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

Generation 3 Concentrating Solar Power Systems
FOA: DE-FOA-0001697
Topic Area 2B - Gen3 Research and Analysis

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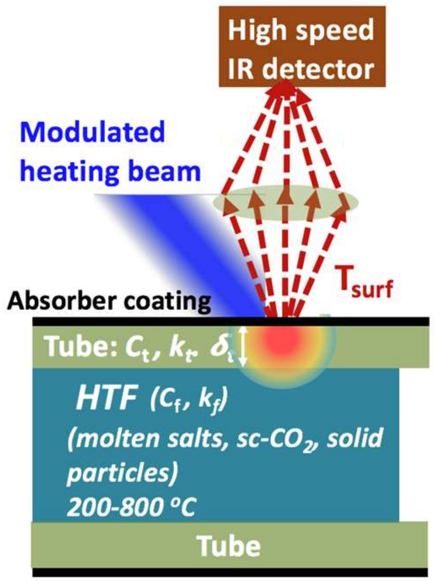
Objectives and Impacts

- **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^{o}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.

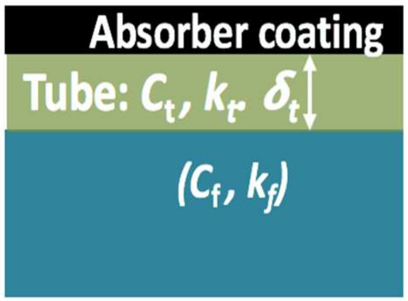
Working Principles of MPR

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



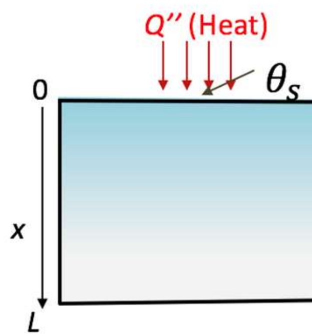
Layer	Rep. materials	k@600°C (W/m-K)	C@600°C (J/m³-K)	α@600°C (m²/s)	Thickness (L)	Frequency (Hz)
Solar coating	Black oxide	1- 10 (?)	~0.5 – 2×10⁶ (?)	0.2-3 ×10⁻⁶(?)	>10 um	> ~60 kHz
Tube shell	Inconel or Haynes	22	5×10⁶	4.3×10⁻⁶	0.5 mm	> ~6
HTF	Molten salt	~0.5	2.8×10⁶	1.8×10⁻⁷	10 mm	0.1-6



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.

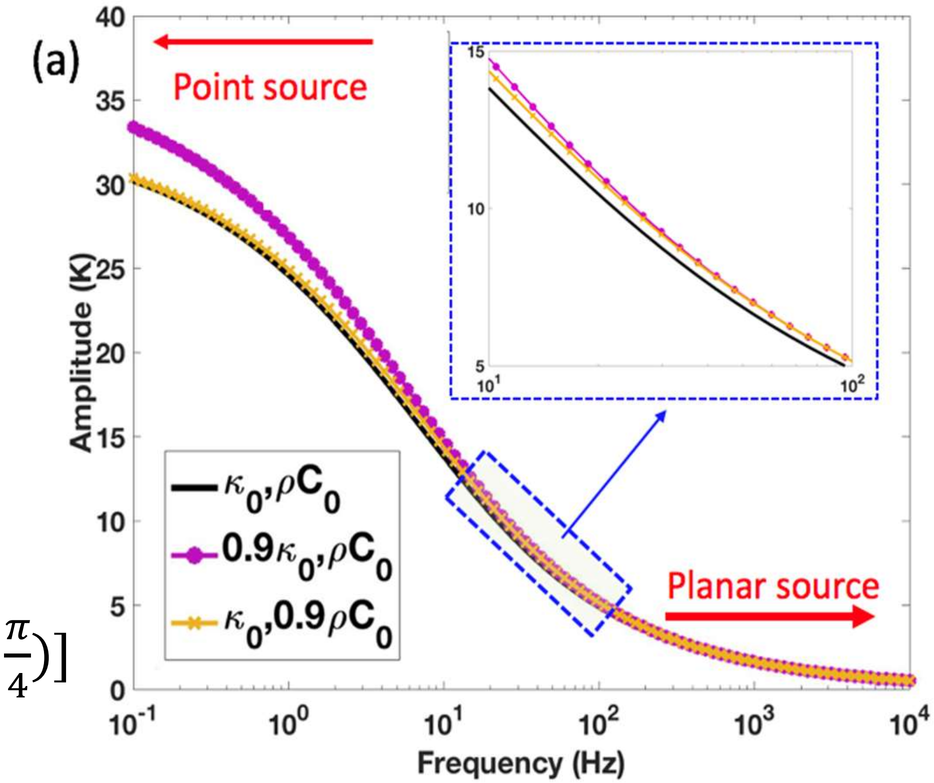


- Point heat source (spot size < L_p)

$$\theta_{s,point}(\omega) = \frac{Q_0}{2\pi\boldsymbol{\kappa} r}\exp(i\omega t)$$

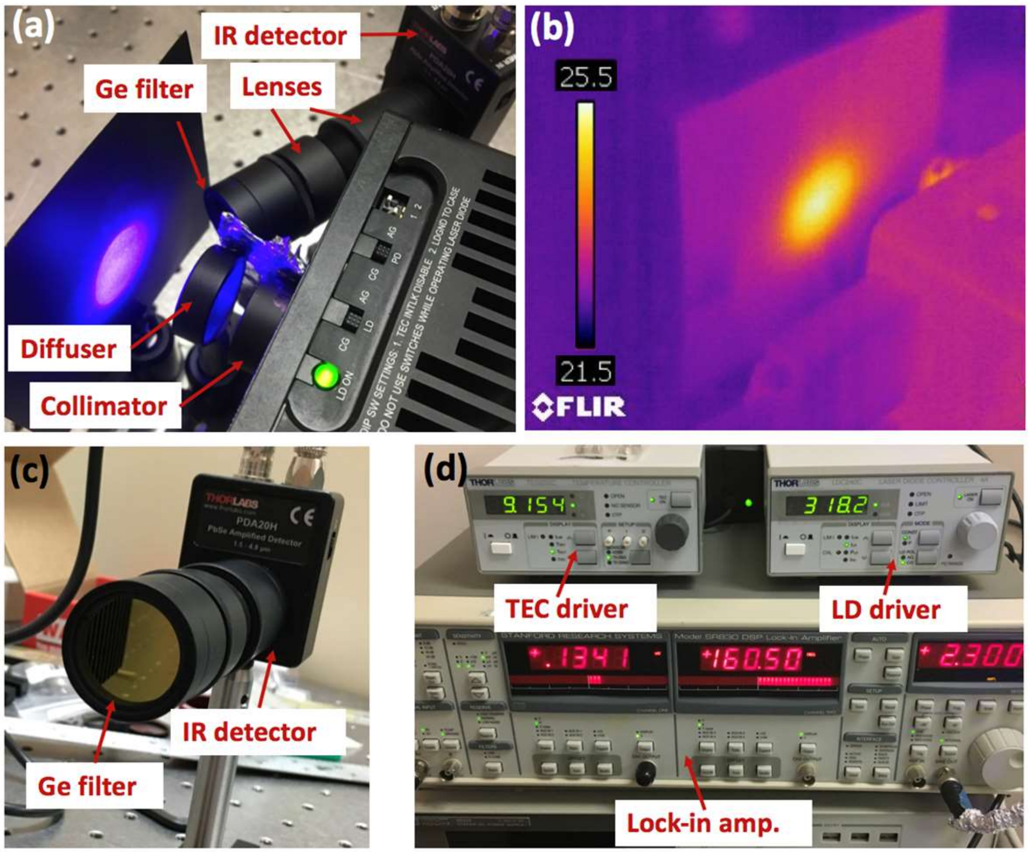
- Planar heat source (spot size > L_p)

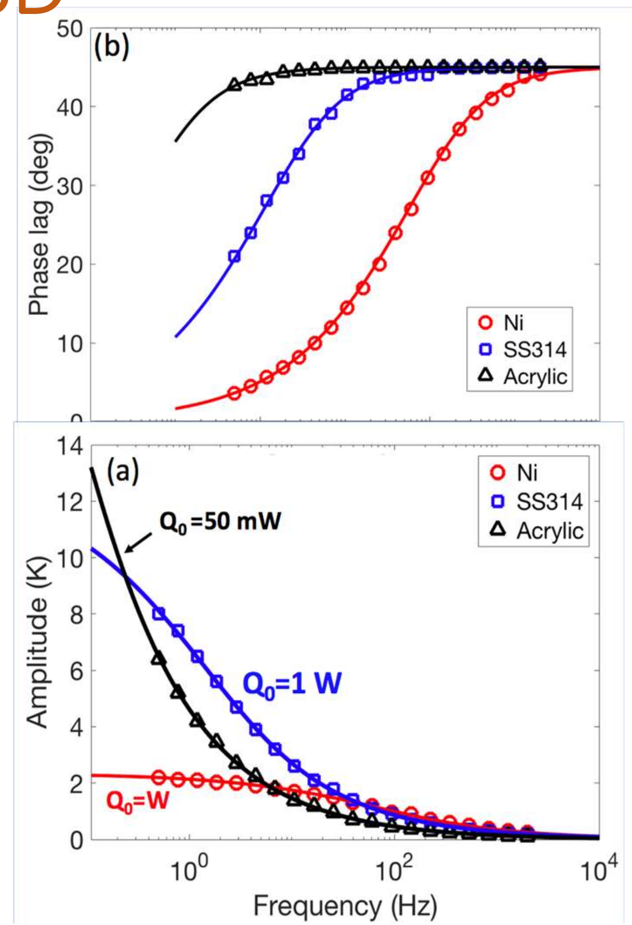
$$\theta_{s,planar}(\omega) = q_0/\sqrt{\boldsymbol{\kappa\rho C}\omega}\exp[i(\omega t - \frac{\pi}{4})]$$



[1] "Measurement of Thermal Properties of Thin Films up to High Temperatures-Pulsed Photothermal Radiometry System and Si-B-C-N Films", Rev Sci Instrum, 2010.
[2] "Using Pulsed and Modulated Photothermal Radiometry to Measure the Thermal Conductivity of Thin Films" Thermochim Acta, 2013.

MPR at UCSD



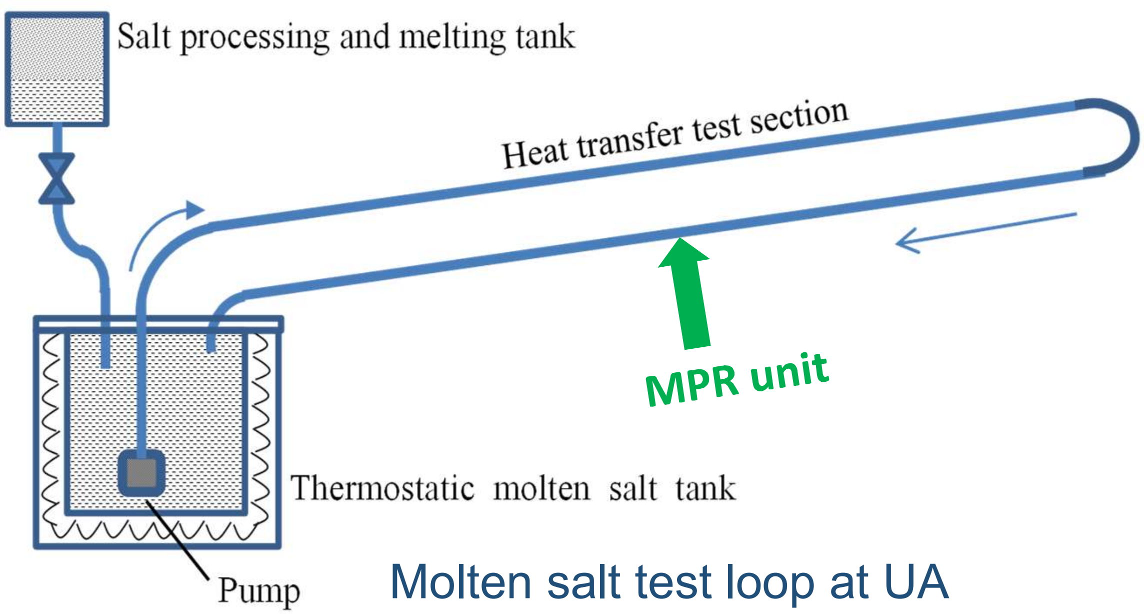


	k (W/m-K)		C (kJ/m³-K)	
	Fitting	Ref	Fitting	Ref
Ni	85	90	3754	3920
SS 314	15.5	17.5	3471	3900
Acrylic	0.25	0.2	1880	1750

MPR can also measure flowing fluids and falling particles

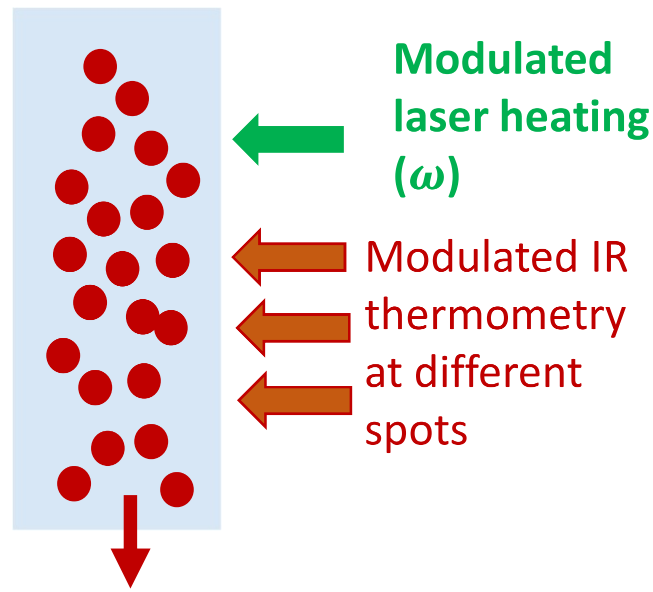
- Governing equation (no viscous dissipation): $\alpha \nabla^2 T = \frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T$
- With the known velocity field $\vec{v}$, the equation can be exactly solved.
- We will test this idea on a molten salt test loop (U Arizona) and also on falling particles

Molten salt



Molten salt test loop at UA

Falling particles



Work Plan and Milestones

	Year 1	Year 2	Year 3	Year 4
Tool dev.:	Establishment of MPR	High-T setup	Tool Transition	
Fluids:	Stationary fluids	flowing fluids	High-T/*in-situ* testing of molten salts	
Particles:	Packed particles	falling particles	High-T/*in-situ* testing of falling particles	