Non-contact thermophysical characterization of solids and fluids for Gen3 concentrating solar power

Generation 3 Concentrating Solar Power Systems
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Topic Area 2B - Gen3 Research and Analysis

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Objectives and Impacts

• Problem Statement
  • Challenging and time consuming to measure thermophysical properties of high-temperature HTFs, e.g., molten salts and particles.
  • Lack of in-situ diagnostic tools to monitor thermophysical properties of HTFs

• Objectives
  • Develop a non-contact technique based on “modulated photothermal radiometry” or “MPR”, to measure thermal conductivity ($k$) and specific heat ($C$) of heat transfer fluids (HTFs), solar receiver tubes, coatings, up to 800°C
  • Use the tool for in-situ diagnostics of materials in CSP plants and of their corrosion behaviors.

• Impacts to Gen3 CSP
  • Facile and room-to-high temperature thermophysical measurements of emerging fluids (e.g., molten salts) and solids (e.g., particles) for Gen3 CSP systems.
  • Transition of the diagnostics tool for laboratory and in-situ testing in other Gen3 awardees.
Working Principles of MPR

Key Principles and Merits

- By changing the modulation frequency and the thermal penetration depth of the heating beam, the surface temperature will be sensitive to $k$ and $C$ of different layers (HTF, tube, and coating).
- Lock-in technique for surface IR thermometry with mK resolution.
- Works for both rough and smooth surfaces (unlike thermoreflectance that requires a smooth surface)
- Suitable for high temperature measurements (IR emission is stronger at higher temperature)
- Non-contact, minimal sample preparation (fast), Low-cost

<table>
<thead>
<tr>
<th>Layer</th>
<th>Rep. materials</th>
<th>$k@600°C$ (W/m-K)</th>
<th>$C@600°C$ (J/m²-K)</th>
<th>$\alpha@600°C$ (m²/s)</th>
<th>Thickness (L)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar coating</td>
<td>Black oxide</td>
<td>1-10 (?)</td>
<td>$\sim 0.5 - 2\times10^6$ (?)</td>
<td>$0.2-3\times10^{-6}$ (?)</td>
<td>&gt;10 um</td>
<td>&gt;~60 kHz</td>
</tr>
<tr>
<td>Tube shell</td>
<td>Inconel or Haynes</td>
<td>22</td>
<td>$5\times10^6$</td>
<td>$4.3\times10^{-6}$</td>
<td>0.5 mm</td>
<td>&gt;~6</td>
</tr>
<tr>
<td>HTF</td>
<td>Molten salt</td>
<td>$\sim 0.5$</td>
<td>$2.8\times10^6$</td>
<td>$1.8\times10^{-7}$</td>
<td>10 mm</td>
<td>0.1-6</td>
</tr>
</tbody>
</table>

Thermal penetration depth: $L_p = \sqrt{2 \alpha / \omega}$
Simultaneous Measurement of $k$ and $C$

- Using Modulated or Pulsed Photothermal Radiometry to measure $k$ and $C$ of thin films and bulks has already been demonstrated in the literature (e.g., refs 1-2).
- We can tune the spot and frequency to yield both $k$ and $C$.
- Measurement sensitivity $> 0.5$ within suitable frequency range.

<table>
<thead>
<tr>
<th>Material</th>
<th>$k$ (W/m-K)</th>
<th>$C$ (kJ/m$^3$-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>SS 314</td>
<td>15.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Acrylic</td>
<td>0.25</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Table:**

- **Fitting** and **Ref** columns indicate fitting and reference values, respectively.
MPR can also measure flowing fluids and falling particles

- Governing equation (no viscous dissipation): \[ \alpha V^2 T = \frac{\partial T}{\partial t} + \bar{v} \cdot \nabla T \]
- With the known velocity field \( \bar{v} \), the equation can be exactly solved.
- We will test this idea on a molten salt test loop (U Arizona) and also on falling particles
Work Plan and Milestones

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool dev.: Establishment of MPR</td>
<td>High-T setup</td>
<td>Tool Transition</td>
<td></td>
</tr>
<tr>
<td>Fluids: Stationary fluids</td>
<td>flowing fluids</td>
<td>High-T/in-situ testing of molten salts</td>
<td></td>
</tr>
<tr>
<td>Particles: Packed particles</td>
<td>falling particles</td>
<td>High-T/in-situ testing of falling particles</td>
<td></td>
</tr>
</tbody>
</table>