Transient Thermal Measurements Using Thermographic Phosphors for Temperature Rate Estimates

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Why are we studying this?

- Want alternative method of determining heat flux
- Current methods
  - Direct measurement – expensive, difficult to calibrate
  - Data reduction using temperature measurements – ill-posed, uncertainty is amplified
    - Temperature measurements are preferred due to reliability and cost
    - This method is known as the inverse heat conduction problem
    - Noise and uncertainty in the data are amplified during differentiation
Inverse heat conduction problem

- Solution for heat flux from temperature measurements is generally an integral equation of the first kind
- Solution for heat flux from heating rate measurements involves an integral equation of the second kind
- Second kind integral equations are inherently more stable than integral equations of the first kind
- Heat flux estimates from heating rate should be more stable with less error
Inverse heat conduction problem

- Forward solution to the conduction problem
  - Temperature
  - Temperature with added noise
Inverse heat conduction problem

- Heating Rate
  - Exact solution
  - Exact solution with added noise
  - Differentiated measured temperature
Inverse heat conduction problem

- Heat flux
  - Original square heat flux wave
  - Solution to the IHCP using measured temperature
Inverse heat conduction problem

- Heat flux
  - Original square heat flux wave
  - IHCP solution using measured heating rate
  - IHCP solution using differentiated measured temperature
Our New Approach

- Measure a different quantity to make the inverse heat conduction problem more stable
- Estimate heating rate using thermographic phosphors
**Thermographic Phosphors**

- Rare-earth doped ceramics that fluoresce when exposed to light
- Emission intensity, decay rate, and wavelength are temperature dependent

![Phosphor Emission Graph](image-url)

**Graph Details:**
- **Y-axis:** Intensity (V)
- **X-axis:** Time (s)
- **Marker:** Decay rate
Mathematical models

- **Steady model**
  \[
  \frac{I}{I_0} = \exp\left(-\frac{t}{\tau}\right)
  \]

- **Power model**
  \[
  \frac{I}{I_0} = \left(\frac{\tau_0}{\tau_0 + \frac{d\tau}{dt} t}\right)^{\frac{1}{d\tau/dt}}
  \]

- **Exponential model**
  \[
  \frac{I}{I_0} = \exp\left(-\frac{t}{\tau_0 + \frac{d\tau}{dt} t}\right)
  \]
Heating rate

- Chain rule
- Use power model or exponential model to estimate derivative of decay time
- \( \frac{dT}{d\tau} \) comes from the calibration curve
- Calibration curve gives the relationship between the decay time and temperature
- We used europium-doped lanthanum oxysulfide, \( \text{La}_2\text{O}_2\text{S}:\text{Eu} \)
Experimental Setup
Experiment

- LED excites phosphor at 350nm, phosphor reemits at 630nm
- LED is pulsed at 100Hz, with a 20% duty cycle
- Photomultiplier tube converts emission intensity to voltage
- Voltage data is recorded at 50,000 Hz
- Tungsten filament heats phosphor to 300 °C in one second
- Infrared thermal imaging camera records the temperature of the phosphor as it is heated
Steady State

- At steady state, the decay time is constant (~0.345 ms at room temperature)
- The change in decay time should then be constant and zero
- The graph shows constant but non-zero
- Inconsistency in expectations and results suggests a bias in the data
Transient data

- During heating, emission intensity and decay time decrease.
Transient data

From negative trend in plot of decay time, change in decay time should be negative
Results

- Slope of transient decay time plot \( \frac{d\tau}{dt} \) is about -0.00013
- At 50°C, \( \frac{dT}{d\tau} \) is about 4,430°C/s
- From chain rule, heating rate should be about 575°C/s
- From filament heating plot, \( \frac{\Delta T}{\Delta t} \) is about 640°C/s at 50°C
- Heating rates agree from decay time data and temperature data
Conclusions

- Match of intensity and decay time estimates is good for the three models
- Results of change in decay time for steady state and transient conditions suggest periodic bias
- Bias is present, so current results are inconclusive
- Bias must be removed to see results of decay time rate
- Same order of magnitude of heating rate using different methods