. While the greatest signal frame 
deviation from the average, 0.068, would indicate a temperature
uncertainty of approximately 0.7 °C (1.26 °F), the deviation of the 10 frame average for each set from the overall average is much less, as shown in Table 4.

**TABLE 4 La$_2$O$_2$S:Eu$^{3+}$ INTENSITY RATIO DATA FROM A DISK SURFACE ROTATING AT 1000 RPM**

<table>
<thead>
<tr>
<th>Data Set</th>
<th>10 Frame Average Ratio</th>
<th>Deviation from 80 Frame Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.902</td>
<td>0.015 (0.28 °F)</td>
</tr>
<tr>
<td>2</td>
<td>1.891</td>
<td>0.004 (0.13 °F)</td>
</tr>
<tr>
<td>3</td>
<td>1.899</td>
<td>0.012 (0.22 °F)</td>
</tr>
<tr>
<td>4</td>
<td>1.892</td>
<td>0.008 (0.10 °F)</td>
</tr>
<tr>
<td>5</td>
<td>1.884</td>
<td>0.003 (0.05 °F)</td>
</tr>
<tr>
<td>6</td>
<td>1.880</td>
<td>0.007 (0.13 °F)</td>
</tr>
<tr>
<td>7</td>
<td>1.868</td>
<td>0.019 (0.28 °F)</td>
</tr>
<tr>
<td>8</td>
<td>1.879</td>
<td>0.008 (0.15 °F)</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The calibration data presented here indicate that LIF thermal imaging may be used to obtain accurate, two-dimensional temperature measurements on rotating surfaces with exceptional spatial resolution. Compared with conventional surface temperature measurement techniques requiring the tedious installation of numerous thermocouples, LIF thermal imaging is particularly attractive. It is also preferable to other optical temperature measurement techniques such as infrared imaging or liquid crystal thermography. While infrared imaging is a viable technique for use in high temperature environments, room temperature measurement is difficult due to the inability to accurate screen background radiation. The chief disadvantage of liquid crystal thermography is the limited temperature measurement range, which is from -25 °C to 250 °C. Furthermore, because this technique relies on the measurement of reflected light, results are sensitive to both illumination intensity and viewing angle. As has been demonstrated, LIF thermal imaging is a robust technique capable of accurate temperature measurement. With the choice of an appropriate thermographic phosphor, this technique can be used over a broad temperature range, encompassing the cryogenic conditions encountered in superconductor research and the high temperature environment associated with combustion research. In addition, measurements using the ratio of two emission lines are independent of the viewing angle and variations in fluorescence intensity caused by surface coating nonuniformities and spatial excitation energy deviations.

**ACKNOWLEDGEMENTS**

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