Analysis of Transient Heating of Phosphor Coatings

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- Develops with his close associates thermometry based on phosphor materials. Applications include turbine engines, heat pump efficiency studies, motor-surface measurements, aerodynamic model thermometry, and other applications. He has coauthored about 100 papers and has 9 patents. His current plans concern the development of phosphor thermometry, new optical materials (including nanoposphors and LEDs), and fiber sensor applications.
Outline

• Justification
• Areas of Application
• Railgun Example of Transient Heating
• Modeling and its Results
• Some previous test results evaluated in light of the model
• Conclusion
Justification

• Transient heating situations present a challenging class of problems for temperature diagnostics

• Approaches
  – Thin Film Thermocouples – require connection
  – Pyrometry – expensive/direct line of sight
  – Thermographic phosphors – film thickness dependent
Areas of Application

- Micro and Nano devices
- High Pulse Current Devices eg. railguns
Railgun Video - Transient Temperature Demonstration
Approach

- How well does a phosphor layer follow a temperature that rises by 200 C over a period of about 15 ms?

- The purpose here is to examine the relationship between the thickness of a phosphor layer and how faithfully in time its temperature matches the temperature of the underlying surface.
Modeling – Penetration Depth

\[ l = 4 \sqrt{\alpha t}, \]

Where \( l \) is the penetration depth for a semi-infinite slab, the distance into the material to which heat penetrates in time \( t \). \( \Delta T \approx 99\% \). (It is analogous to a boundary layer.)

Assuming \( \alpha \) is equivalent to glass:

\[ l = 4\sqrt{(8 - 7m^2/s)(15ms)} = 440\mu m. \]
Modeling continued

\[ T(x, t) = \frac{2}{L} \sum_{n=0}^{\infty} \alpha \beta_n (-1)^n \exp \left( -\alpha \beta_n^2 t \right) \cos(\beta_n x) \int_0^t \phi(t') \exp \left( \alpha \beta_n^2 t' \right) dt' , \]

\[ T(x, t) = \frac{2\xi}{\alpha L} \sum_{n=0}^{\infty} \frac{(-1)^n}{\beta_n^3} \cos(\beta_n x) \left[ \alpha \beta_n^2 t - 1 + \exp \left( -\alpha \beta_n^2 t \right) \right] \]

T(x,t) is conduction solution where \( \varphi(t) = \xi t \) and \( \xi \) is the change in temperature per second.

If the armature heats up by 200K in 15ms, then the heating rate is \( x \approx 13,000 \text{K/s} \). The solution of latter equation is shown in the following figure.
Temperature solution for a layer of phosphor being heated at $x=100\mu m$. The exposed surface is at $x=0$. 
50 μm and 20 μm coating results

Temperature solution for a layer of phosphor being heated at \( x = 50 \mu m \). The exposed surface is at \( x = 0 \).

Temperature solution for a layer of phosphor being heated at \( x = 20 \mu m \). The exposed surface is at \( x = 0 \).
Temperature of top layer vs thickness of layer.
# Table of Results

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Top layer lag (ms)</th>
<th>ΔT top and bottom surface (°C) at 200°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1/3</td>
<td>-3</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>-25</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>-79</td>
</tr>
</tbody>
</table>
Nichrome wire coated with phosphor is a good laboratory test bed for producing rapid temperature changes.
Periodic Current Applied to Nichrome

Square wave current impulse duration = 80 ms
300 C temperature swing 1560 cycles/hr
signal at beginning of heating pulse (t=0)
signal at t = 80 ms

Phosphor-coated nichrome

Intensity

Temperature C

time ms
Conclusions

• Nichrome wire test case shows 300°C rise in 80 ms.
• Given the difficulty of such measurements, the error associated with a 50 micron coating might be acceptable.
• After a sufficient lag time, the temperature rate of change is faithful regardless of coating thickness.
• It can be envisioned that the time lag could be an in situ thickness indicator.
• Clearly more detailed and rigorous analysis is desirable and the present work is another step toward that goal.
References


