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Non-contact Thermophysical Characterization of Solids and Fluids for Gen3 Concentrating Solar Power

Generation 3 Concentrating Solar Power Systems
DE-EE0008379
Topic Area 2B - Gen3 Research and Analysis

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U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
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Objectives and Impacts

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Problem Statement

- Challenging and time-consuming to measure thermophysical properties of high-temperature heat transfer fluids (HTFs), e.g., particles and molten salts.
- Lack of *in-situ* diagnostic tools to monitor thermophysical properties of HTFs。

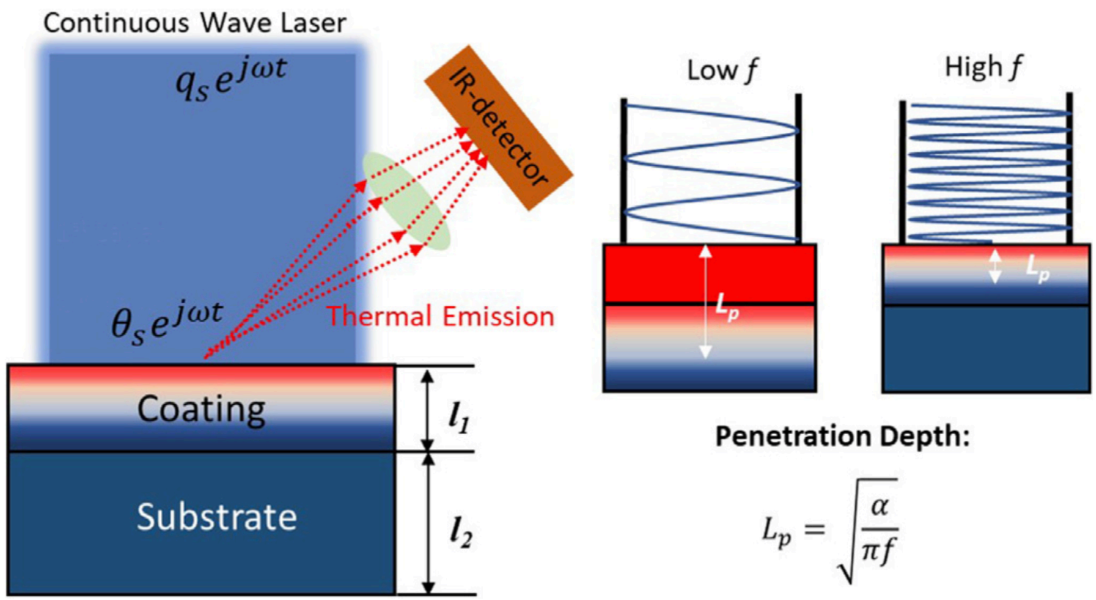
Objectives

- Develop and apply Modulation Photothermal Radiometry (MPR) as an ***accurate and non-contact*** method to characterize high-temperature thermophysical properties of HTFs.
- Characterize and understand the heat transfer mechanism of HTFs at the flowing state.
- *In-situ* diagnostics of HTFs plants and of their corrosion behaviors.

Impacts to Gen3 CSP

- Provide a convenient tool to measure thermophysical properties of emerging solids (e.g., particles) and fluids (e.g., molten salts) under both ***stationary*** and ***moving*** states for Gen3 CSP systems at high temperature
- Transfer the MPR technique a diagnostic tool for other laboratories and *in-situ* tests in other Gen3 projects.

Working Principles of MPR



MPR measurement setup
(a) Schematics of MPR system
(b) Principle of MPR measurement.

<u>At low modulated frequency:</u>

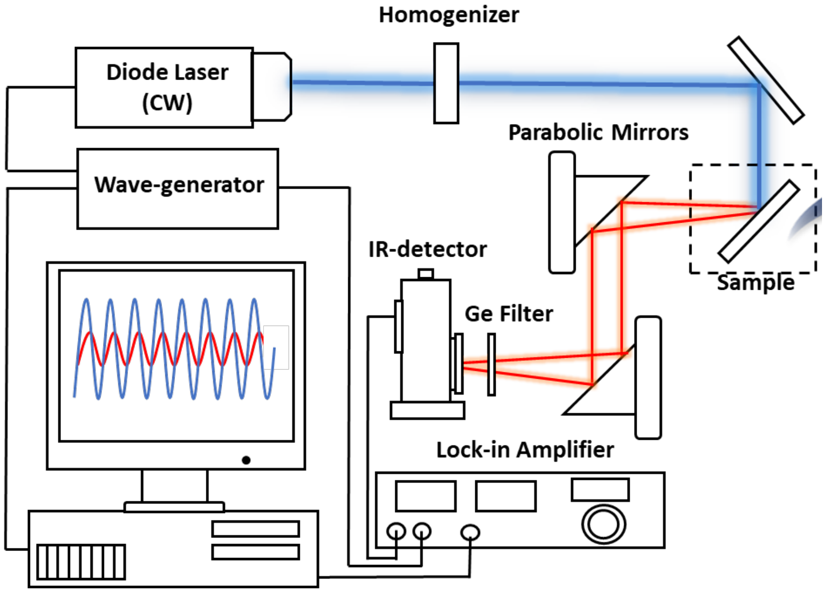
$$\theta_s = q_s\left(\frac{1}{e_m\sqrt{\omega}} + R_{sc}\right)$$

q_s: heat flux
e_m: Thermal effusivity of medium ($e = \sqrt{k\rho c_p}$)
ω: angular frequency
R_{sc}: Thermal resistance of coating and shell.

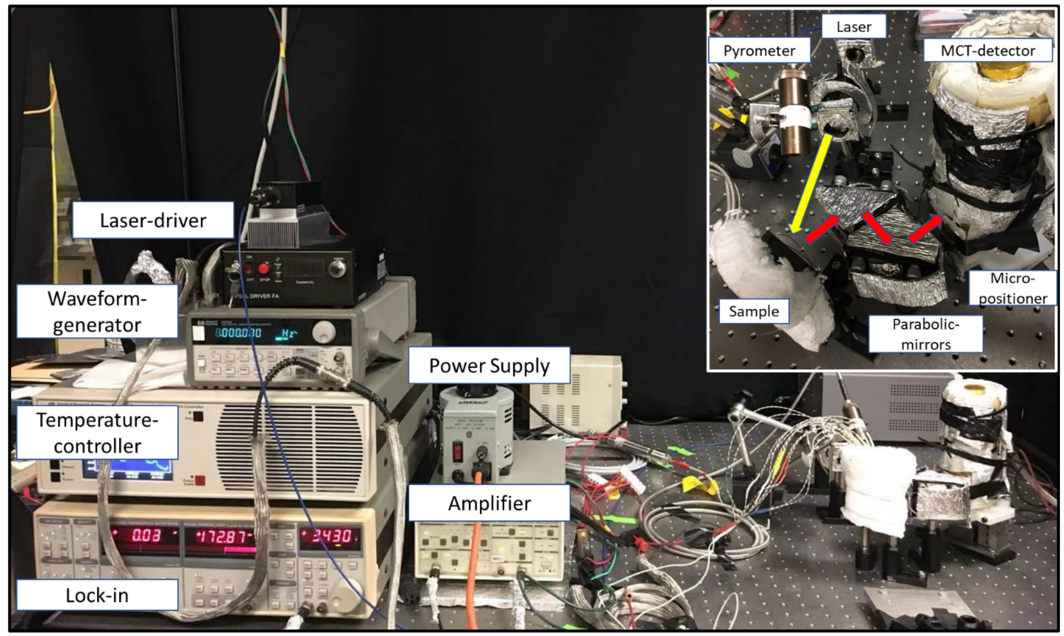
- Thermal effusivity of medium e_m is obtained at low frequency; Thermal conductivity of shell and coating is obtained from the medium and high frequency ranges, respectively.
- Thermal conductivity of medium is obtained with literature or measured values of density ρ and specific heat c_p

MRP Setup

a



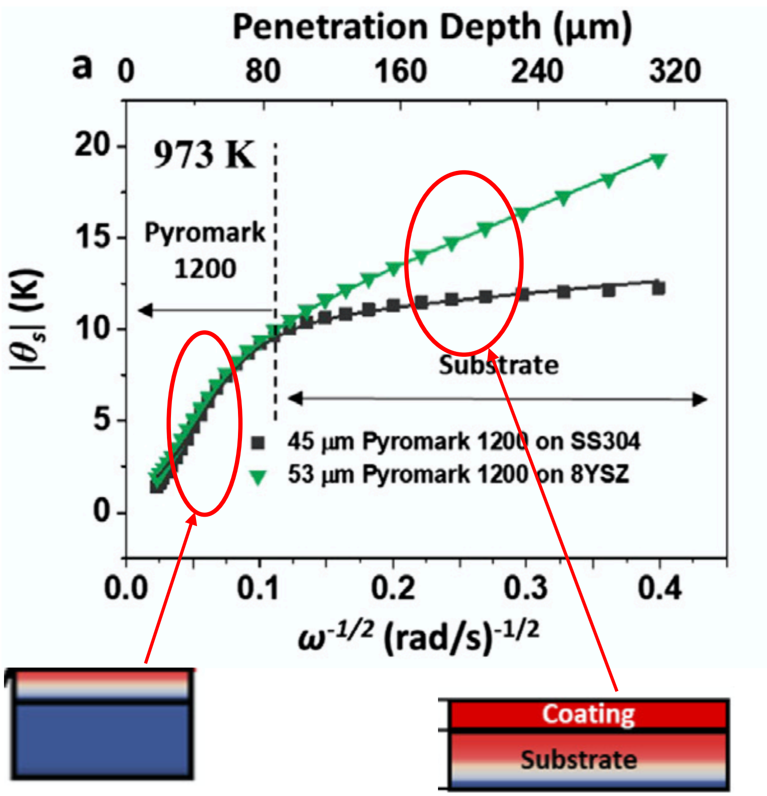
Homogenizer
Diode Laser (CW)
Parabolic Mirrors
Wave-generator
IR-detector
Sample
Ge Filter
Lock-in Amplifier

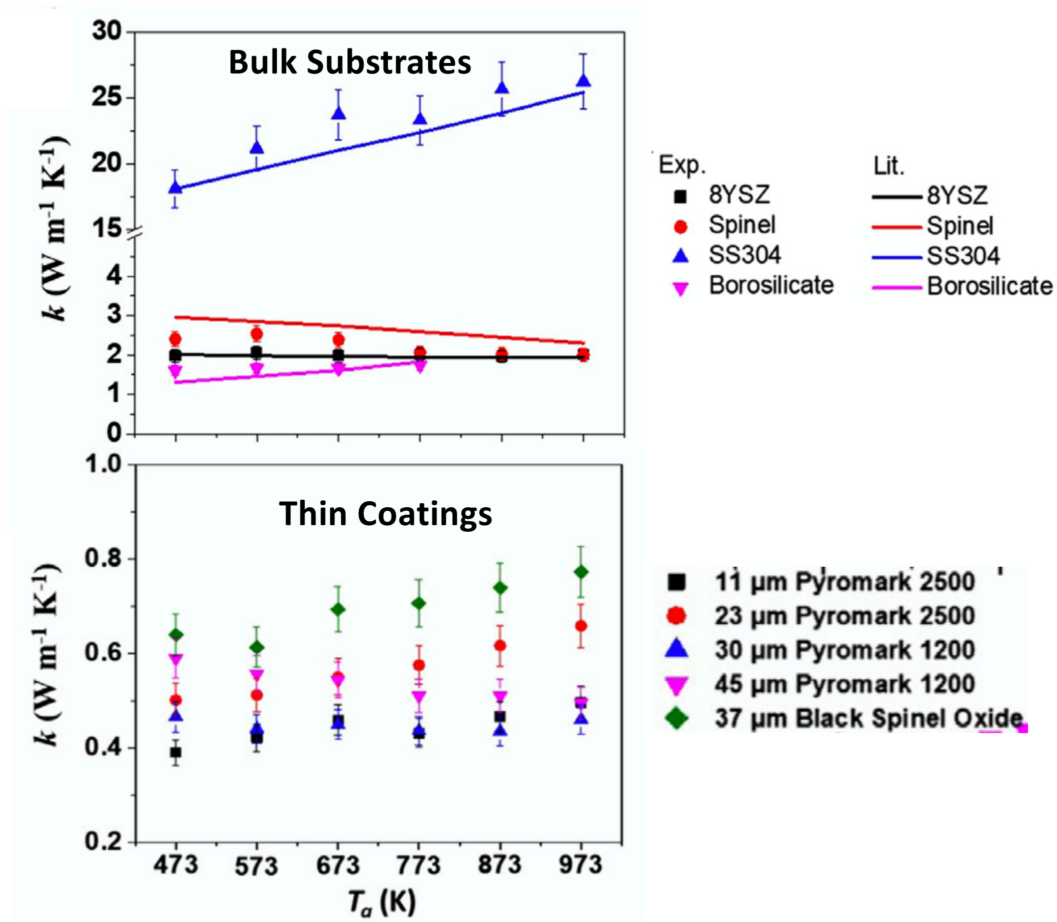


Pyrometer
Laser
MCT-detector
Laser-driver
Waveform-generator
Micro-positioner
Sample
Parabolic-mirrors
Power Supply
Temperature-controller
Amplifier
Lock-in

Measurement on Substrates and Coatings

$$\theta_s = q_s\left(\frac{1}{e_m\sqrt{\omega}} + R_{sc}\right)$$

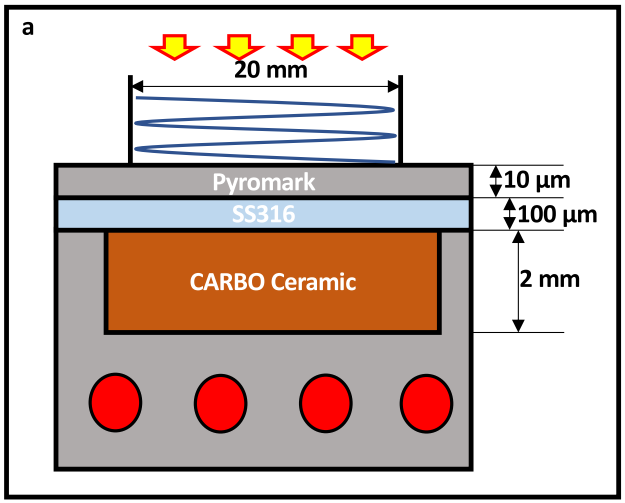




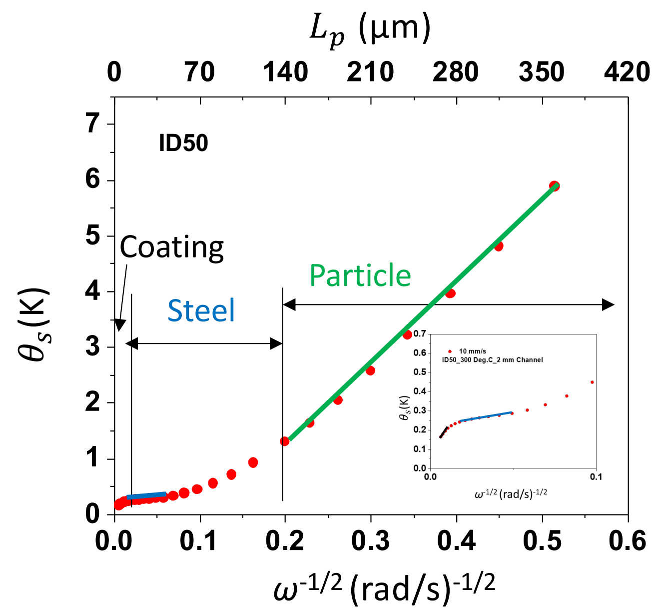
Zeng *et al*. "Measurement of High-temperature Thermophysical Properties of Bulk and Coatings Using Modulated Photothermal Radiometry." ***Intl. J Heat Mass Transf.*** 170 (2021): 120989.

MPR Measurements on Stationary Particles

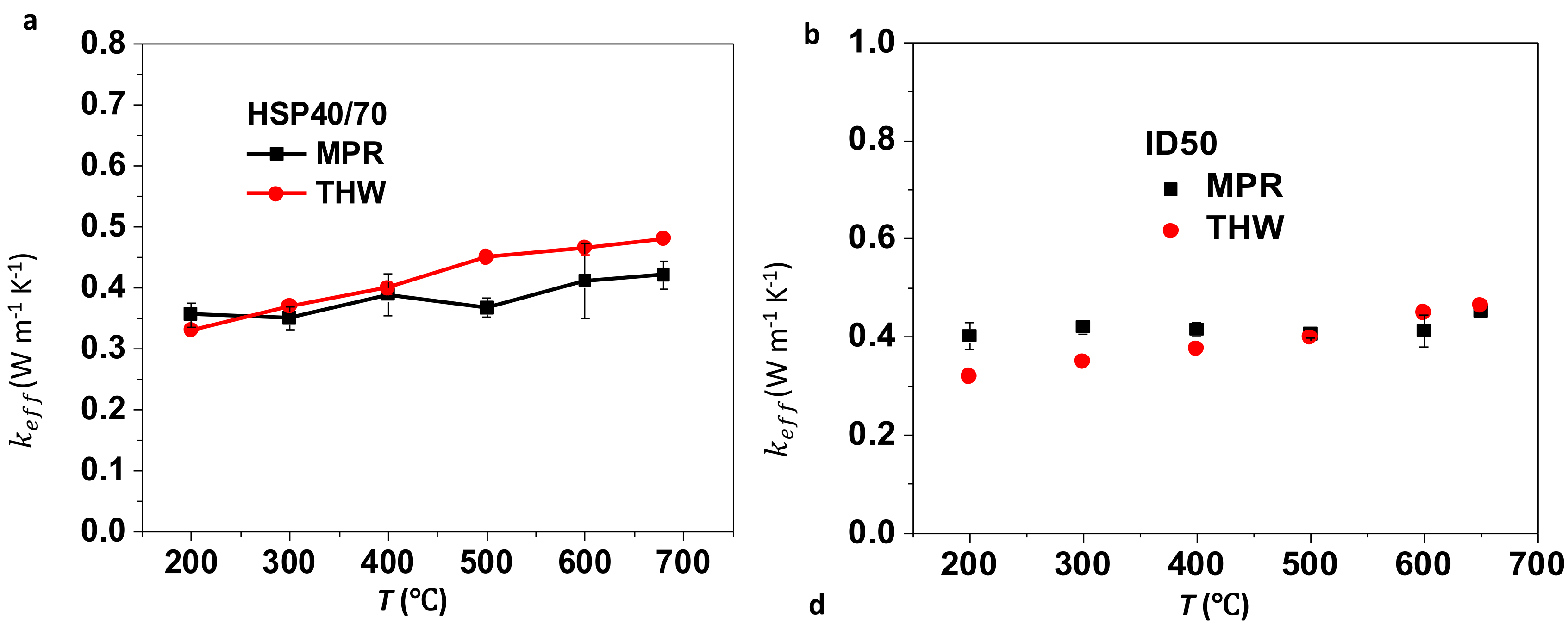
Configuration for ***stationary*** particle measurement



Typical thermal response of a three-layer system (coating-steel-particle)



MPR Measurements on Stationary Particles



Effective thermal conductivity (k_{eff}) of CARBO **HSP 40/70** (dia. ~ 430 µm) and **ID50** (~ 275 µm) agree well with that measured by the transient hot-wire (THW) method [1]

[1] Chung et al., "Measurement and Analysis of Thermal Conductivity of Ceramic Particle Beds for Solar Thermal Energy Storage", ***Sol. Energy Mater Sol. Cells.*** 230, 111271 (2021),

MPR Measurements on Moving Particles

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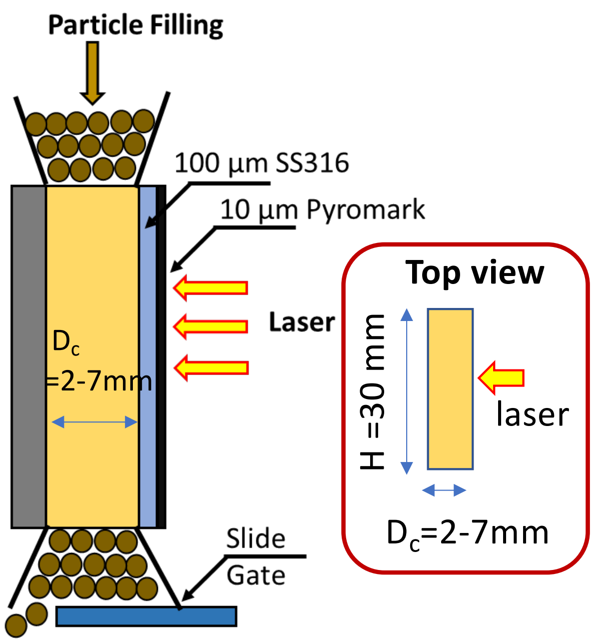
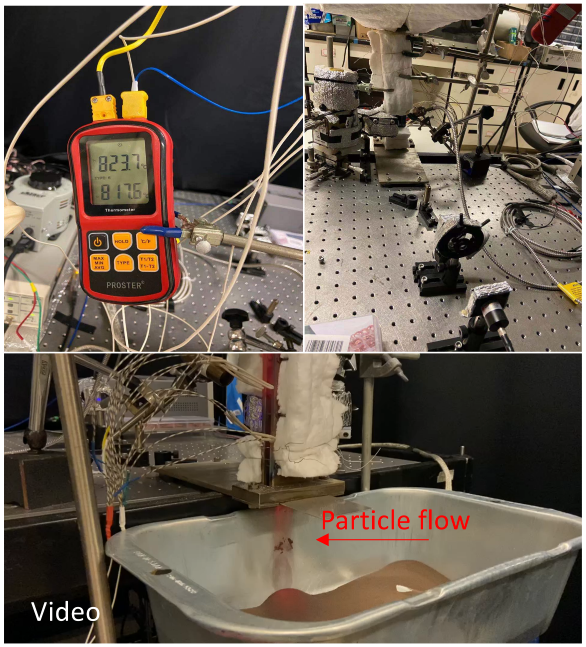
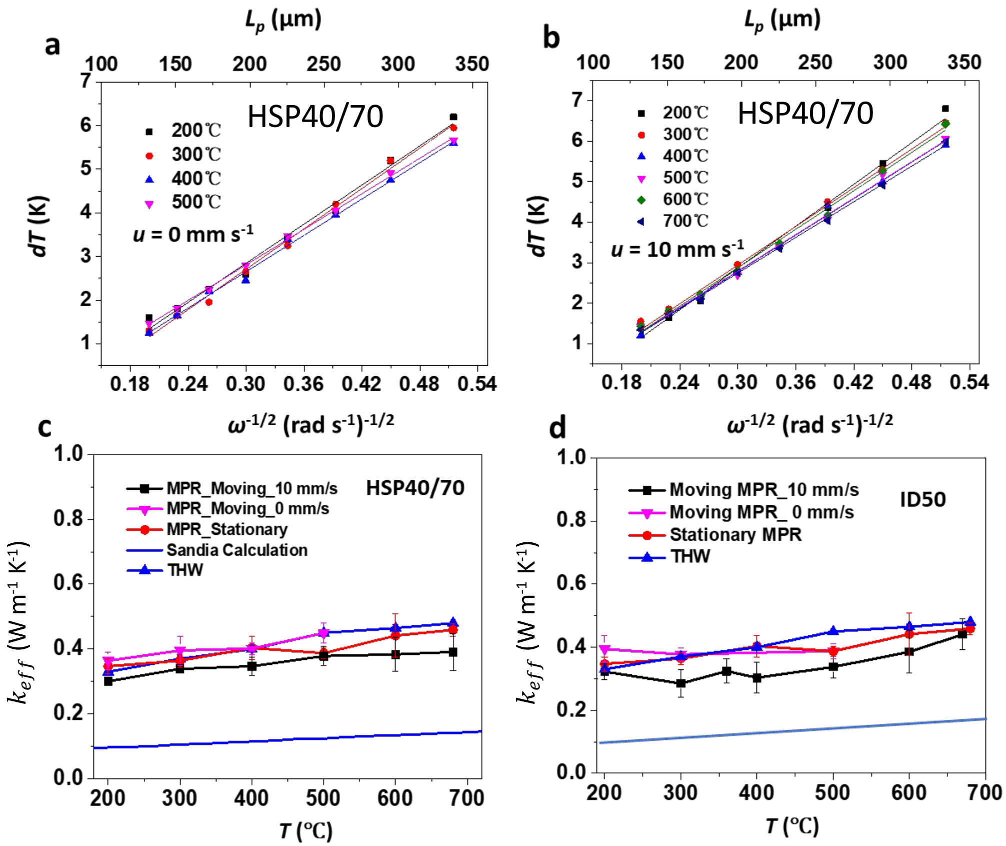
MPR setup for high-temperature Moving Particle Measurement





- Multiple High-temperature heaters are used to achieve the target temperature (~ 700℃).
- High-capacity reservoir (> 30 Gallon) is used for high flowing velocity tests (~ 30 mm s^{-1} for 4 mm channel and 60 mm s^{-1} for 2 mm channel).

k_{eff} of Moving Carbo Particles



Thermal response of HSP 40/70 in the *moving* particle at

(a) 0 mm s^{-1} and

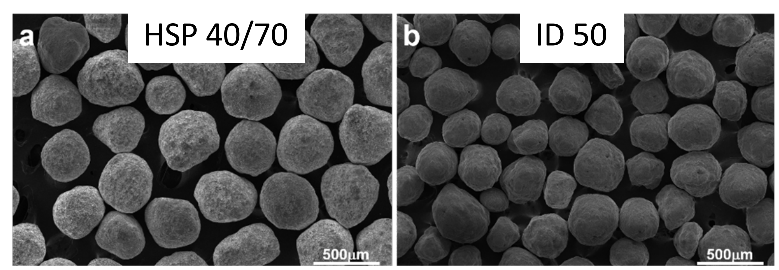
(b) **(b)** 10 mm s^{-1};

k_{eff} of moving particles for

(c) HSP4070 and

(d) ID50 (channel depth: 4 mm)

- k_{eff} at 0 mm s^{-1} is close to that measured by THW and stationary MPR setup
- k_{eff} at 10 mm s^{-1} is **15-20% lower**



k_{eff} vs. velocity of Moving Carbo Particles

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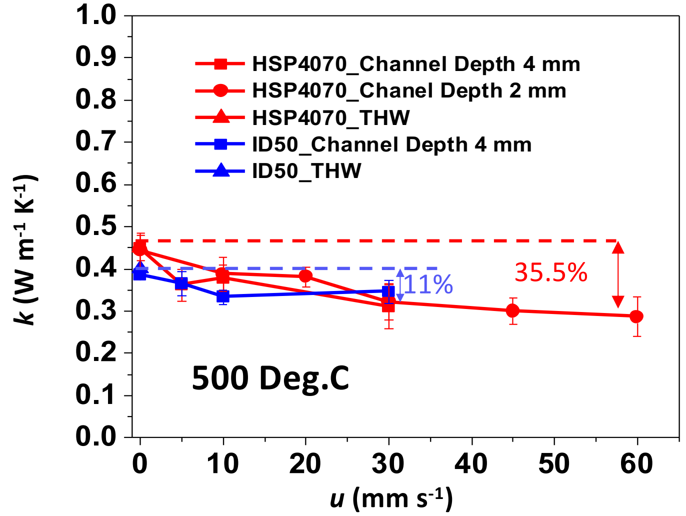
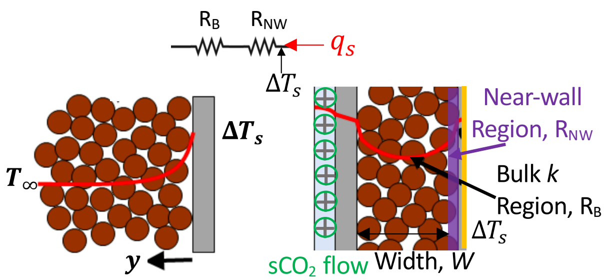
Comparison between ID 50 (~275 µm) and HSP 40/70 (~ 430 µm)

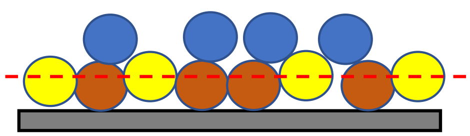


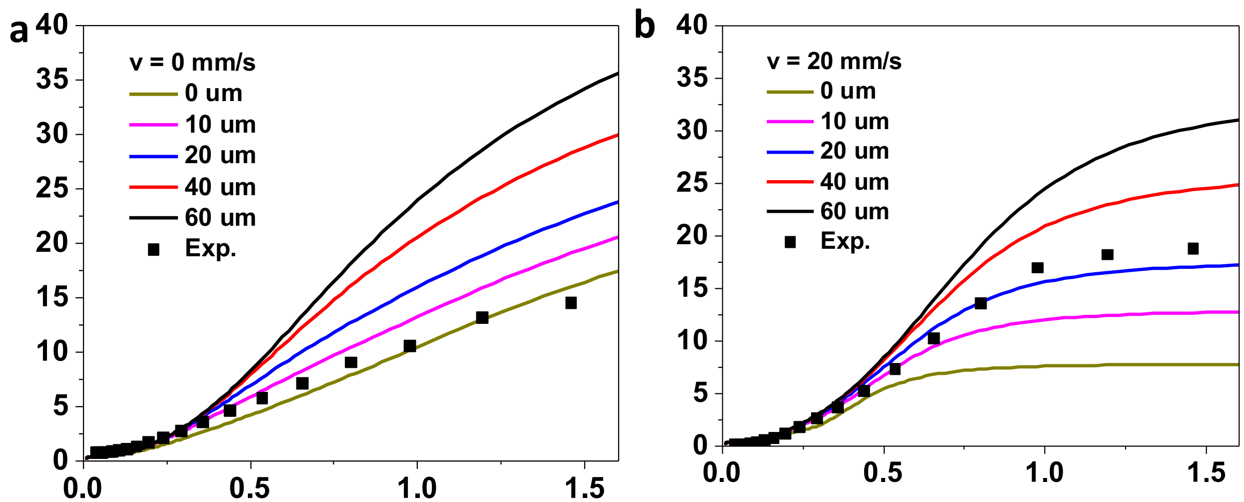
- Thermal conductivity decreases more for the HSP 40/70, possibly due to the large particle size.
- The effect of channel size is not significant in the tested velocity range for HSP 40/70.

Near-wall and Bulk Resistance of Moving Particles



(a)Semi-infinite domain (b)Bounded domain



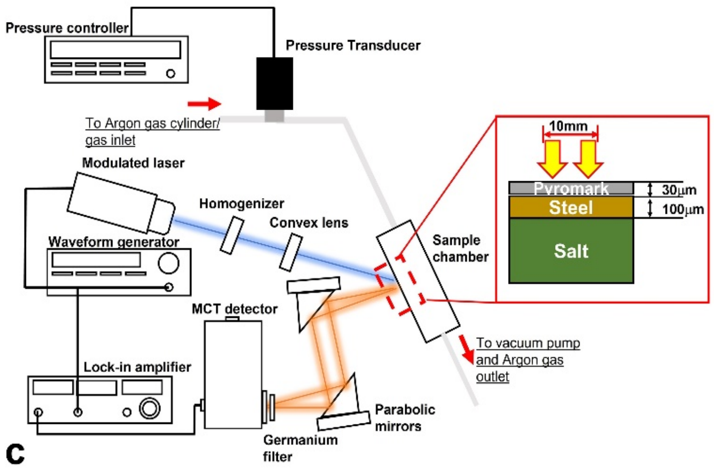


Fitting of Moving ID-50 with different airgap thickness at **(a)** 0 mm s^{-1} and **(b)** 20 mm s^{-1} flowing velocity

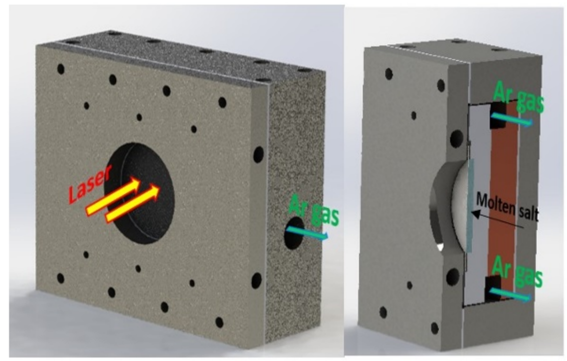
- The finite-element model (COMSOL model, solid lines) captures the trend of the thermal response well
- To fit the experimental results, both the velocity and the airgap thickness effects should be included. Fitting results show D_{air} = 20-40 µm for ID50 (D_p~275 µm) at 20 mm s^{-1}.
- More measurements and analysis are being conducted to quantify both the near-wall air-gap resistance and bulk thermal conductivity of particles under various operation conditions.

MPR Measurement of Stagnant Fluids

a

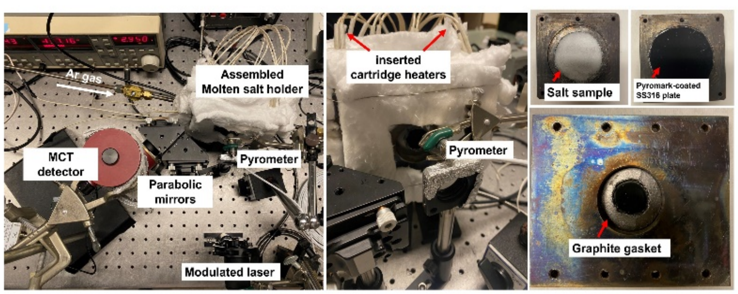


b

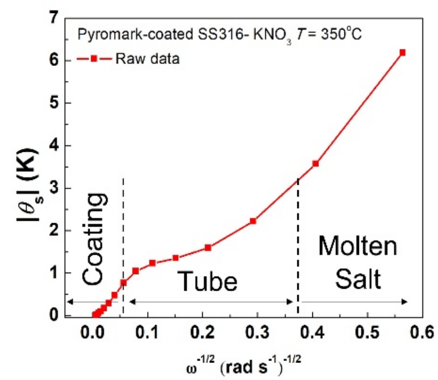


$$\theta_s = q_s\left(\frac{1}{e_m\sqrt{\omega}} + R_{sc}\right)$$

c



d



(a) Schematic of the MPR setup;

(b) Schematic of the MPR molten salt holder

(c) Photographs of the MPR setup;

(d) Plot of $|\theta_s|$ versus $\omega^{-1/2}$ of a typical MPR measurement of stagnant molten salts

MPR Measurement of Stagnant Fluid

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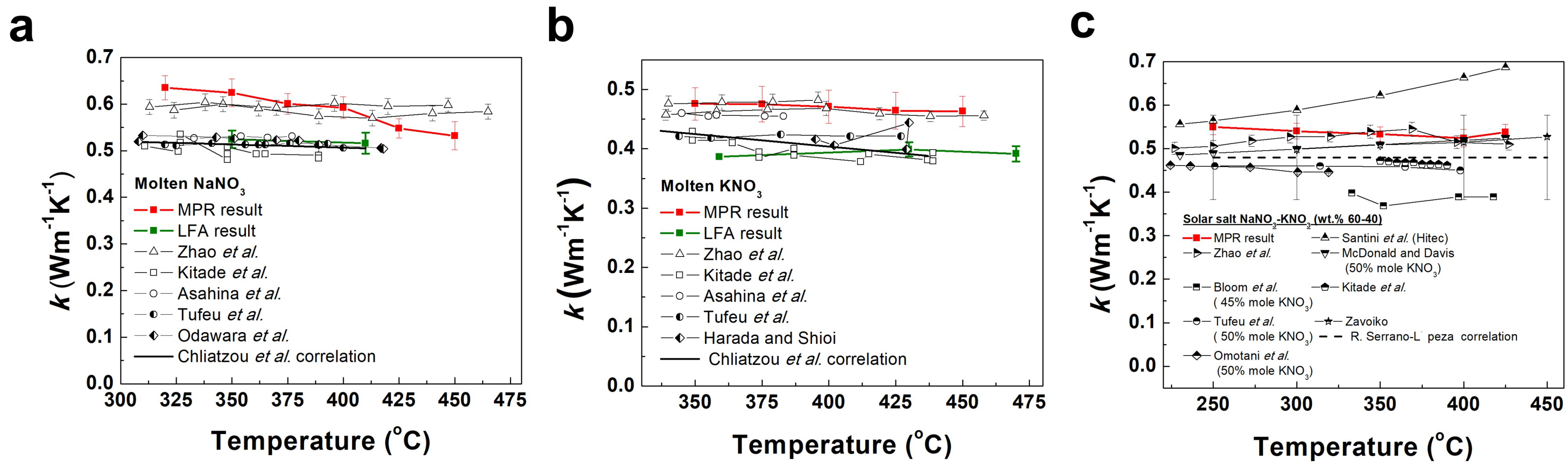
Molten Nitrate Salts



The measured k of the molten $NaNO_3$, KNO_3 and solar salt mixture, $NaNO_3$-KNO_3 (wt.% 60-40) are higher than the LFA results and most of the literature values but agree well with the results from a frequency-domain THW method by Zhao *et al.* (UCSD).

[1] Zhao, Andrew Z., Matthew C. Wingert, and Javier E. Garay. "Frequency-Domain Hot-Wire Measurements of Molten Nitrate Salt Thermal Conductivity." *Journal of Chemical & Engineering Data* (2020).
[2] Chliatzou, Ch D., et al. "Reference correlations for the thermal conductivity of 13 inorganic molten salts." *Journal of physical and chemical reference data* 47.3 (2018): 033104.
[3] Tufeu, R., et al. "Experimental determination of the thermal conductivity of molten pure salts and salt mixtures." *International journal of thermophysics* 6.4 (1985): 315-330.
[4] Odawara, Osamu, Isao Okada, and Kazutaka Kawamura. "Measurement of the thermal diffusivity of HTS (a mixture of molten sodium nitrate-potassium nitrate-sodium nitrite; 7-44-49 mole%) by optical interferometry." *Journal of Chemical and Engineering Data* 22.2 (1977): 222-225.
[5] Bloom, Ho, A. Doroszkowski, and S. B. Tricklebank. "Molten salt mixtures. IX. The thermal conductivities of molten nitrate systems." *Australian Journal of Chemistry* 18.8 (1965): 1171-1176.
[6] Tufeu, R., et al. "Experimental determination of the thermal conductivity of molten pure salts and salt mixtures." *International journal of thermophysics* 6.4 (1985): 315-330.
[7] Omotani, T., Yuji Nagasaka, and A. Nagashima. "Measurement of the thermal conductivity of KNO 3-NaNO 3 mixtures using a transient hot-wire method with a liquid metal in a capillary probe." *International Journal of Thermophysics* 3.1 (1982): 17-26.
[8] Santini, R., et al. "Measurement of thermal conductivity of molten salts in the range 100-500/sup 0/C." *Int. J. Heat Mass Transfer;(United Kingdom)* 27.4 (1984).
[9] McDonald, John, and Howard Ted Davis. "Thermal conductivity of binary mixtures of alkali nitrates." *The Journal of Physical Chemistry* 74.4 (1970): 725-730.
[10] Pfleger, Nicole, et al. "Thermal energy storage–overview and specific insight into nitrate salts for sensible and latent heat storage." *Beilstein journal of nanotechnology* 6.1 (2015): 1487-1497.
[11] Serrano-López, Roberto, Jordi Fradera, and Santiago Cuesta-López. "Molten salts database for energy applications." *Chemical Engineering and Processing: Process Intensification* 73 (2013): 87-102.

MPR Measurement of Stagnant Fluid

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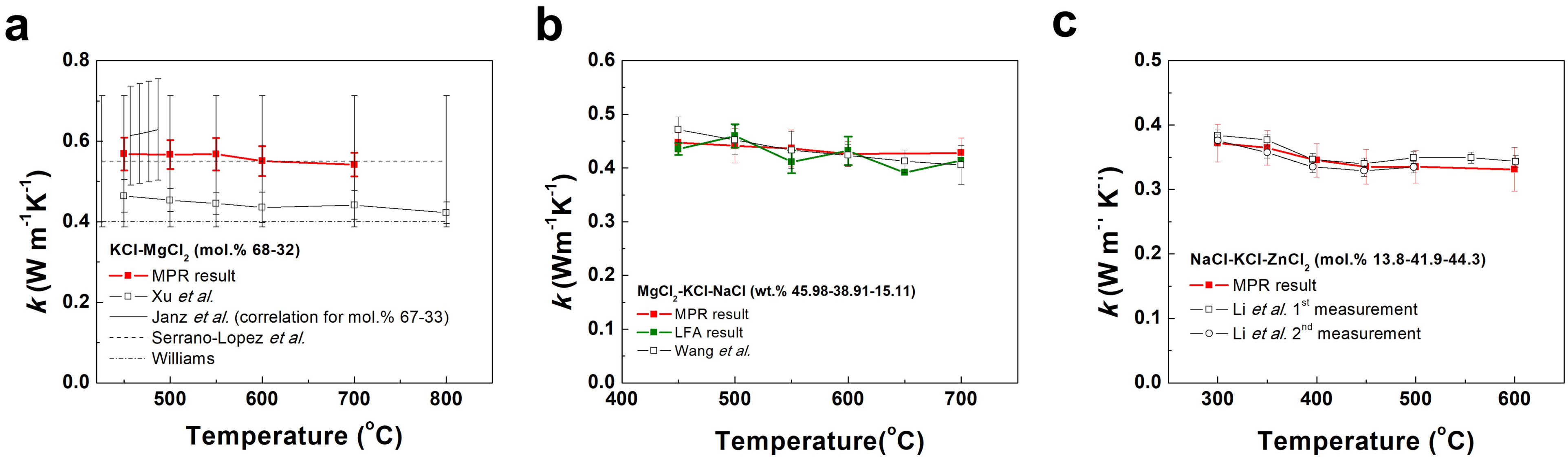
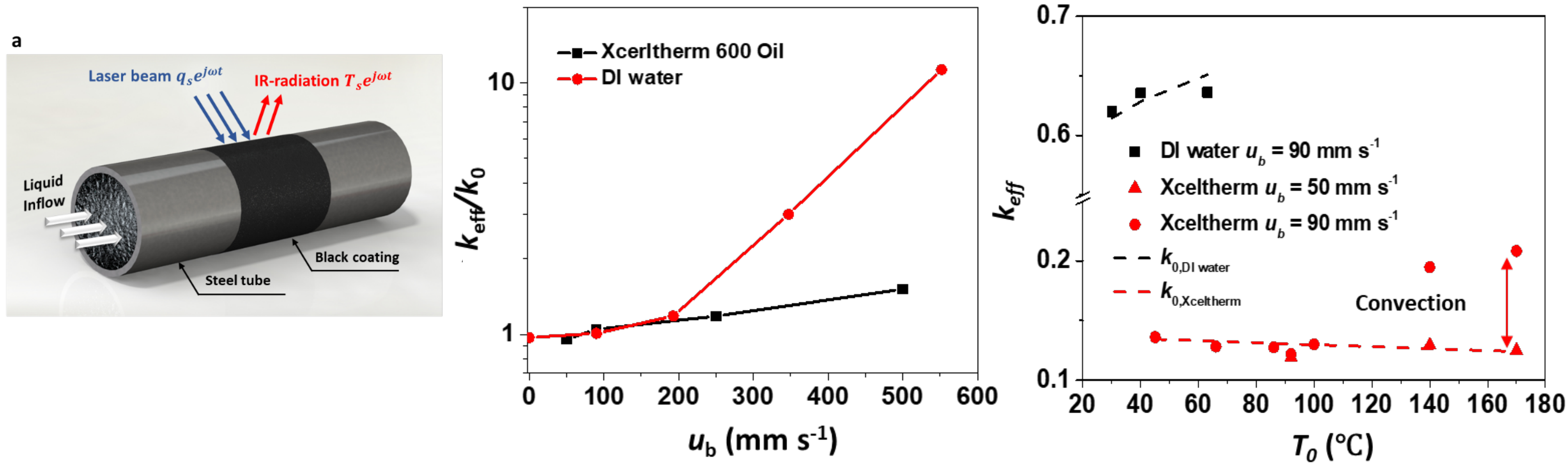
Molten Chloride Salts



The measured *k* of the molten $KCl\text{-}MgCl_2$, $MgCl_2\text{-}KCl\text{-}NaCl$, and $NaCl_2\text{-}KCl\text{-}ZnCl_2$ are consistent with the reported values and the reported correlations

[1] X. Xu, X. Wang, P. Li, Y. Li, Q. Hao, B. Xiao, H. Elsentriecy, D. Gervasio, Experimental test of properties of KCl–MgCl2 eutectic molten salt for heat transfer and thermal storage fluid in concentrated solar power systems, Journal of Solar Energy Engineering, 140(5) (2018).
[2] M.S. Sohal, M.A. Ebner, P. Sabharwall, P. Sharpe, Engineering database of liquid salt thermophysical and thermochemical properties, Idaho National Laboratory (INL), 2010.
[3] R. Serrano-López, J. Fradera, S. Cuesta-López, Molten salts database for energy applications, Chemical Engineering and Processing: Process Intensification, 73 (2013) 87-102.
[4] D. Williams, Assessment of candidate molten salt coolants for the NGNP/NHI heat-transfer loop, Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 2006.
[5] X. Wang, J.D. Rincon, P. Li, Y. Zhao, J. Vidal, Thermophysical Properties Experimentally Tested for NaCl-KCl-MgCl2 Eutectic Molten Salt as a Next-Generation High-Temperature Heat Transfer Fluids in Concentrated Solar Power Systems, Journal of Solar Energy Engineering, 143(4) (2021) 041005.
[6] P. Li, E. Molina, K. Wang, X. Xu, G. Dehghani, A. Kohli, Q. Hao, M.H. Kassaee, S.M. Jeter, A.S. Teja, Thermal and transport properties of NaCl–KCl–ZnCl2 eutectic salts for new generation high-temperature heat-transfer fluids, Journal of Solar Energy Engineering, 138(5) (2016).

MPR Measurement of Flowing Fluid



The intrinsic k_o of the flowing fluids can be obtained at a **low flow velocity** , where the forced convection effect is small.

Zeng et al., *In-situ Thermal Transport Measurement of Flowing Fluid using Modulated Photothermal Radiometry*. **Intl. J. Heat Mass Transf.** (in press, 2021)

Critical Conditions to Obtain k_o of Flowing Fluids

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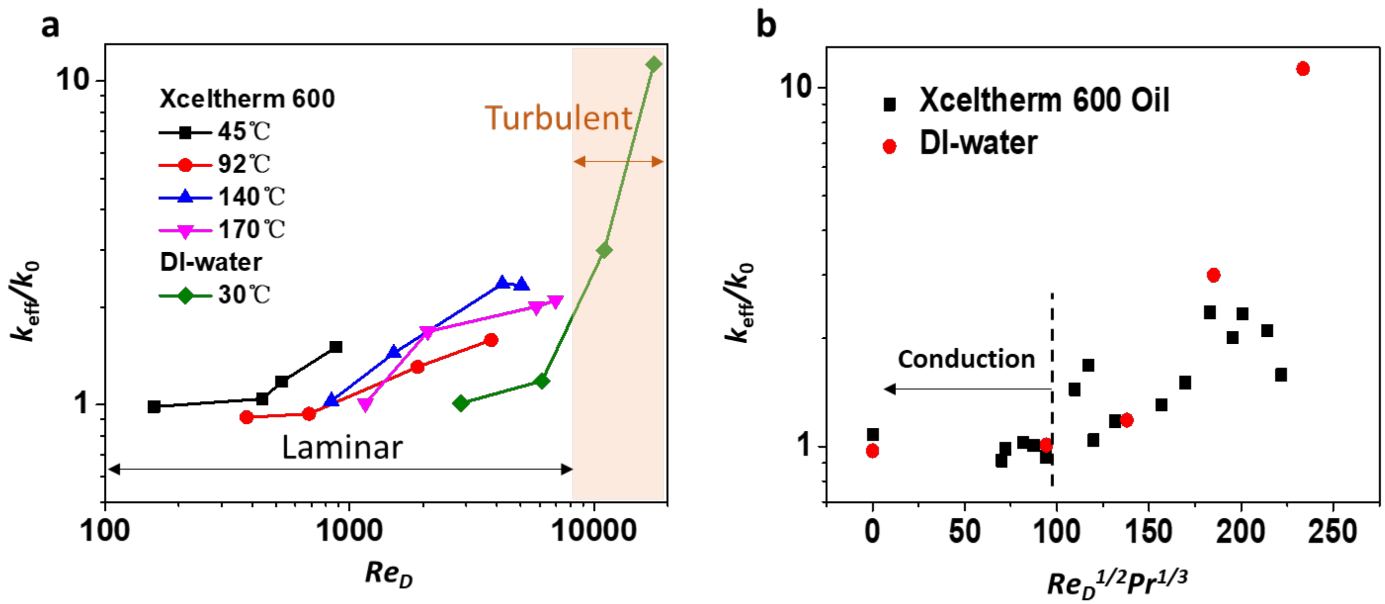
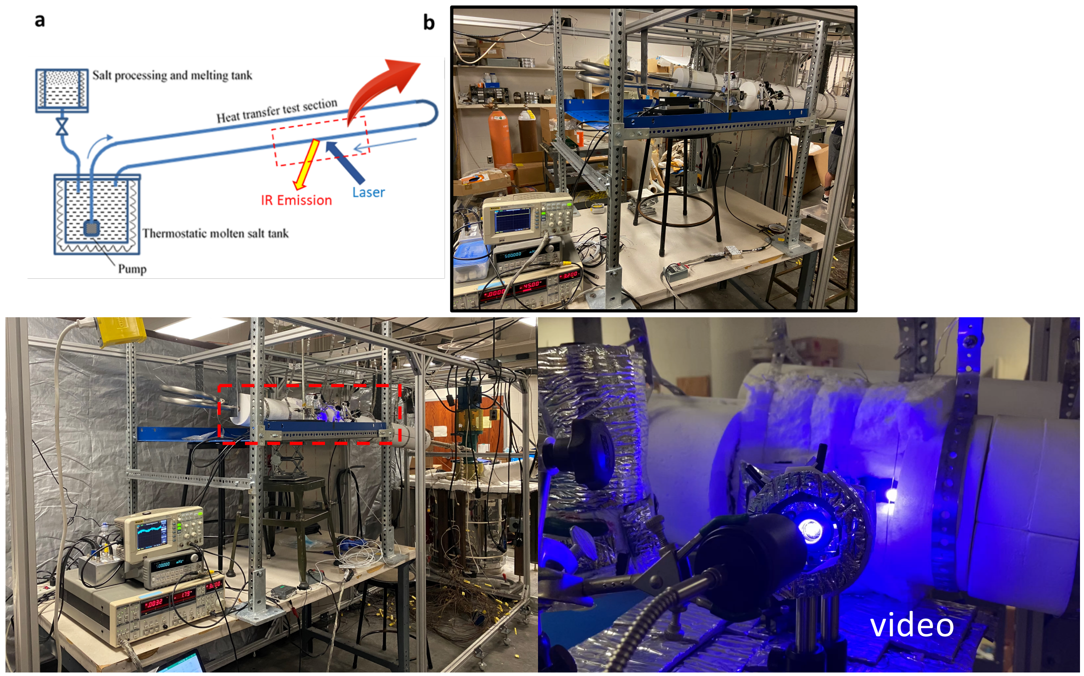


To obtain the intrinsic thermal conductivity (k_o) of flowing fluid, $Re_D^{1/2}Pr^{1/3}$ should be less than ~100, which agrees with the analysis (thermal penetration depth shorter than both the momentum and thermal boundary layers).

Zeng et al., *,In-situ Thermal Transport Measurement of Flowing Fluid using Modulated Photothermal Radiometry*. **Intl. J. Heat Mass Transf.** (in press, 2021)

MPR on Flowing Molten Salt (in progress)

We have integrated the MPR section with the thin wall-thickness (100 µm) and set up the MPR tools for the molten salt loop at U. Arizona . The MPR system is set up and the loop is being prepared for flowing molten salt test soon



(a) Schematics of molten salt loop with MPR setup;
(b), **(c) and (d)** Photo and video of molten salt loop in test.

Summary of the MPR Measurement

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For Particles:

- Measured k_{eff} of stationary particles, which agrees well with that by THW.
- Measured k_{eff} of moving particles with temperature up to 700°C and velocity up to 60 mm s^{-1}. k_{eff} decreases by 10-40% depending on the particle morphology and velocity.
- MPR shows the potential to differentiate the near-wall thermal resistance and bulk thermal conductivity of moving particles in a particle heat exchanger.

For Molten salts:

- Measured k of a variety of nitrate and chloride salts using MPR up to 700°C.
- Systematic measurement and analysis of flowing fluid using MPR and identify the critical condition to obtain intrinsic thermal conductivity of flowing fluid.
- MPR tool integration with molten salt loop in U. Arizona and continuing work on the *In-operando* flowing molten salts measurement.

Discussions on Plans and Challenges for Future *In-operando* Measurements

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Plan

For Moving Particles:

- Systematic measurement on CARBO ceramic particles and silica sands with a wide range operation conditions, i.e., particle sizes, channel sizes and velocity at high temperature
- Analysis of near-wall thermal resistance and bulk thermal conductivity of moving particles.

For Molten salts:

- Understand the difference between conventional thermal conductivity measurement method (i.e., steady-state method, transient hot wire, and LFA), compared with the MPR technique.
- Measure the thermal conductivity flowing molten salts and study the corrosion effect.

Challenges

For Moving Particles:

- Thermal noise and 2D heat spreading issue at the low frequency measurement (down to 0.1 Hz for the sensitivity on R_{NR}).
- Mechanical strength of the thin MPR section when integrated with particle heat exchangers.

For Molten salts:

- Corrosion and thermal stress on the thin MPR section in the flowing molten salt loop.