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TRANSIENT THERMAL MEASUREMENTS USING THERMOGRAPHIC PHOSPHORS FOR TEMPERATURE RATE ESTIMATES

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ABSTRACT

This paper addresses the potential for predicting heat flux from thermographic phosphor measurements. Temperature can be measured using thermographic phosphors by extracting the intensity decay of the phosphor, which is temperature dependent. This measured temperature can then be used to estimate boundary heat fluxes, which is often called the inverse heat conduction problem. Heating rate can also be estimated with the use of thermographic phosphors, from which heat flux can also be determined. In this case, the solution to the inverse problem appears more stable. The purpose of this work is to demonstrate the feasibility of measuring change in decay rates and the ability to determine the first derivative of temperature from these measurements. Preliminary analysis shows that by determining dT/dt instead of temperature, a better estimate of heat flux can be made. The experiment uses a millisecond phosphor, excited by an LED pulsed at 100 Hz. The phosphor is painted on a tungsten filament, which can be heated to hundreds of degrees in under a second. The temperature change during a single pulse is significant enough to affect the decay rate, which is necessary to achieve reasonable heating rate measurement. The measurements of heating rate are used to determine the volumetric generation rate (Joule heating) and the heat transfer loss from the system by convection and radiation. Early data show that estimates from heating rate data, as opposed to temperature data, result more accurate predictions with less error.

NOMENCLATURE

G generation (W/m^3)
k thermal conductivity (W/m °C)
α thermal diffusivity (m^2/s)
T temperature (°C)
t time (s)
h convection heat transfer coefficient (W/m °C)
I emission intensity (V)
I_0 initial emission intensity(V)
n^* number of excited luminescence centers
W_R transition rate of radiative mechanisms (s^{-1})
W_{NR} transition rate of non-radiative mechanisms (s^{-1})
τ decay time (s)
τ_0 initial decay time (s)

INTRODUCTION

Because current methods of heat flux determination are inaccurate or unstable [Kress, 1989], it is necessary to explore new techniques for measuring heat flux. There are two general methods of determining heat flux. The first is through direct measurement, in which a device is calibrated to output a voltage proportional to the heat flux. These devices tend to be expensive and difficult to calibrate. The second method consists of measuring temperature and estimating heat flux from the use of data reduction techniques. Temperature measurements are preferred over heat flux measurements due to reliability and relative ex-

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pense. However, the reduction of heat fluxes from temperature measurements is an ill-posed problem, and any uncertainty in the temperature measurement is amplified during the data reduction process.

It is the differentiation of data that causes problems in the method of determining heat fluxes from temperature measurements [Kress, 1989]. To stabilize the inverse heat conduction solution, Frankel and Keyhani [1997] suggest using the first time derivative of temperature, known as the heating rate. Other work [Frankel and Keyhani, 1999, Frankel and Osborne, 2003, Walker, 2005, e.g.] since then has identified the utility of heating rate mesurement devices. One technique for measuring heating rate is accomplished using thermographic phosphors. This technique was first identified as a legitimate method for measuring heating rate by Walker and Schetz [2003]. Walker [2005] went on to show that from intensity measurements of thermographic phosphors, it is possible to measure heating rates and heat flux stably.

The present work focuses on the quality of heating rate estimates from thermographic phosphors intensity measurements. A bulk model is used to describe the thermographic phosphor coated tungsten filament that is heated in the experiment, such that

$$\frac{G}{k} = \frac{1}{\alpha}\frac{dT}{dt} + h(T - T_\infty). \tag{1}$$

By determining dT/dt and T from experimental data, solutions can be made for the unknown generation, G, and convection heat transfer coefficient, h. We intend to show that the solution for generation using measured heating rate is more stable and more accurate than the solution using differentiated measured temperature.

THEORY

Thermographic phosphors are rare-earth doped ceramics that fluoresce when exposed to light. The intensity, decay rate, and wavelength of the emission are temperature dependent. Therefore, by measuring any of these three properties, a temperature prediction can be made. The choice of phosphor and measurement technique are generally determined by the application and the data requirements [Allison and Gillies, 1997]. Thermographic phosphor emission is inherently transient, therefore intensity meaurements can be used to extract transient temperature data, such as the heating rate. The method of extracting heating rate from intensity measurements will be covered later in a following section.

When a phosphor is excited by incident photons, in this case from a light emitting diode, it begins to emit light at a specific wavelength determined by its electronic band structure [Shionoya and Yen, 1999]. The intensity of the emission is a function of multiple factors, such as material properties, doping, temperature, and the excitation source. The phosphor emission intensity I is proportional to the time rate of change of excited luminescence centers n^* [Shionoya and Yen, 1999],

$$I \propto \frac{dn^*}{dt}. \tag{2}$$

The number of luminescence centers (electron/hole pairs available for recombination) is governed by the radiative and non-radiative recombination of electrons with holes as

$$\frac{dn^*}{dt} = -(W_R + W_{NR})n^*, \tag{3}$$

where W is the transition rate of radiative and non-radiative mechanisms [Shionoya and Yen, 1999]. The transition rates are commonly combined into an overall lifetime τ , also known as the decay rate, such that

$$\tau^{-1} = W_R + W_{NR}. \tag{4}$$

In general, this lifetime is temperature dependent. The emission of the phosphor is a function of the lifetime, and therefore also a function of temperature. This makes it possible to use emission measurements to predict the temperature of a phosphor.

Crim et al. [2004] outlined three methods for extracting temperature and heating rate information from phosphor emission intensity measurements. The standard model assumes a constant decay rate, and the normalized intensity is given as

$$\frac{I}{I_0} = \exp\left(-\frac{t}{\tau}\right), \tag{5}$$

where I_0 is the intensity when the excitation source is turned off, at time $t = 0$. When we examine transient heating, where the change in temperature is of the order of the decay time, the assumption of constant decay rate is not valid, so the standard model will contain errors for a transient case. As a result, one of two other models must be used.

In general, the lifetime is a function of temperature, which varies in time. Therefore the lifetime will vary in time and is given as a truncated Taylor series expansion, i.e.

$$\tau = \tau_0 + \frac{d\tau}{dt}t. \tag{6}$$

Substituting equation 6 into equation 3, the normalized intensity is given as

$$\frac{I}{I_0} = \left(\frac{\tau_0}{\tau_0 + \frac{d\tau}{dt}t}\right)^{1/\frac{d\tau}{dt}}, \tag{7}$$

where τ_0 is equal to τ at $t = 0$. The third model, known as the exponential model, retains the form of equation 5 (the standard model), but τ is assumed to be a linearly varying function of time. The exponential model is given as

$$\frac{I}{I_0} = \exp\left(-\frac{t}{\tau_0 + \frac{d\tau}{dt}t}\right). \tag{8}$$

Notice that for steady state, $d\tau/dt \rightarrow 0$, and the exponential model (equation 8) reduces to the standard model (equation 5). This makes the exponential model a more attractive choice for very small $d\tau/dt$, because if $d\tau/dt = 0$, there is a singularity in the power model. Both models can now be compared to experimental data to extract an estimate for $d\tau/dt$. Use of the chain rule directly gives us the heating rate

$$\frac{dT}{dt} = \frac{dT}{d\tau}\frac{d\tau}{dt}. \tag{9}$$

The derivative of temperature with respect to τ can be found by differentiating the calibration curve. The calibration curve gives the relationship between the decay time and the temperature, and it can be obtained by measuring the decay time of the phosphor at different steady state temperatures [Allison and Gillies, 1997].

MEASUREMENTS

The setup of the experiment consists of a tungsten filament coated with a thermographic phosphor. The phosphor, europium-doped lanthanum oxysulfide, La_2O_2S:Eu, was chosen for its decay time, which is approximately 0.345 milliseconds at room temperature. When exited by an LED at 350 nm, the phosphor reemits light with peak intensity at 630 nm. The LED is controlled with a pulse generator set at 100 Hz, with a duty cycle of 20%. The phosphor emission is measured with a photomultiplier tube, which converts the emission intensity to a voltage. An infrared thermal imaging camera captures still images and video of the filament during each run of the experiment to measure the temperature.

The experiment consists of two parts, one steady state, and one transient. The steady state portion of the experiment gives the calibration curve. The calibration curve is a plot of decay time τ versus temperature. The phosphor emission intensity is recorded at various steady state temperatures, and the decay times are extracted from the intensity measurements. The transient portion of the experiment consists of heating the filament while taking phosphor emission intensity measurements. The power supply to the filament is initially turned off, and once the power is switched on, the filament is supplied with 7.5 volts. This amount of power heats the filament and phosphor coating to 300^0 C in approximately one second. After one second of heating, the temperature change in the filament is at 94% of the total temperature change that will take place. The filament reaches steady state after 2 two seconds of heating.

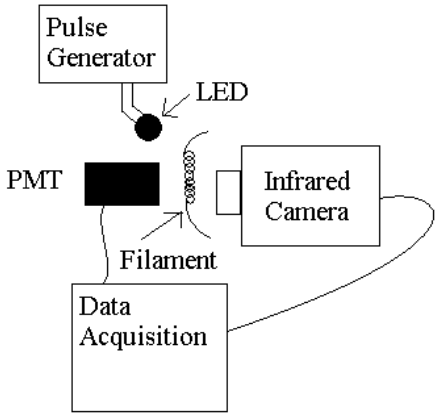

Figure 1. SCHEMATIC

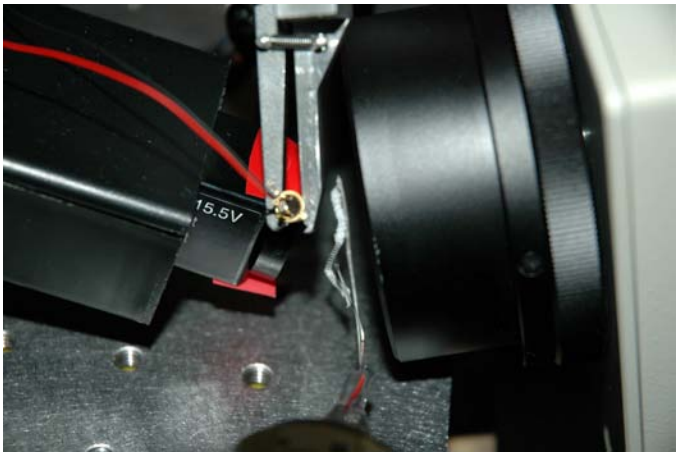

Figure 2. EXPERIMENTAL SETUP

RESULTS AND DISCUSSION

The calibration curve consists of twenty data sets, each taken at steady state conditions, that range in temperature from ambient temperature to 280^0 C. For each data set, the voltage applied to the heater is adjusted to the desired setting, and the temperature is checked to be steady using the thermal imaging camera. At this point the camera records the filament temperature. The emission intensity is recorded for one second at 50,000 Hz while the LED

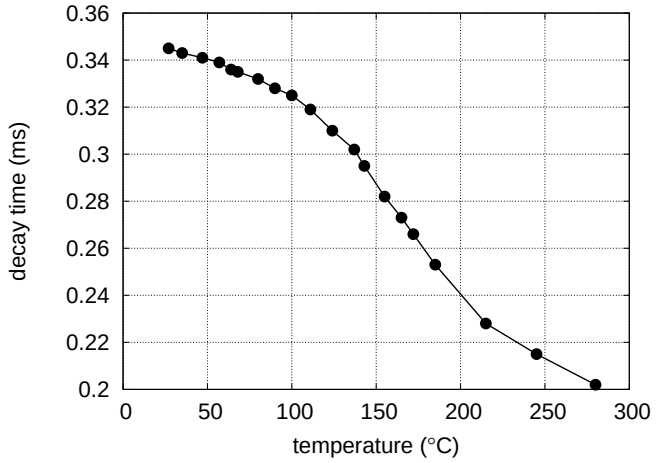

Figure 3. CALIBRATION CURVE FOR La_2O_2S:Eu PHOSPHOR.

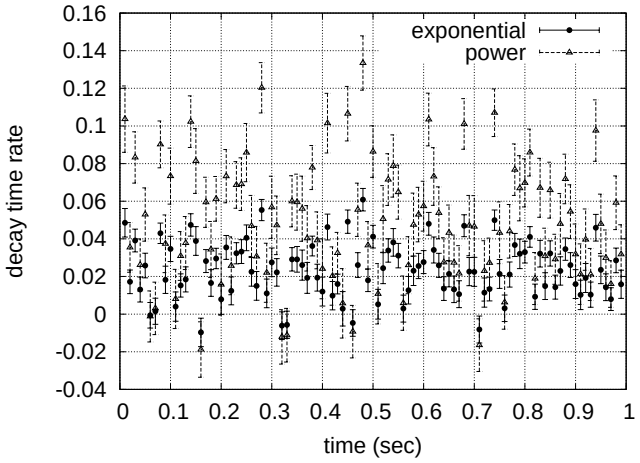

Figure 4. CHANGE IN DECAY TIME FOR La_2O_2S:Eu PHOSPHOR AT AMBIENT TEMPERATURE.

pulses at 100 Hz. The data from each pulse are reduced and decay time is extracted using a curve fit of equation 5. Thus each point on the calibration curve represents the average decay time of the 100 pulses. Although figure 3 does not appear to be linear, note that the slope is negative throughout the region of interest. From this data we can infer that for this phosphor, the decay time τ is inversely proportional to temperature. A numerical analysis can be performed on the calibration curve data to differentiate the curve. The differentiation results give $d\tau/dT$, which can simply be inverted to give $dT/d\tau$.

For steady state conditions, each of the three models, standard, power, and exponential, can be used to extract the initial intensity I_0 and the decay time τ from each pulse. The estimates of initial intensity remain constant in time, with a magnitude of approximately 1.7 volts. This is to be expected at constant temperature, as emission intensity is inversely proportional to the temperature. Likewise, we expect τ to remain constant at constant temperature as well, because decay time is also a function of temperature. The estimate of each model gives a constant value of approximately 0.345 ms, which is in agreement with the calibration curve. Given the results of constant intensity and decay time, we are confident that the three models fulfill the purpose of extracting initial intensity and τ at steady state. The power model and exponential model can also be used to extract the time rate of change of decay time, $d\tau/dt$. Given constant decay time at steady state, we expect $d\tau/dt$ to be constant and equal to zero over the data set. From the plot we see that $d\tau/dt$ is in fact constant but is non-zero. The models result in a positive value of $d\tau/dt$, which cannot be true if the decay time is constant over the data set. This discrepancy suggests a bias in the data, which will be addressed after examining transient data.

The transient data to be examined consists of the emission intensity measurements recorded during the heating process only.

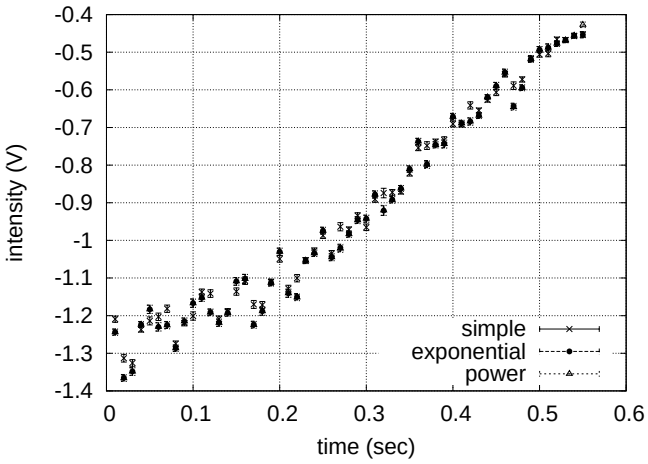

Figure 5. INITIAL EMISSION INTENSITY OF La_2O_2S:Eu PHOSPHOR IN HEATING.

The data recorded during and after the heating serves to check that the process begins and ends at steady state. The examined data covers a temperature range from ambient temperature to approximately 200^o C over a period of 0.57 seconds. All three models are used to estimate I_0 and τ, but the equation for the simple model does not include $d\tau/dt$, so only the power model and the exponential model are used to extract $d\tau/dt$ for the plots in transient conditions.

In the plot of initial emission intensity versus time (figure 5), notice that the values of initial emission intensity are negative. This occurs because the photomultiplier tube gives negative output voltages. Therefore, when values of intensity are discussed, it is actually the magnitude of the value that is under consideration,

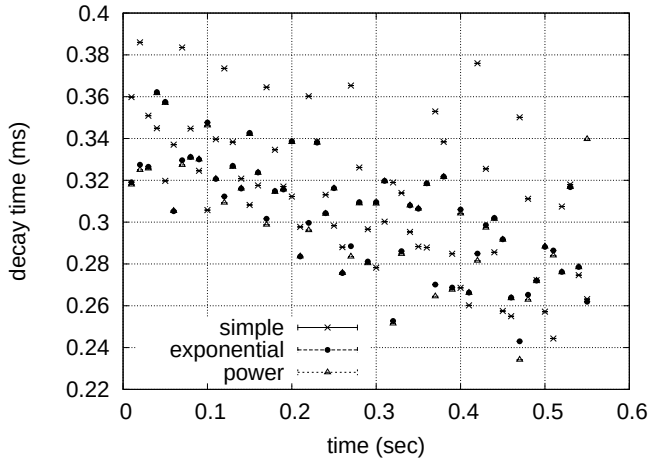

Figure 6. DECAY TIME FOR La_2O_2S:Eu PHOSPHOR IN HEATING.

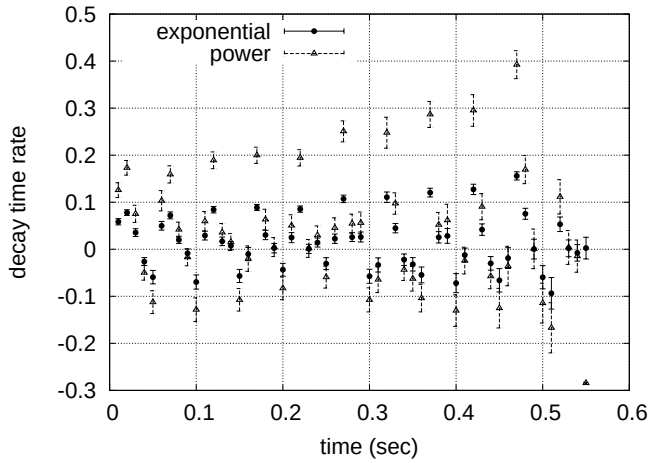

Figure 7. CHANGE IN DECAY TIME FOR La_2O_2S:Eu PHOSPHOR IN HEATING.

because there cannot physically be a negative value for intensity. Both models show that the initial intensity decreases over time as the temperature increases. The decrease in intensity magnitude indicates that the temperature is increasing. Looking at the plot of decay time versus time (figure 6), we see that τ also decreases as the temperature rises. This is also the expected result given the relationship between decay time and temperature. Note that the inverse proportionality of τ to temperature is valid for both steady state and transient conditions.

Given the information from figure 6, we expect $d\tau/dt$ to be negative throughout the data set. Looking at the plot of $d\tau/dt$ versus time, we see that this is not the case. These results again show that there is bias in the data. Without much knowledge of the bias or its cause, a comparison of the solutions for generation cannot be made at this point.

Looking at the steady state data, there appears to be bias present in the results. $d\tau/dt$ is constant, as it should be, but is non-zero. If the cause of this bias is determined and can be removed, the models are still valid for determining $d\tau/dt$. In figure 7, the bias appears to be periodic, which is not noticeable in any of the other plots. The frequency of the bias appears to be 15 Hz. Noticing the periodicity of the bias gives us more information, such as the expectation that the bias is an interference frequency of 60 Hz combined with the 100 Hz pulse rate of the LED. Furthermore, there seems to be a trend of the bias increasing as the temperature is increased. The effects of the bias on the results from the power model are more severe than the effects on the exponential model, especially at high temperatures. Eliminating this bias should give better results for $d\tau/dt$ from the data.

CONCLUSIONS

Direct measurement of heating rates has never been accomplished, and the technique employed in the present work represents a novel approach (using thermographic phosphors) to obtaining heating rate estimates. For steady-state measurements the rate of change in decay time is expected to be zero. However, the data indicate a bias in the measurement, which appears to be a function of temperature. Nevertheless, the match of the estimates for intensity and decay time is good for each of the three models. In the transient case, a non-zero value for the change in decay time is predicted, but the sign is opposite from expectations. We notice that if the bias observed in the steady case were used as an offset in the transient measurements, the data would predict an increasing temperature as expected. We also notice that the bias is periodic, which was not apparent before examining the $d\tau/dt$ data. The nature of the bias is unknown so the results are inconclusive, however, we expect that the bias may be an interference frequency of 60 Hz and 100 Hz. Shielding the experiment from any 60 Hz interference will give more information about the bias and may reduce it.

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