TFAWS Passive Thermal Paper Session

Characterization of thermal conductivity and thermal transport in lithium-ion battery

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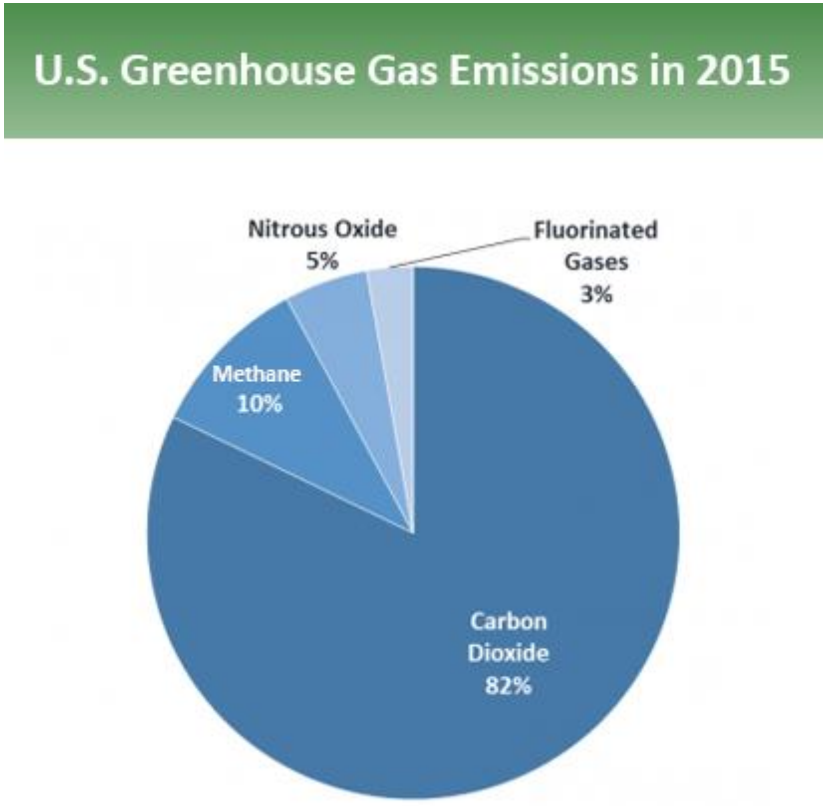
Thermal & Fluids Analysis Workshop
TFAWS 2018
August 20-24, 2018
NASA Johnson Space Center
Houston, TX

Motivation

- Global warming → Paris Agreement, 2015 → Reduce greenhouse gases
- How to go "green"?
  - Electric vehicles
  - Solar + wind energy and electrochemical energy storage
- Lithium-ion battery (LIB) most promising
  - Safety of LIBs is a major issue



U.S. Environmental Protection Agency (2017). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015*.

Thermal Runaway in LIBs

Samsung Galaxy Note 7

http://www.techionix.com/articles/why-are-samsungs-galaxy-note-7-phones-exploding/

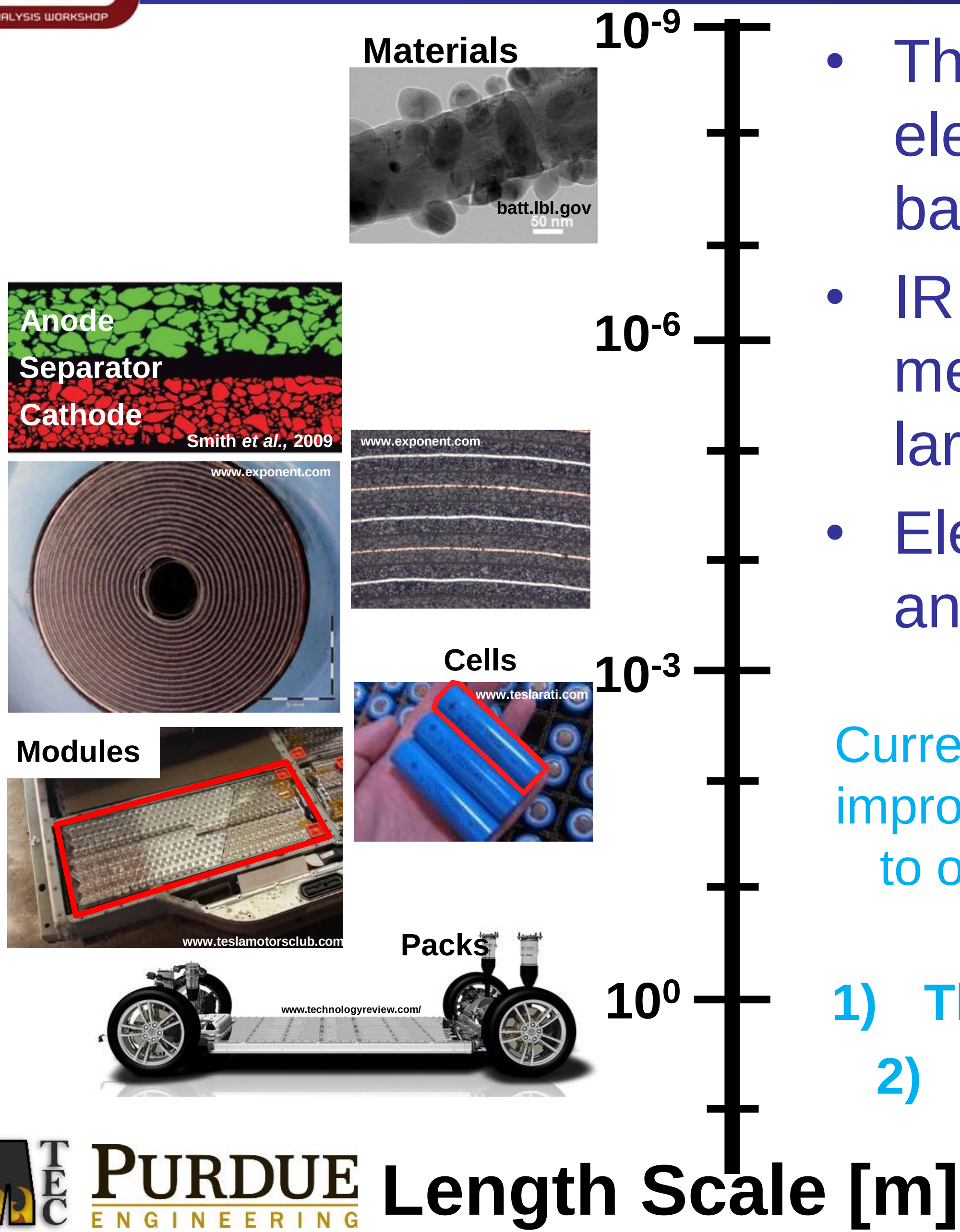
Boeing 787 battery pack

http://www.ntsb.gov/investigations/2013/boeing_787/photos/1-7-12_JAL787_APU_Battery_s.jpg

Tesla Model S

https://greentransportation.info/ev-ownership/safer/tesla-model-s-2013.html

Battery Thermal Characterization

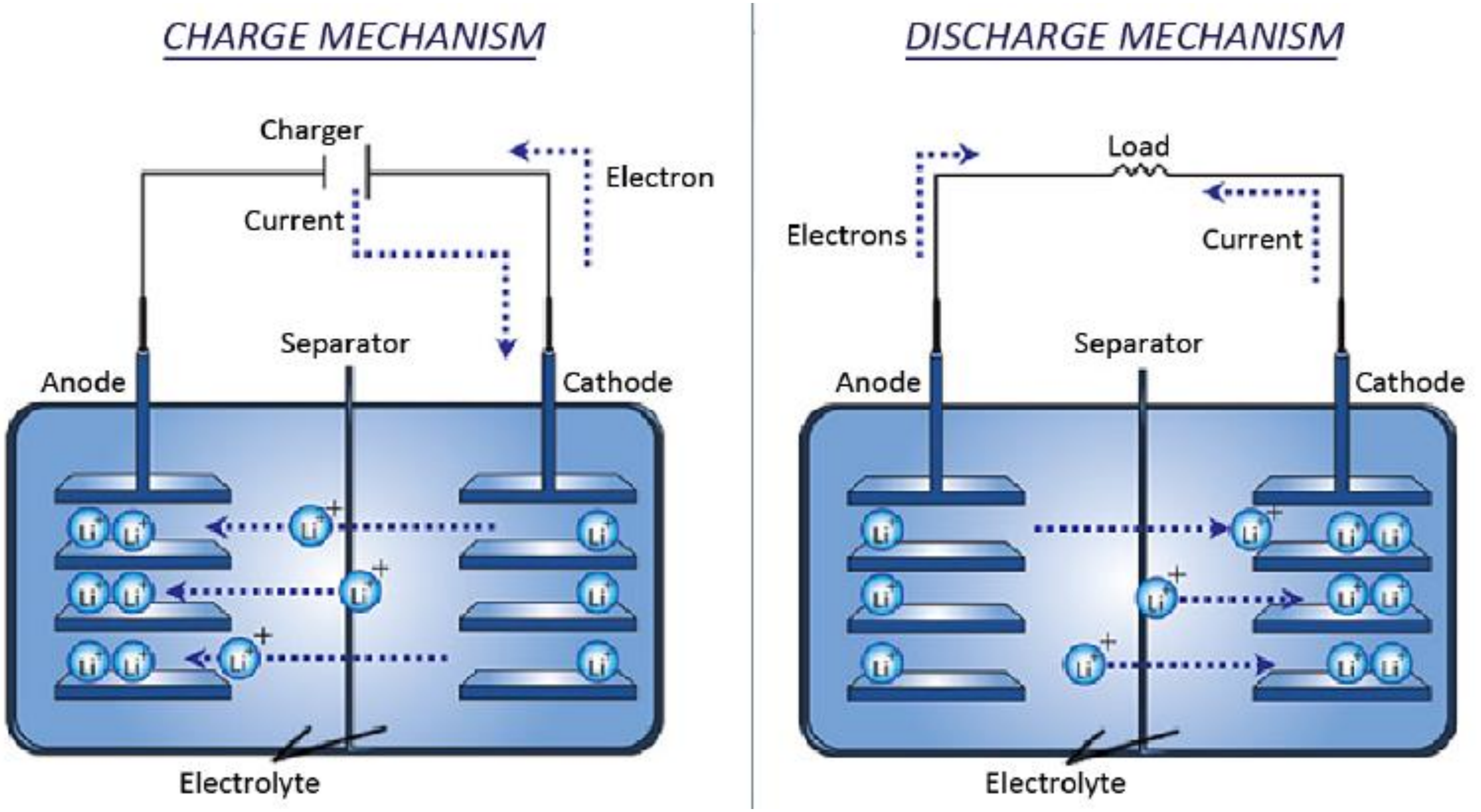


- Thermocouples can short the electrodes and disturb the battery operation
- IR imaging is a surface measurement and there can be large gradients within the cells
- Electrolyte can degrade in air and cause toxic fumes

Currently, we are working on methods to improve our thermal imaging capabilities to overcome these challenges in two types of experiments:

1) **Thermal Property characterization**
2) **In Situ Thermal Measurements**

Working Principle of LIB



Noshin Omar, Mohamed Daowd, Peter van den Bossche, Omar Hegazy, Jelle Smekens, Thierry Coosemans and Joeri van Mierlo F, "Rechargeable Energy Storage Systems for Plug-in Hybrid Electric Vehicles—Assessment of Electrical Characteristics" Energies 2012, 5, 2952-2988; doi:10.3390/en508295

Prior thermal property measurements

Cell geometry	Cell specific heat capacity [$J\ kg^{-1}K^{-1}$]			
	LFP	LCO	LMO	NMC
Cylindrical	1700 [3]	1300 [4]	837.4 [8]	---
Prismatic	---	850 [7]	---	1000 [7]
Pouch	1400 [5]	---	---	1090 [7]

Electrolyte content	Material specific heat capacity [$J\ kg^{-1}K^{-1}$]				
	LFP	LCO	LMO	NMC	Graphite
Dry	700 [9]	601 [4]	830 [10]	775 [6,7]	632 [1,11]
Wet	1260* [2]	1269 [10]	1321* [12]	---	1437 [4]

- Cell-level specific heat capacity measurements exist for a few electrode material combinations
- At the electrode level, more experiments need to be done for a better estimate of electrode specific heat capacity
- Electrolyte increases specific heat capacity as the electrolyte fills in voids

[1] R. Spotnitz and J. Franklin, "Abuse behavior of high-power , lithium-ion cells," vol. 113, 2003, pp. 81–100.
[2] 3Y. Lai, S. Du, L. Ai, L. Ai, and Y. Cheng, "Insight into heat generation of lithium ion batteries based on the electrochemical-thermal model at high discharge rates," International Journal of Hydrogen Energy, vol. 40, 2015, pp. 13039–13049, DOI:10.1016/j.ijhydene.2015.07.079.
[3] K. Shah, V. Vishwakarma, and A. Jain, "Measurement of Multiscale Thermal Transport Phenomena in Li-Ion Cells: A Review," *Journal of Electrochemical Energy Conversion and Storage*, vol. 13, 2016, p. 030801, DOI:10.1115/1.4034413.
[4] S.J. Drake, D.A. Wetz, J.K. Ostanek, S.P. Miller, J.M. Heinzel, and A. Jain, "Measurement of anisotropic thermophysical properties of cylindrical Li-ion cells," Journal of Power Sources, vol. 252, 2014, pp. 298–304, DOI:10.1016/j.jpowsour.2013.11.107.
[5] H. Maleki, S. Al Hallaj, J.R. Selman, R.B. Dinwiddie, and H. Wang, "Thermal Properties of Lithium-Ion Battery and Components," Journal of The Electrochemical Society, vol. 146, 1999, p. 947, DOI:10.1149/1.1391704.
[6] F. Richter, S. Kjelstrup, P.J.S. Vie, and O.S. Burheim, "Thermal conductivity and internal temperature profiles of Li-ion secondary batteries," Journal of Power Sources, vol. 359, 2017, pp. 592–600, DOI:10.1016/j.jpowsour.2017.05.045.
[7]\J. Nanda, S.K. Martha, W.D. Porter, H. Wang, N.J. Dudney, M.D. Radin, and D.J. Siegel, "Thermophysical properties of LiFePO4 cathodes with carbonized pitch coatings and organic binders: Experiments and first-principles modeling," Journal of Power Sources, vol. 251, Apr. 2014, pp. 8–13, DOI:10.1016/j.jpowsour.2013.11.022.
[8] P. Gotcu and H.J. Seifert, "Thermophysical properties of LiCoO 2 –LiMn 2 O 4 blended electrode materials for Li-ion batteries," Phys. Chem. Chem. Phys., vol. 18, 2016, pp. 10550–10562, DOI:10.1039/C6CP00887A.
[9] G. Guo, B. Long, B. Cheng, S. Zhou, P. Xu, and B. Cao, "Three-dimensional thermal finite element modeling of lithium-ion battery in thermal abuse application," Journal of Power Sources, vol. 195, Apr. 2010, pp. 2393–2398, DOI:10.1016/j.jpowsour.2009.10.090.
[10] C. Lin, K. Chen, F. Sun, P. Tang, and H. Zhao, "Research on thermo-physical properties identification and thermal analysis of EV Li-ion battery," 5th IEEE Vehicle Power and Propulsion Conference, VPPC '09, 2009, pp. 1643–1648, DOI:10.1109/VPPC.2009.5289653.
[11]B. Koo, P. Goli, A. V. Sumant, P.C. Dos Santos Claro, T. Rajh, C.S. Johnson, A.A. Balandin, and E. V. Shevchenko, "Toward lithium ion batteries with enhanced thermal conductivity," ACS Nano, vol. 8, 2014, pp. 7202–7207, DOI:10.1021/nn502212b.
[12]S. Jin, J. Li, C. Daniel, D. Mohanty, S. Nagpure, and D.L. Wood, "The state of understanding of the lithium-ion-battery graphite solid electrolyte interphase (SEI) and its relationship to formation cycling *," Carbon, vol. 105, 2016, pp. 52–76, DOI:10.1016/j.carbon.2016.04.008.

Missing literature on thermal conductivity

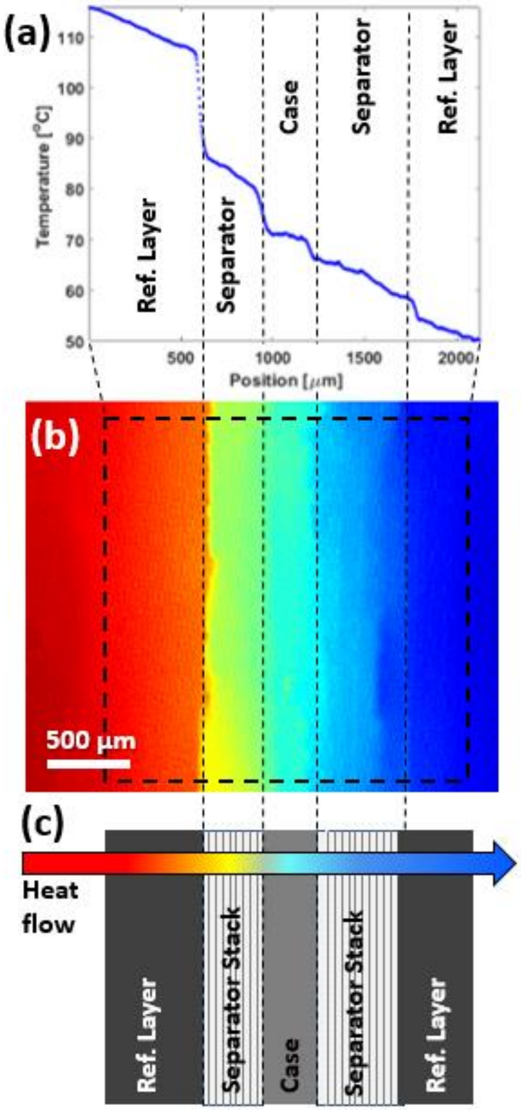
Cell geometry	Cross-plane thermal conductivity [$Wm^{-1}K^{-1}$]		
	LFP	**LCO**	**NMC**
Cylindrical	0.15 [14]	3.4 [15]	---
Prismatic	---	1.4 [13]	---
Pouch	0.4 [16]	---	0.6 [18]

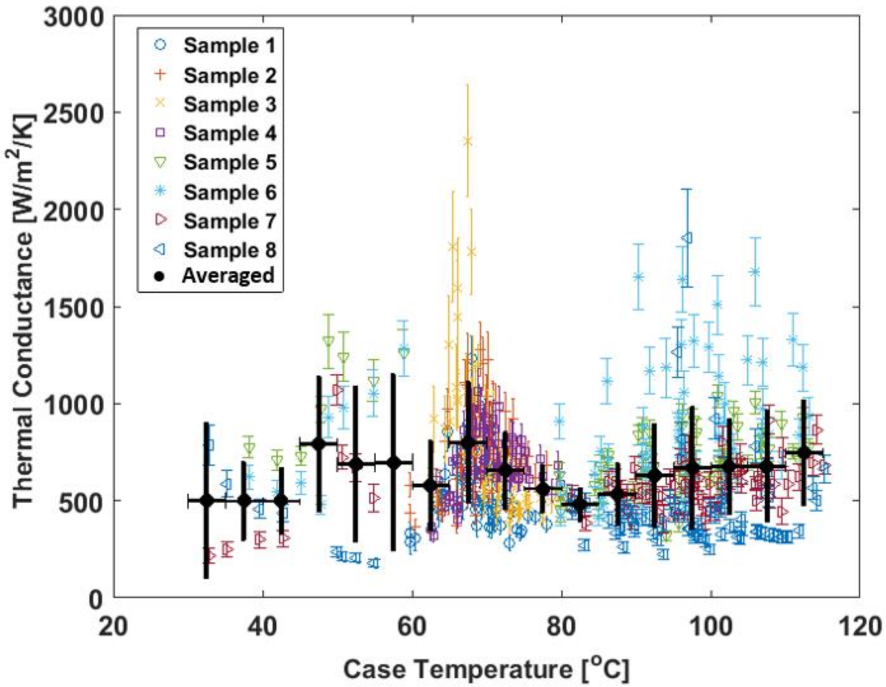
Cell geometry	In-plane thermal conductivity [$Wm^{-1}K^{-1}$]	
	LFP	**LCO**
Cylindrical	30 [14]	20 [15]
Prismatic	---	24 [13]
Pouch	35 [19]	---

- Prior cell-level thermal conductivity measurements exist only for a few cathode materials and graphite anode combinations
- More measurements are needed to accurately quantify the cross-plane conductivity that can be used as inputs for thermal modeling of the battery systems

[13] D. Werner, A. Loges, D.J. Becker, and T. Wetzel, "Thermal conductivity of Li-ion batteries and their electrode configurations – A novel combination of modelling and experimental approach," Journal of Power Sources, vol. 364, 2017, pp. 72–83, DOI:10.1016/j.jpowsour.2017.07.105.
[14] K. Shah, V. Vishwakarma, and A. Jain, "Measurement of Multiscale Thermal Transport Phenomena in Li-Ion Cells: A Review," *Journal of Electrochemical Energy Conversion and Storage*, vol. 13, 2016, p. 030801, DOI:10.1115/1.4034413.
[15] S.J. Drake, D.A. Wetz, J.K. Ostanek, S.P. Miller, J.M. Heinzel, and A. Jain, "Measurement of anisotropic thermophysical properties of cylindrical Li-ion cells," Journal of Power Sources, vol. 252, 2014, pp. 298–304, DOI:10.1016/j.jpowsour.2013.11.107.
[16] H. Maleki, S. Al Hallaj, J.R. Selman, R.B. Dinwiddie, and H. Wang, "Thermal Properties of Lithium-Ion Battery and Components," Journal of The Electrochemical Society, vol. 146, 1999, p. 947, DOI:10.1149/1.1391704.
[18] J. Cho, M.D. Losego, H.G. Zhang, H. Kim, J. Zuo, I. Petrov, D.G. Cahill, and P. V. Braun, "Electrochemically tunable thermal conductivity of lithium cobalt oxide," Nature Communications, vol. 5, Jun. 2014, pp. 1–6, DOI:10.1038/ncomms5035.
[19] A.J. Stershic, S. Simunovic, and J. Nanda, "Modeling the evolution of lithium-ion particle contact distributions using a fabric tensor approach," Journal of Power Sources, vol. 297, 2015, pp. 540–550, DOI:10.1016/j.jpowsour.2015.07.088.

Interface Resistances

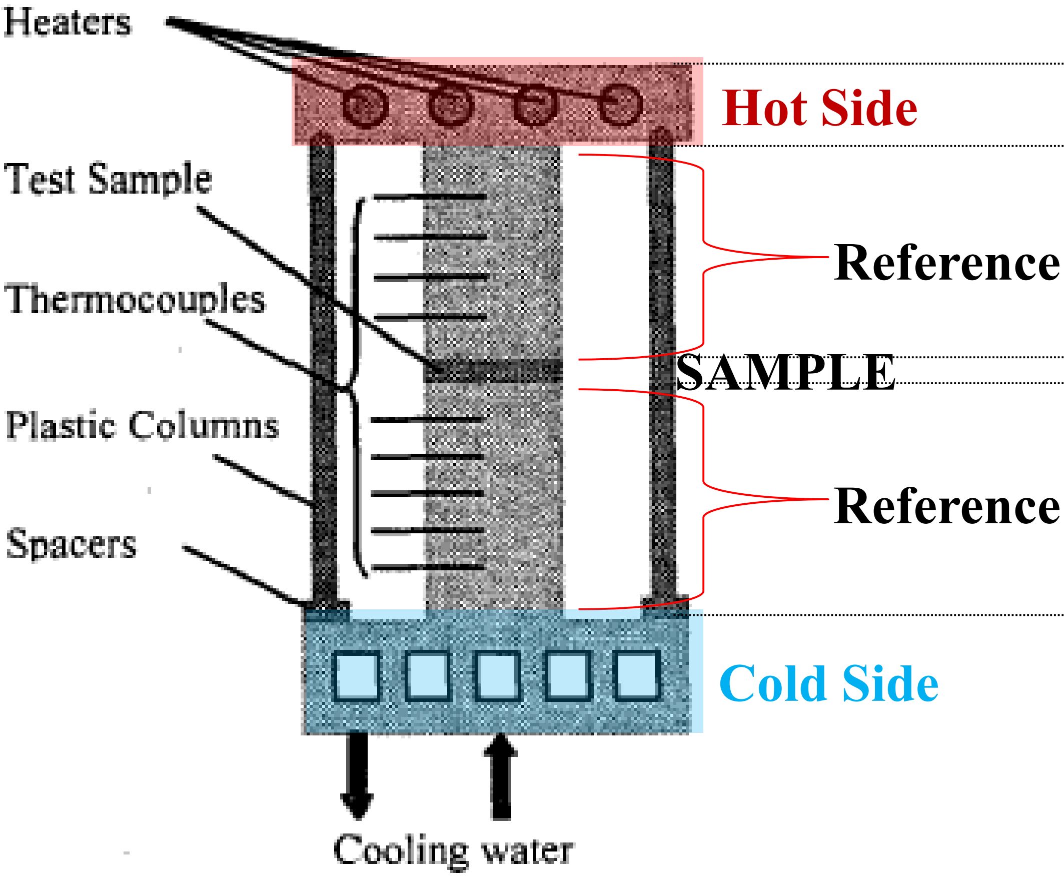


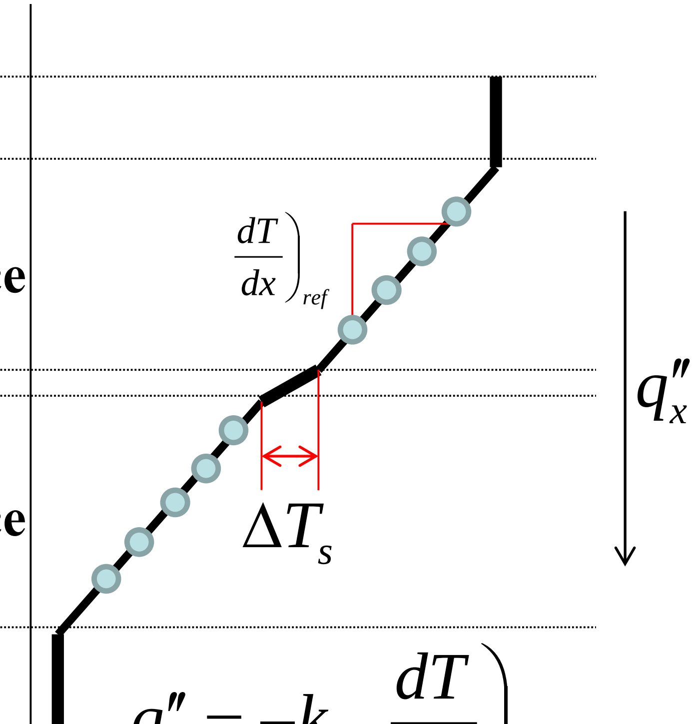


Mean Thermal Conductance: 670 W/(m^{2}K)
Standard Deviation: 275 W/(m^{2}K)

Gaitonde, Nimmagadda, Marconnet: "Measurement of Thermal Conductance in Li-ion Batteries " *Journal of Power Sources* (2017).

ASTM D5470 Reference Bar Method



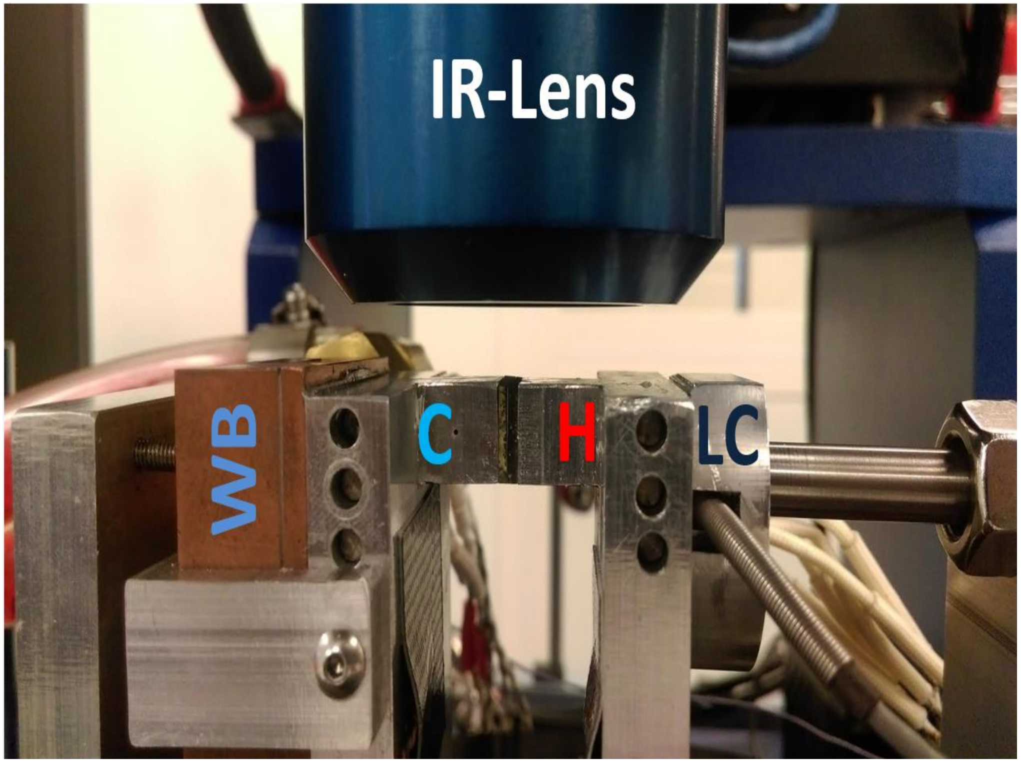


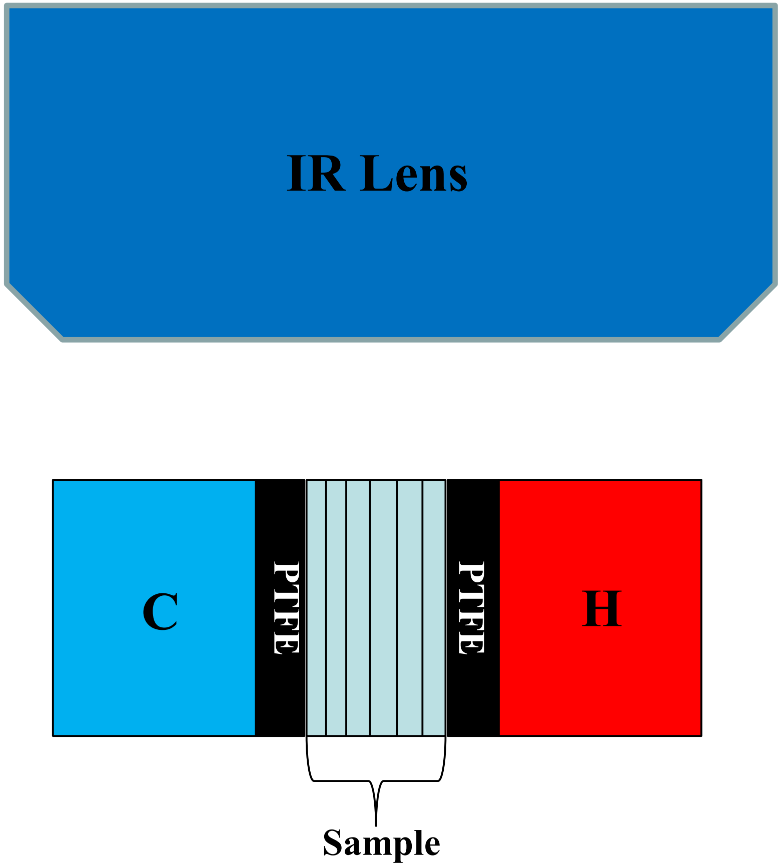
$$q''_x = -k_{ref} \left.\frac{dT}{dx}\right)_{ref}$$

X. Hu, *et al.*, "Thermal conductance enhancement of particle-filled thermal interface materials using carbon nanotube inclusions," in *The Ninth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM '04)*, 2004, pp. 63-69 Vol.1.

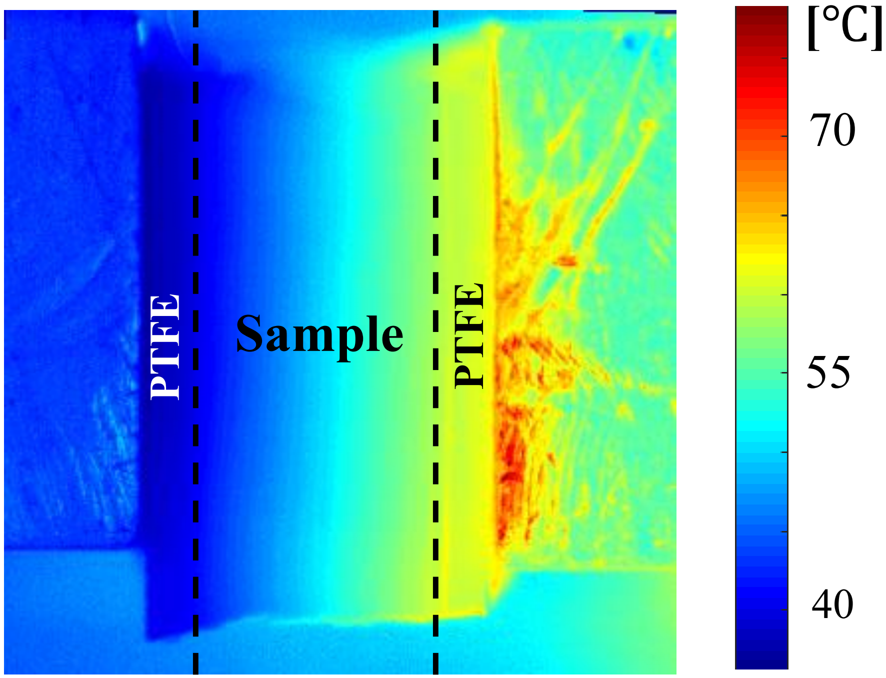
$$q_x = G_{th,s}\Delta T_s = \frac{k_s A}{L_s}\Delta T_s \rightarrow k_s = {q''_x L_s}\big/{\Delta T_s}$$

Experiment Setup

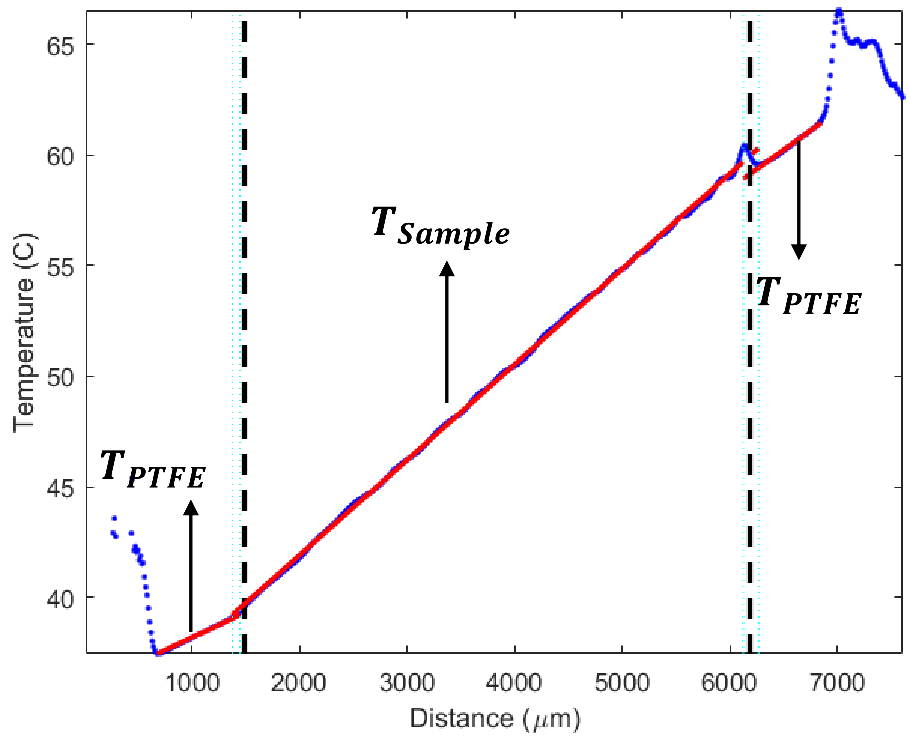




Thermal Imaging

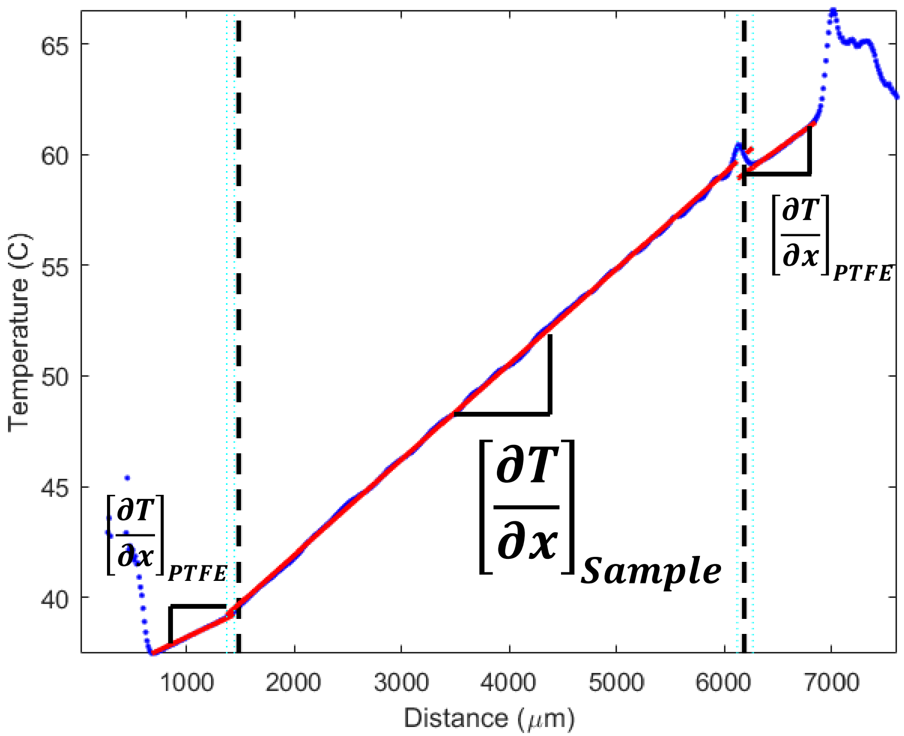


Thermal map of reference-sample-reference



1D Temperature Profile

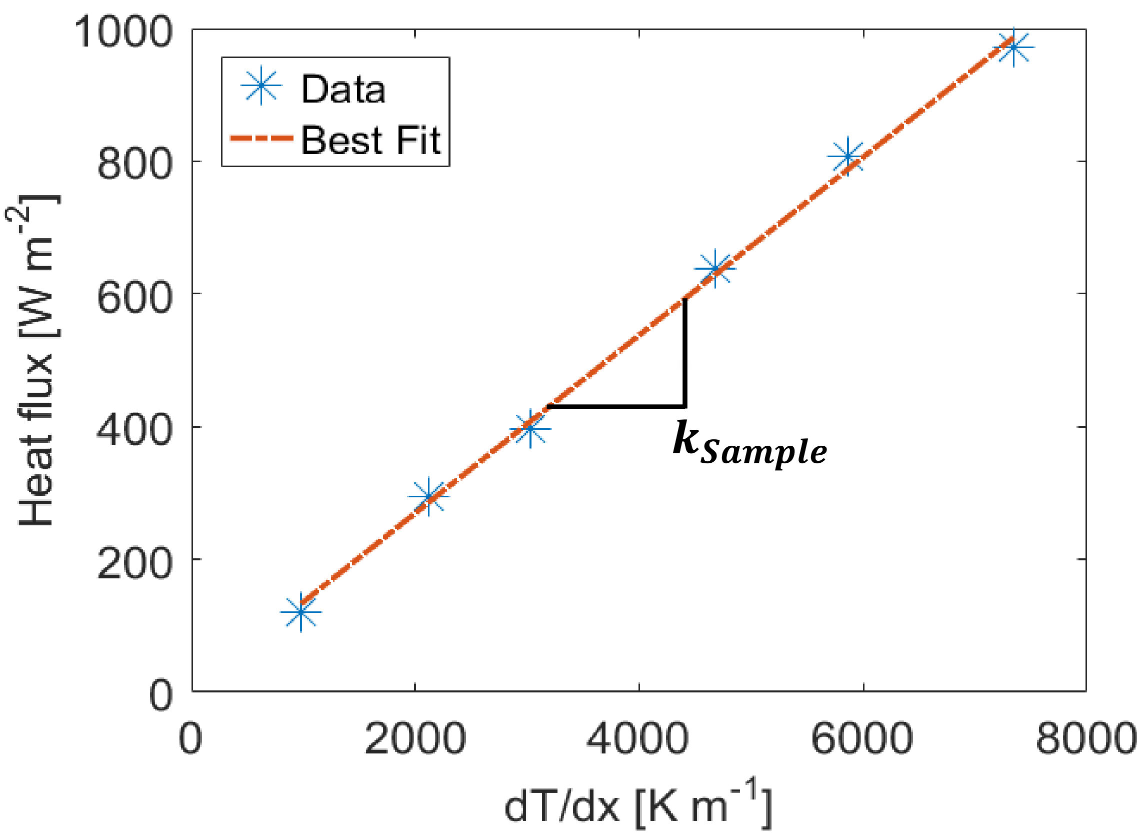
Extracting Thermal Conductivity



$$|q_{in}| = \left[k\frac{\partial T}{\partial x}\right]_{PTFE}$$

$$k_{Sample} = \frac{|q_{in}|}{\left[\frac{\partial T}{\partial x}\right]_{Sample}}$$

Varying Heat Flux

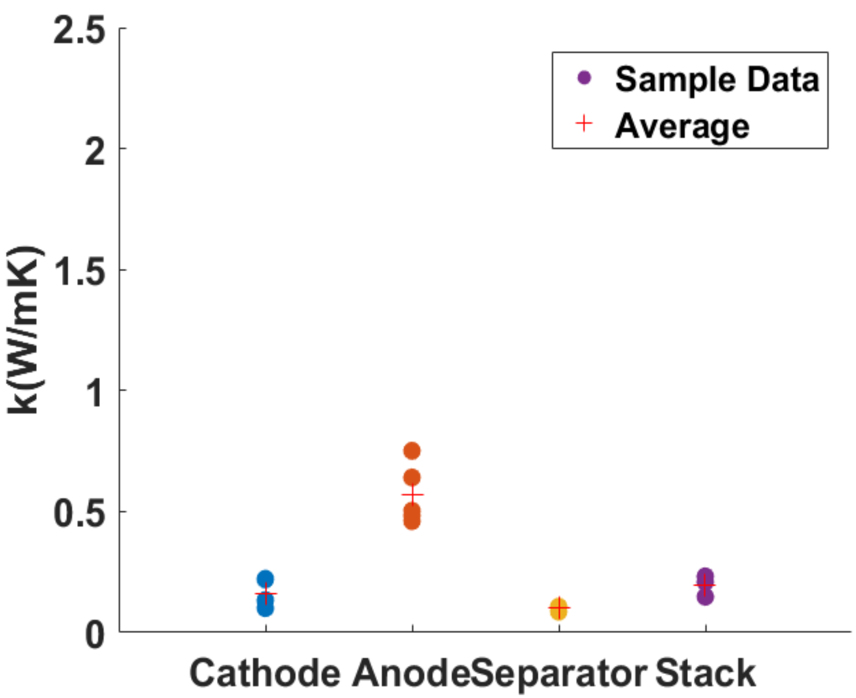


- Experiment temperature range: 40~70 ℃
- Six varying heat flux for each sample.

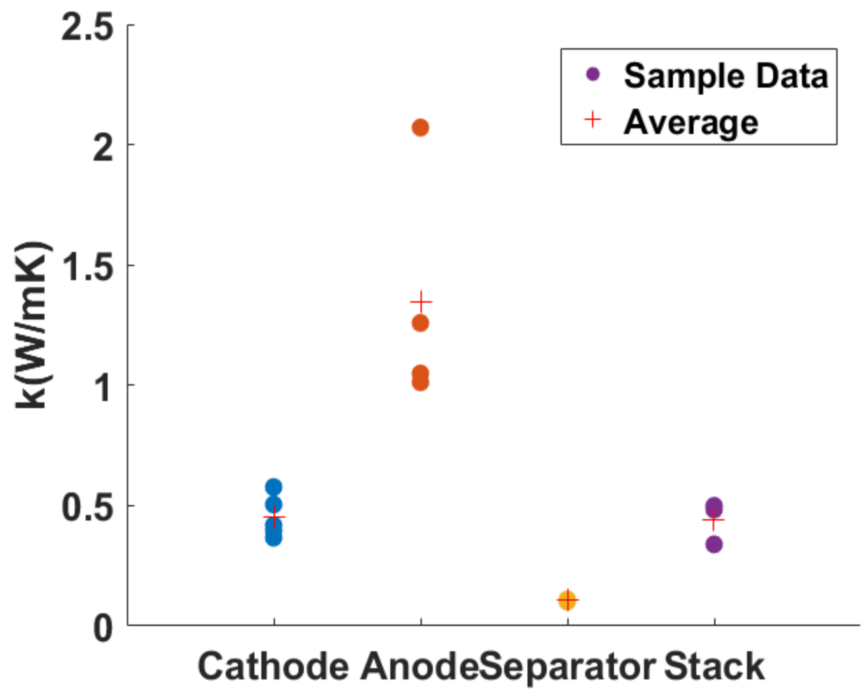
Result

Sample	Component	k(W/mK)	
		Dry	Wet
Cathode (~15 layers)	Cu Foil double side coated by $LiMn_2O_4$	0.16 ± 0.06	0.45 ± 0.09
Anode (~15 layers)	AL Foil double side coated by CMS Graphite	0.57± 0.12	1.35 ± 0.49
Separator (~34 layers)	Ceramic Coated Membrane	0.10 ± 0.01	0.11 ± 0.01
Stack (~12 layers)	Cathode +Separator + Anode	0.20 ± 0.04	0.44 ± 0.09

DRY

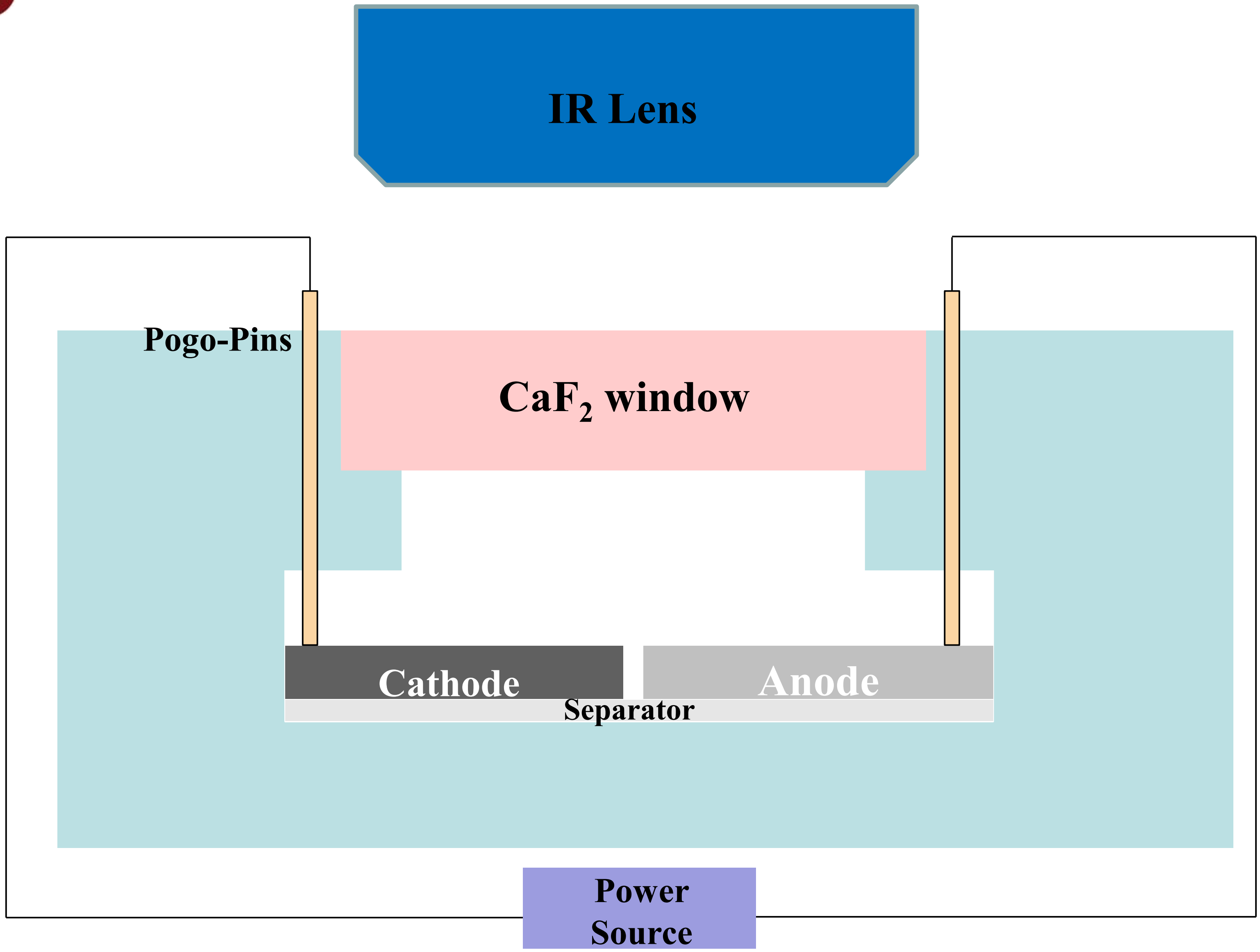


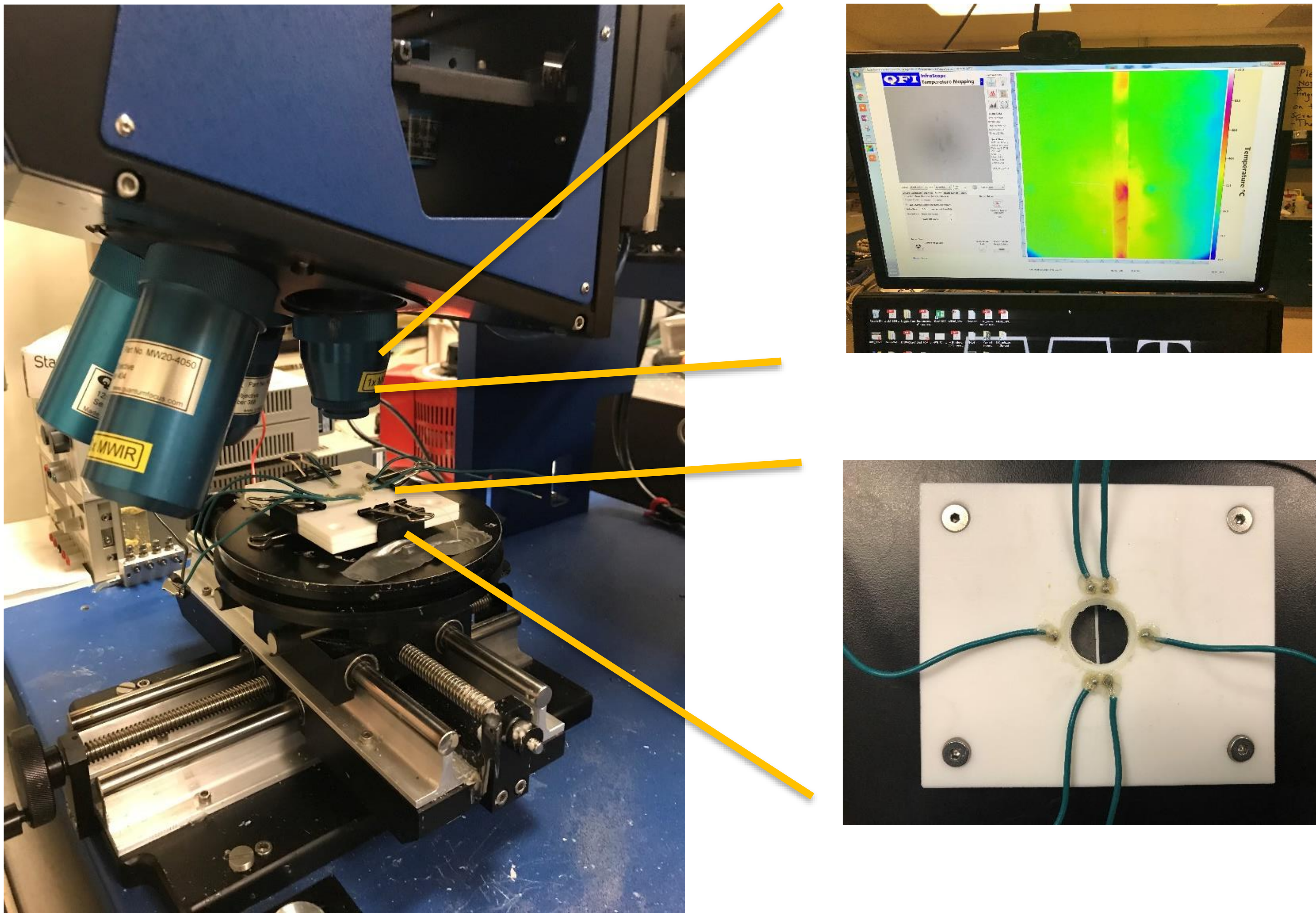
WET



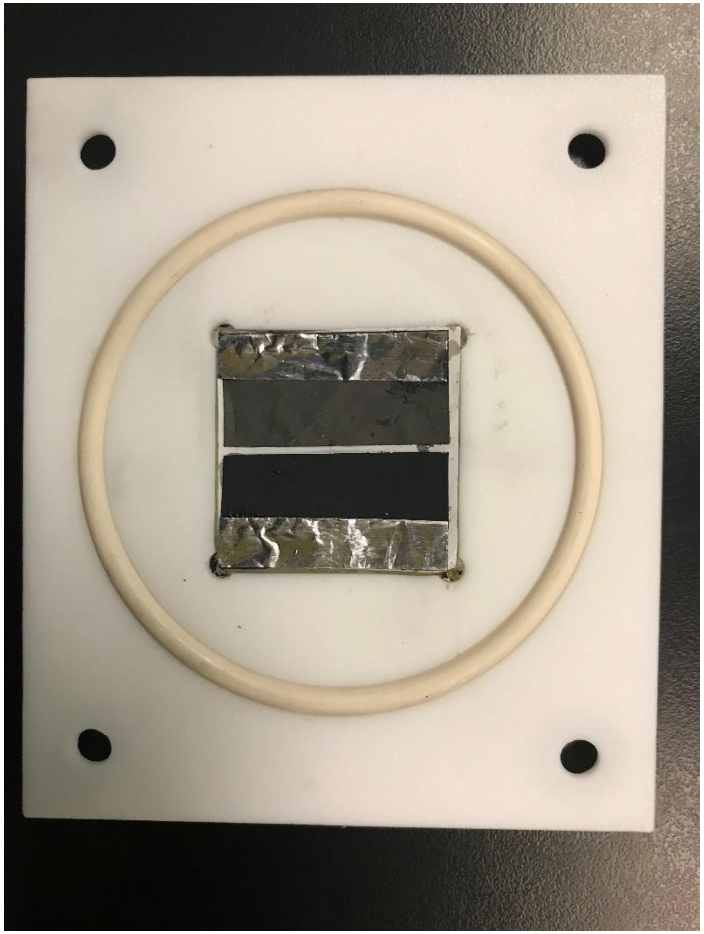
Mimic electrolyte: 1:1 volumetric ratio of
ethylene carbonate (EC), propylene carbonate(PC)

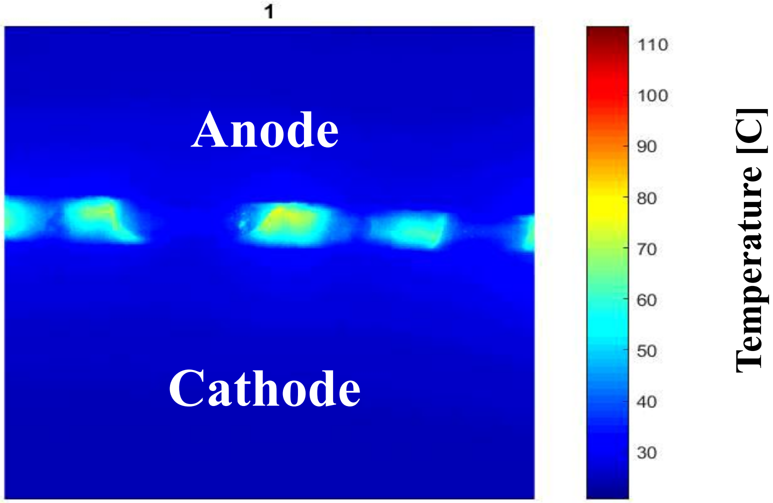
Measurement Device

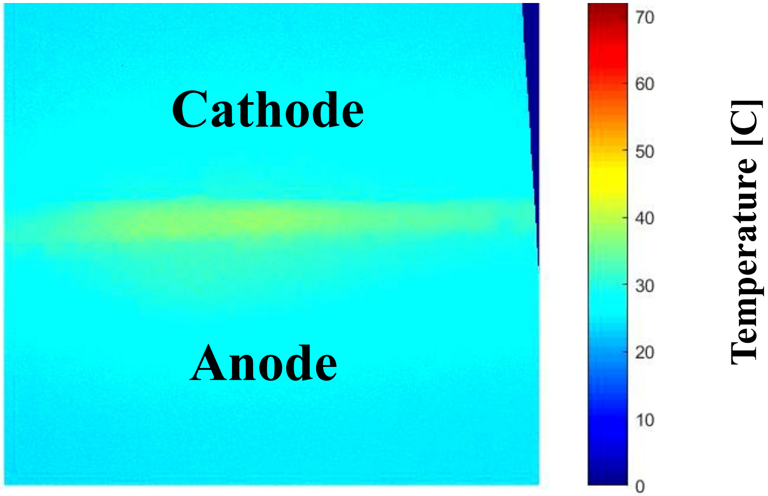



MWIR
QFI

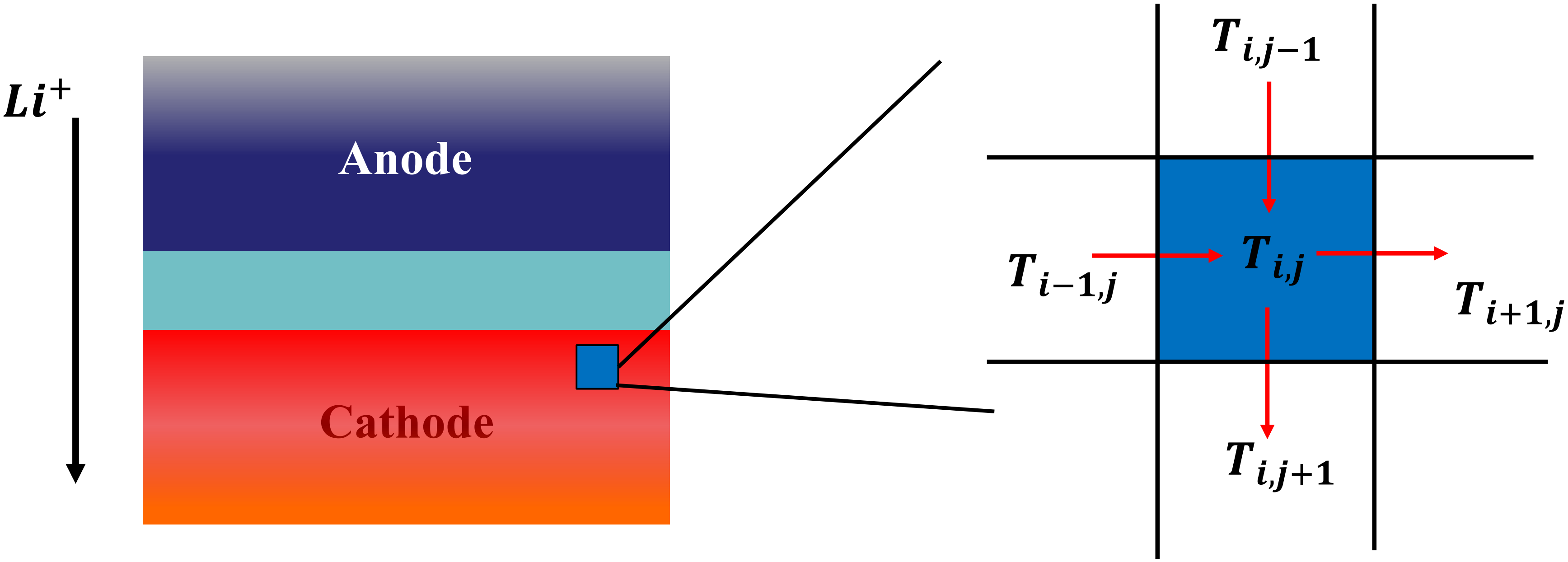
Thermal Transport during Charging







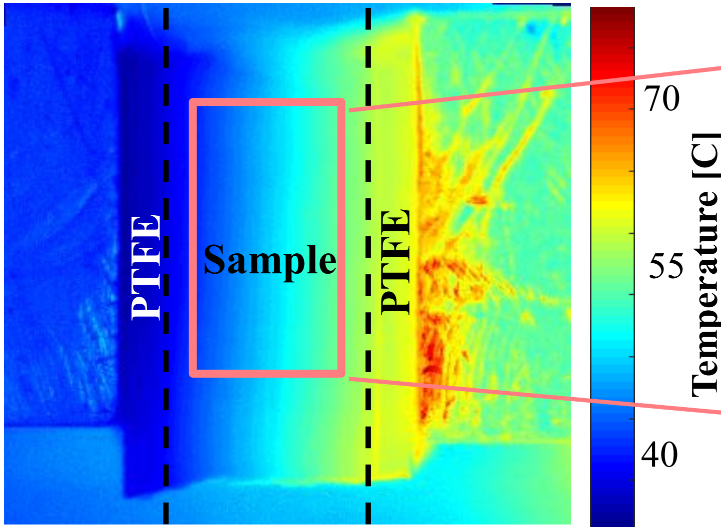
Estimating Local Heat Generation



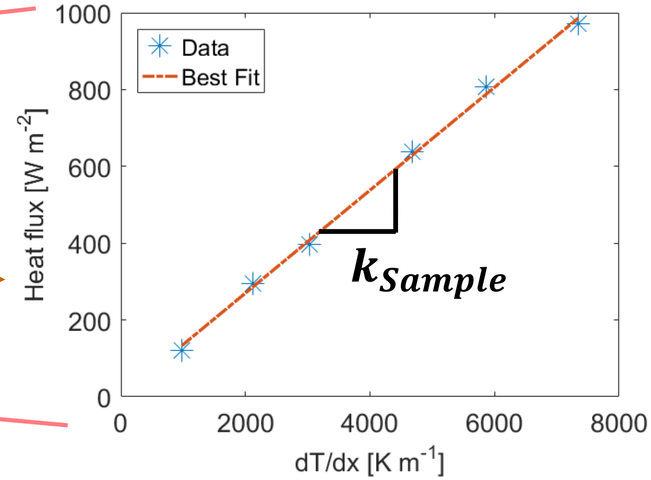
$$Q_{in} - Q_{out} + Q_g = \rho C_p A \frac{\partial T}{\partial t}$$

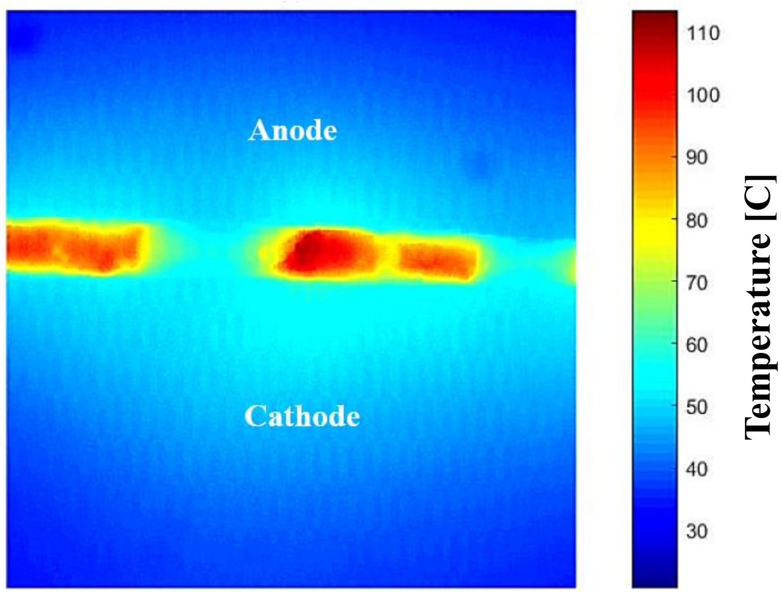
$$\left[\left(-k\frac{T_{i,j}-T_{i-1,j}}{\Delta x}\Delta y\Delta z\right) + \left(-k\frac{T_{i,j}-T_{i,j-1}}{\Delta x}\Delta x\Delta z\right)\right] - \left[\left(-k\frac{T_{i+1,j}-T_{i,j}}{\Delta x}\Delta y\Delta z\right) + \right.$$

Conclusions



Thermal property characterization





Device Performance

Aalok Gaitonde
(now at 3D Systems)

Bhagyashree
Ganore
(now at Intel)

Amulya
Nimmagadda
(now at UIUC)

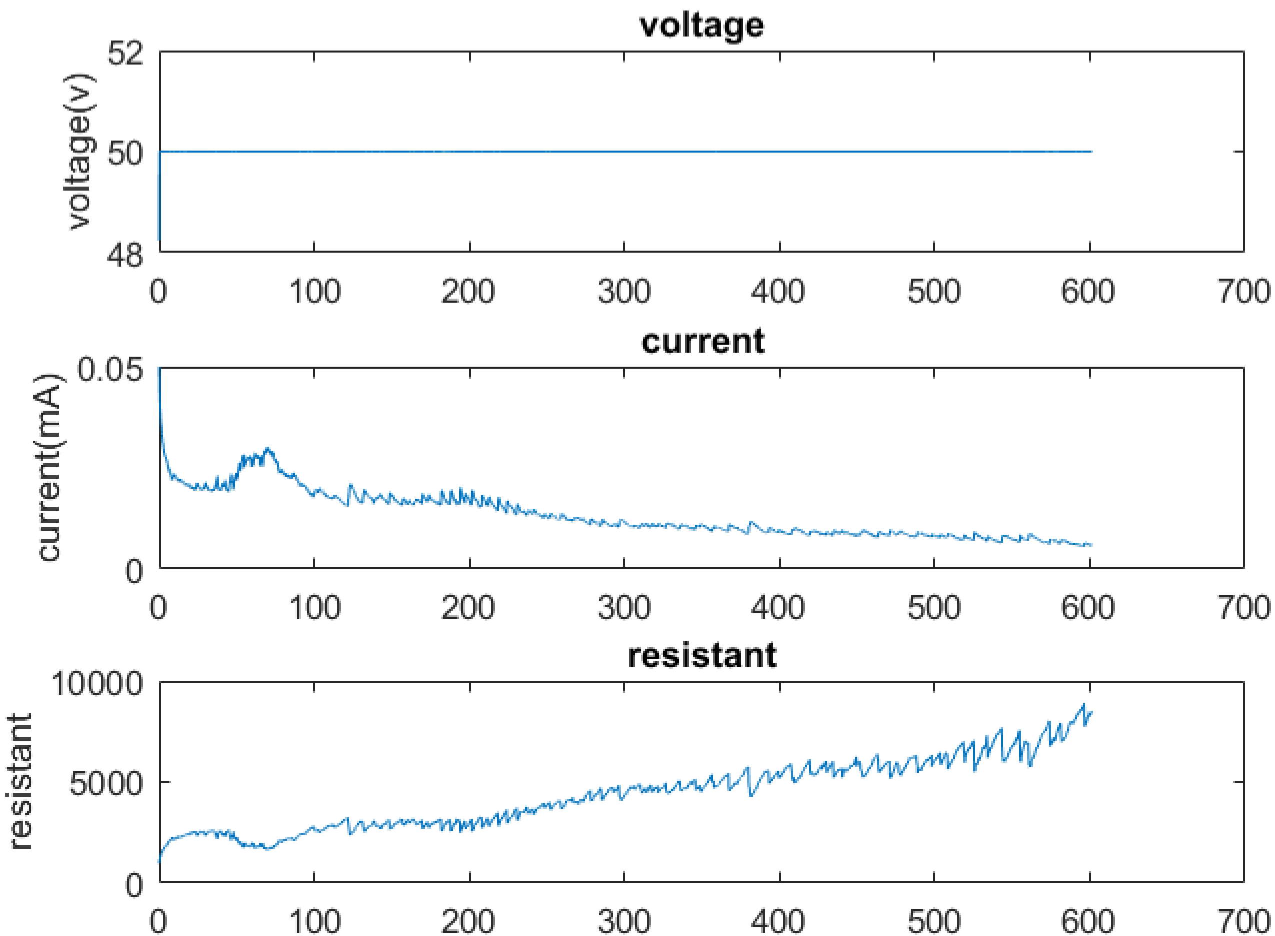
Swagata
Kalve

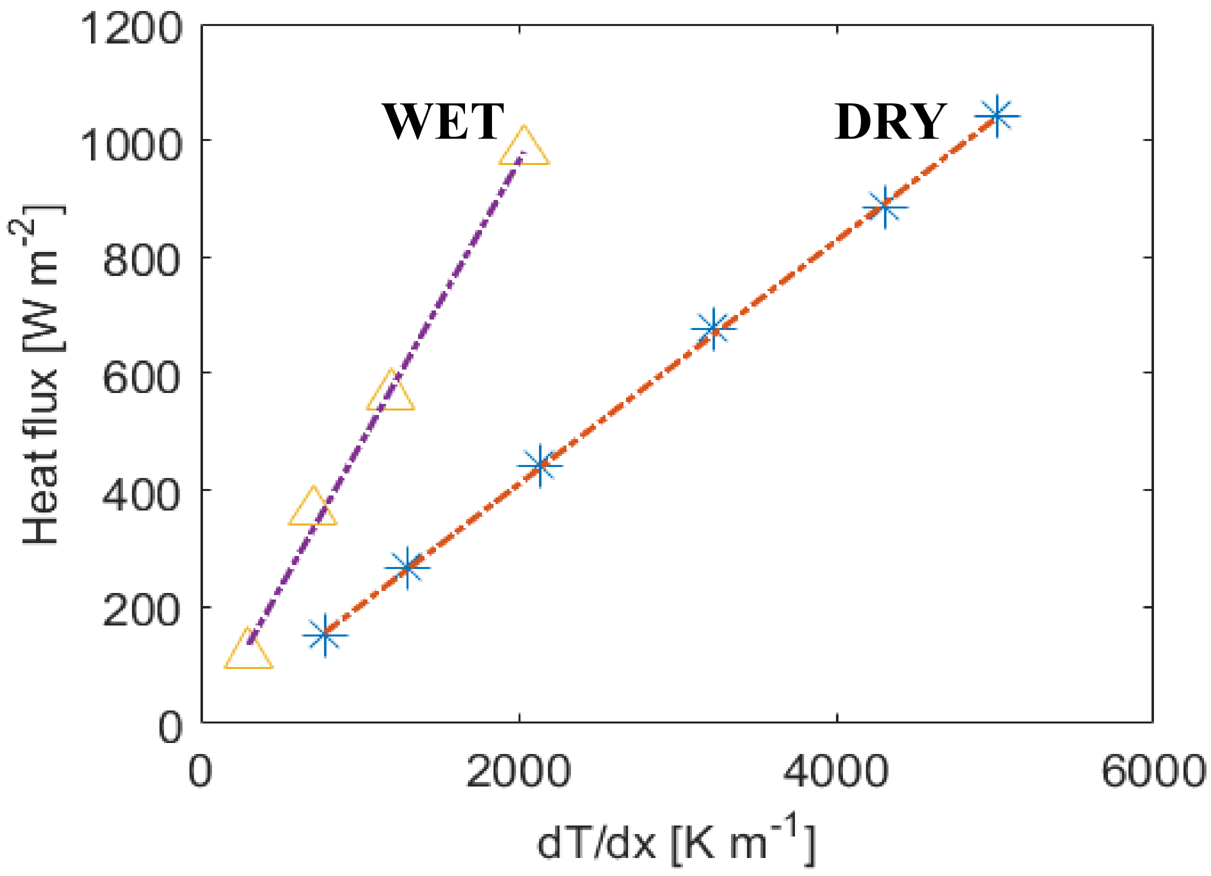
Rajath
Kantaraj

Yexin
Sun

QUESTIONS & COMMENTS

During charging process





WET
DRY
1200
1000
800
600
400
200
0
Heat flux [W m^{-2}]
0
2000
4000
6000
dT/dx [K m^{-1}]