2023 ASHRAE WINTER CONFERENCE

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Seminar 21 - Optimizing Design and Controls for Thermal Energy Storage at the Building and Community Scale

Optimizing phase change composite thermal energy storage using the thermal Ragone framework

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NREL Transforming ENERGY

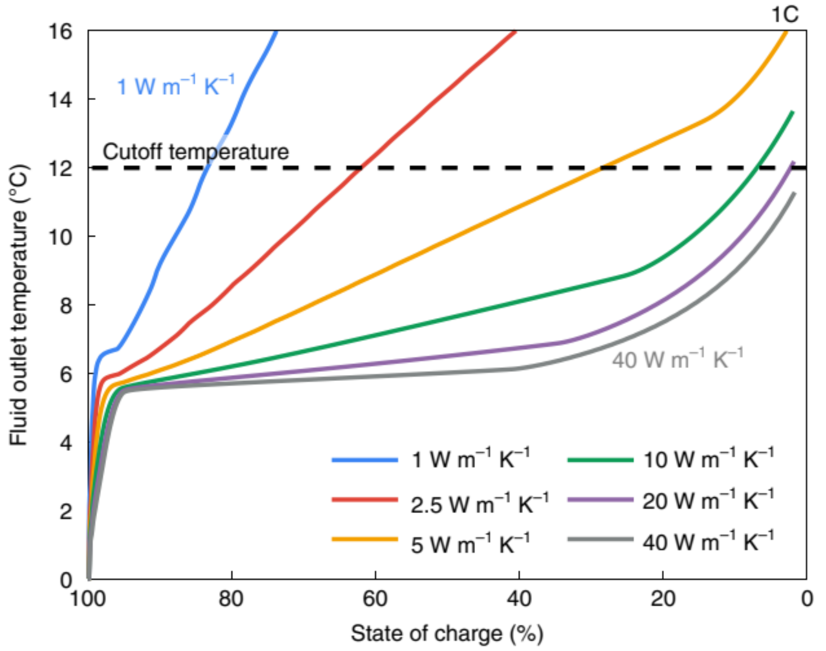
Learning Objectives

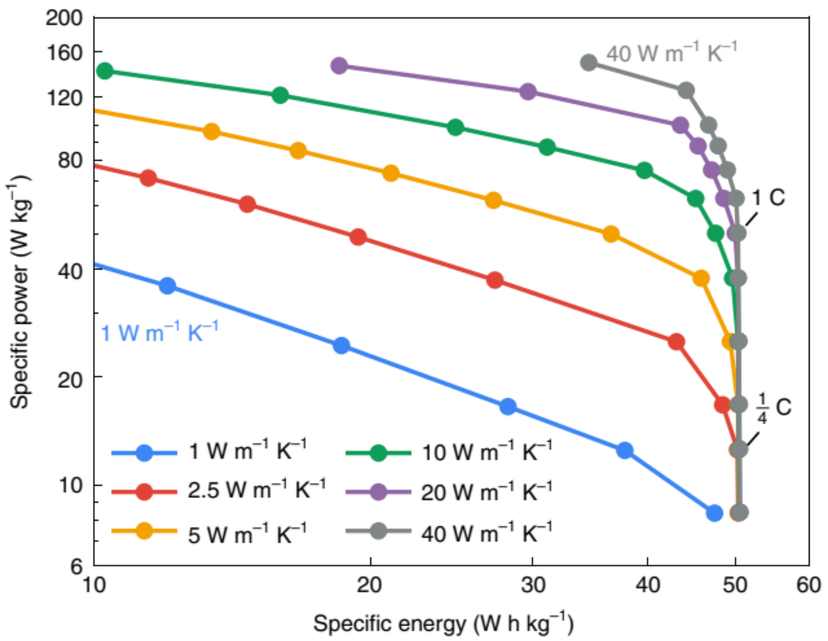
- Describe how thermal energy storage can result in a lower levelized cost of storage than battery energy storage
- Demonstrate how additive manufacturing can result in advanced heat exchanger design and manufacturing for thermal energy storage devices
- Explain how thermal power requirements impact the optimal design needs of thermal energy storage heat exchangers
- Explain the benefits of using optimization to inform distribution and control of mixed types of cool thermal storage across a connected community

Outline

- Thermal Ragone Framework
- Design Optimization
- Finite Difference Model and Results
- Approximate Models
- Model Comparisons
- Conclusions

Thermal Ragone Framework

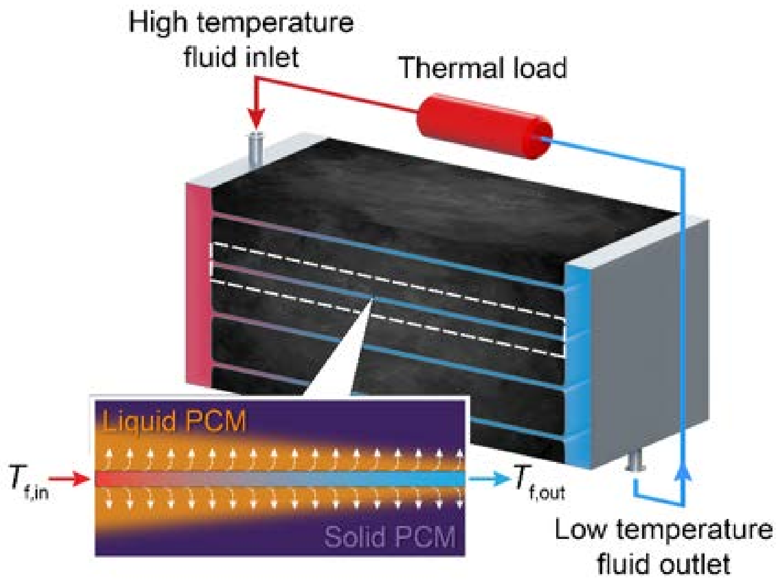




Woods et al. 2021

- Ragone plots have been recently applied to PCM thermal energy storage devices to illustrate the tradeoffs between power requirements and energy storage capacity
- A cutoff temperature can be defined to determine when the useful storage capacity has been depleted
- Material and geometric properties like the PCM thermal conductivity and spacing of the heat transfer fluid channels can have significant impacts on the shape of the Ragone plot for a particular storage device

Device Optimization



Woods et al. 2021

<u>Operational</u>
Power requirement (C-rate)
Fluid temperature difference
Cutoff Temperature
Initial storage temperature

<u>Geometry</u>
Heat transfer fluid tube spacing
Tube thickness
Porosity of composite additives

<u>Material</u>
PCM latent heat capacity
PCM transition temperature
PCM and composite additive densities
Thermal conductivities of PCM and composite additives
Material Costs

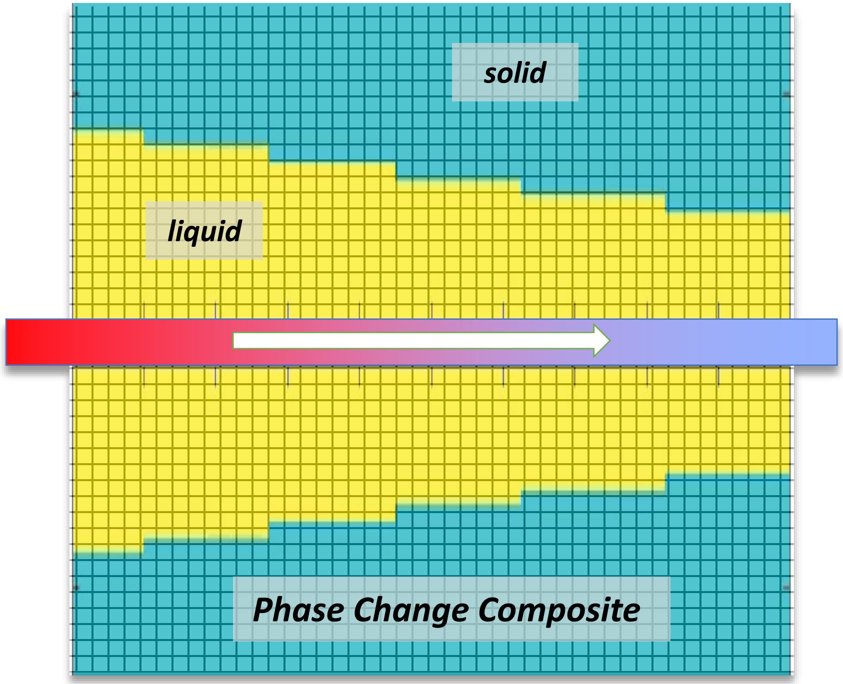
<u>Design Objectives</u>

Maximize Volumetric Energy Density **[kWh/m³]**

Minimize Upfront Costs **[$/kWh$_T$]**

Minimize Levelized Costs of Storage **[$/kWh$_e$]**

Finite Difference Model



$$\frac{dh_{i,j}}{dt} = \frac{W_{HX}}{M_{i,j}}\left[\frac{k_{\parallel}dy}{dx}\left(T_{i,j-1}+T_{i,j+1}-2T_{i,j}\right)+\frac{k_{\perp}dx}{dy}\left(T_{i-1,j}+T_{i+1,j}-2T_{i,j}\right)\right]$$

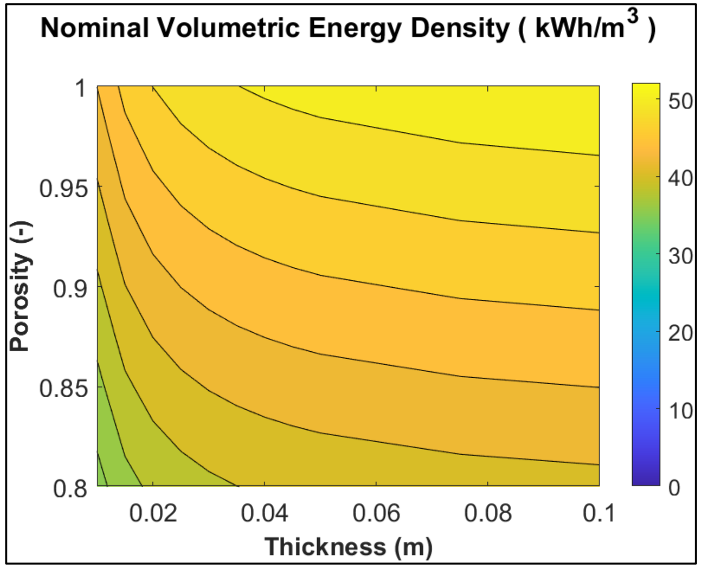
Woods et al. 2021

- A 2D transient numerical model using the finite-difference approach representing a planar thermal energy storage device
- Captures the progression of phase change during the discharge process and the effect that has on the heat transfer fluid outlet temperature
- Assumes the PCM is static, and conduction is the only mode of heat transfer in the composite
- Performed a parametric assessment (>14,000 combinations) to capture the influence of device parameters on the performance of a storage device in a space cooling application.
    - C-rates: 1/6 – 3
    - Transition Temperature: 1^{o}C – 9^{o}C
    - PCM layer thickness: 1cm – 20 cm
    - Porosity of conductivity additives: 80% - 100%

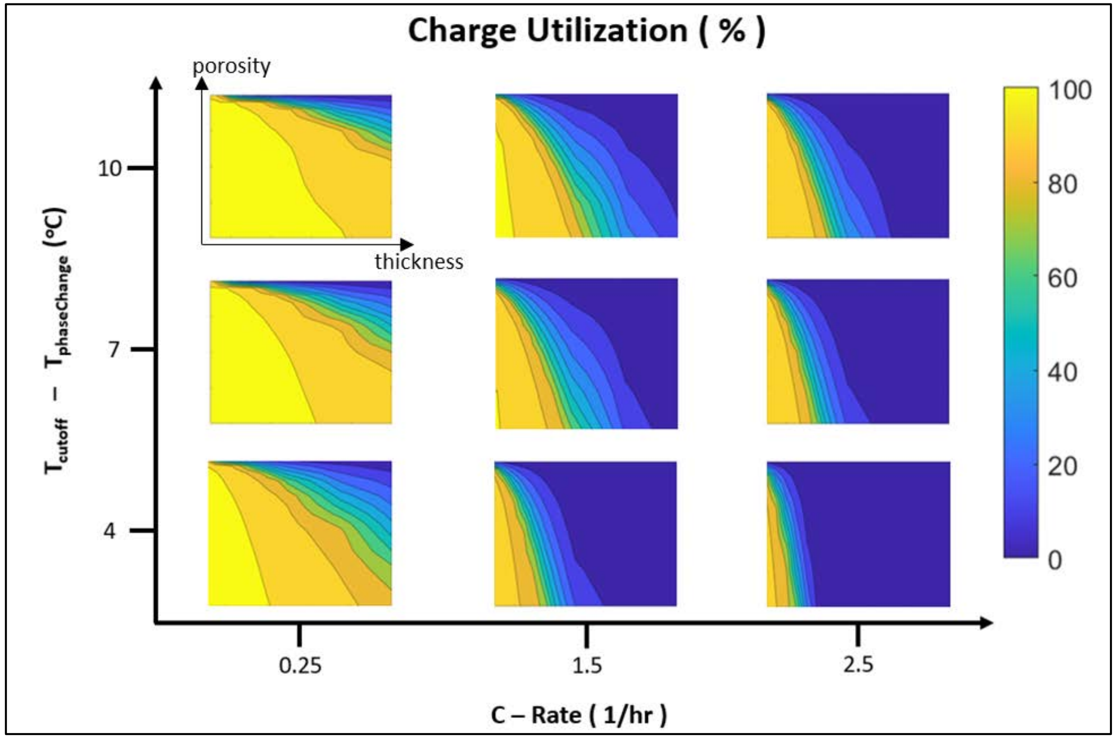
Finite Difference Model - Results

$$\frac{kWh}{m^3}_{effective} = \frac{kWh}{m^3}_{nominal} \cdot Charge\ Utilization$$

Geometry Dependent

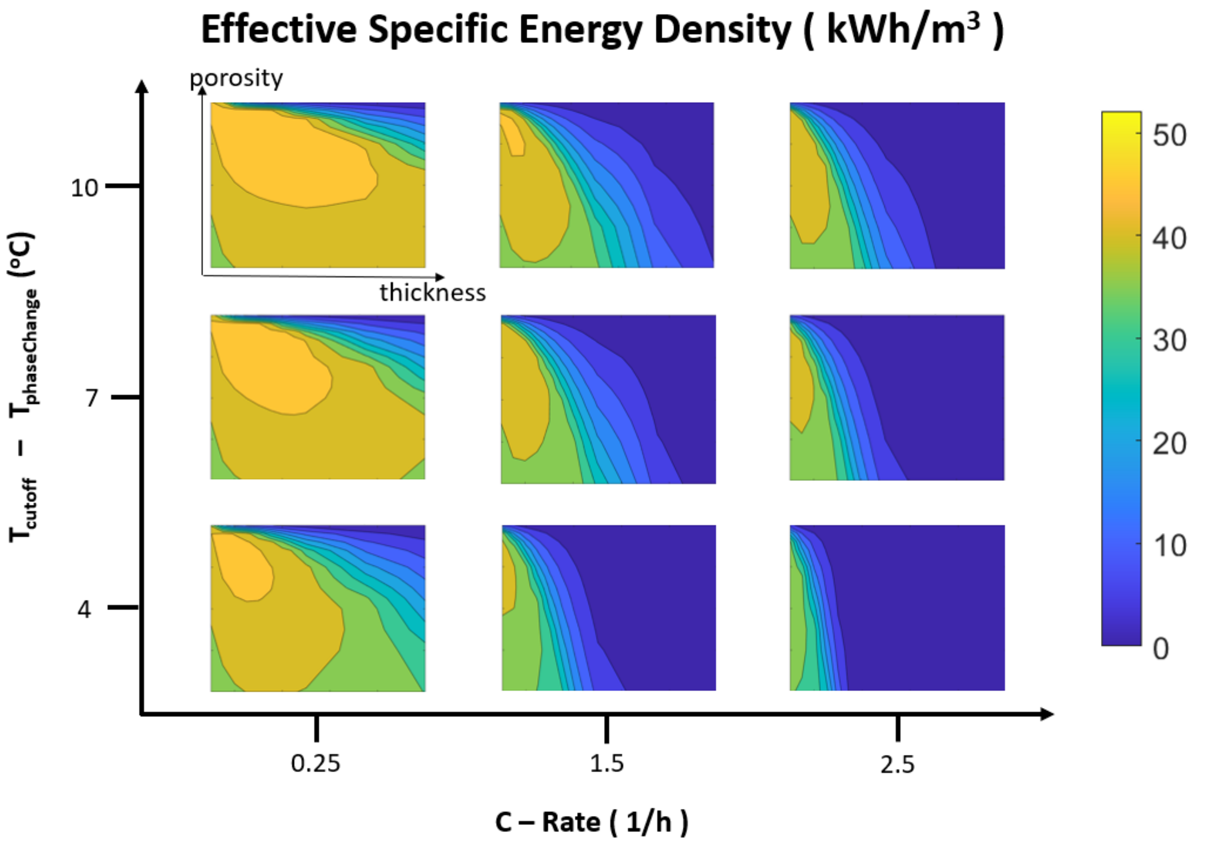


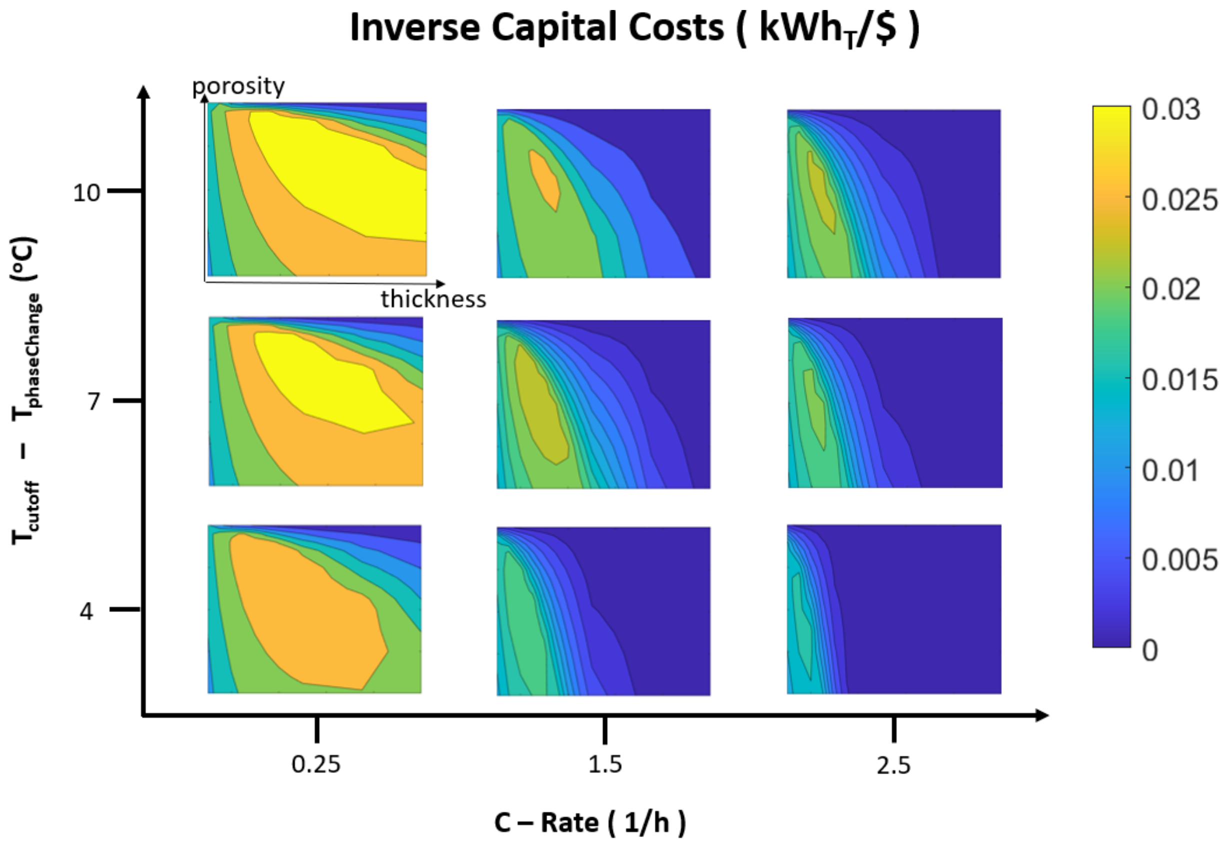
Geometry-Material-Operation Dependent



James et al., 2022

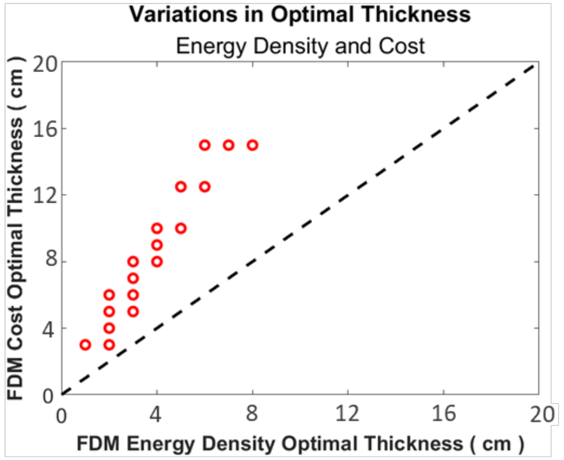
Finite Difference Model - Results

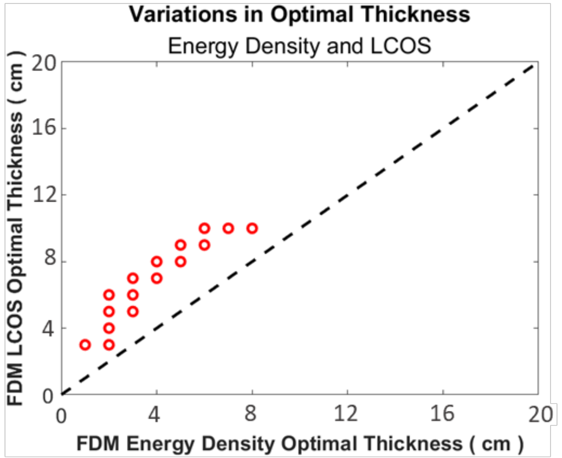


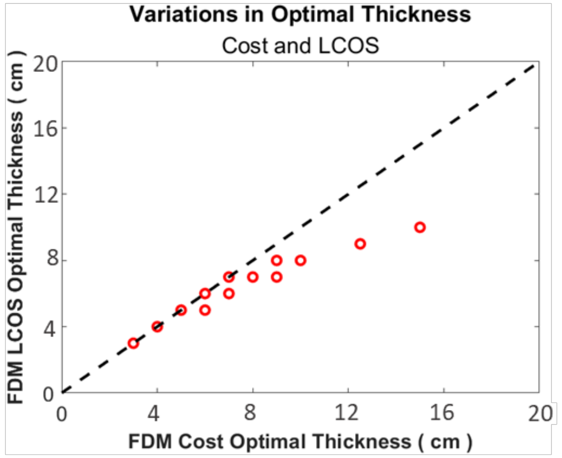


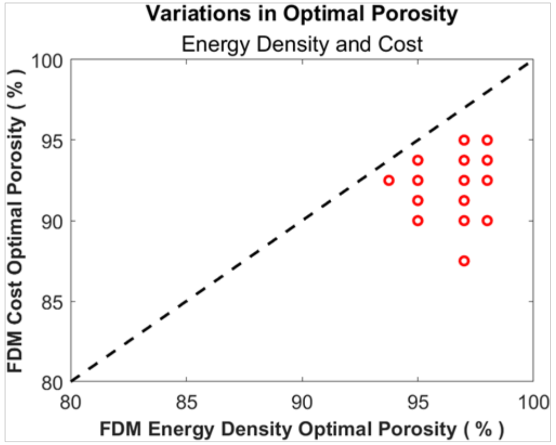
James et al., 2022

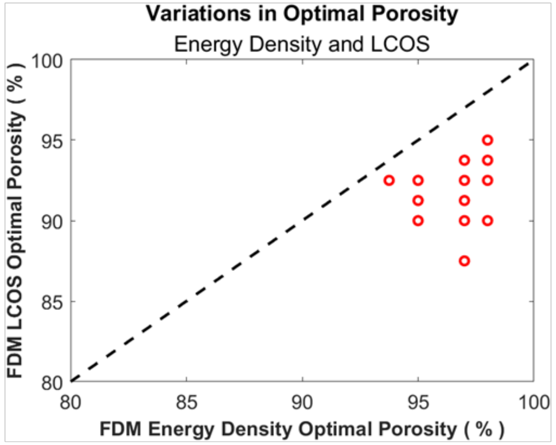
Finite Difference Model - Results

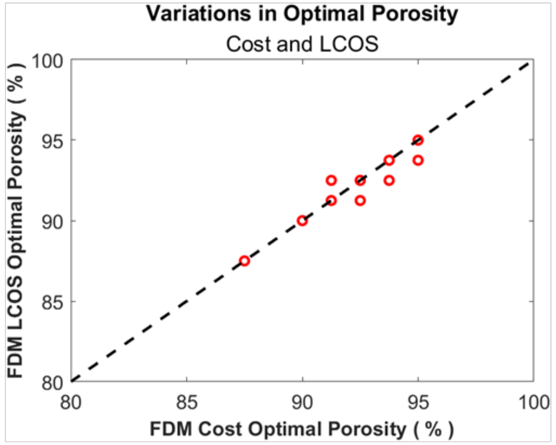












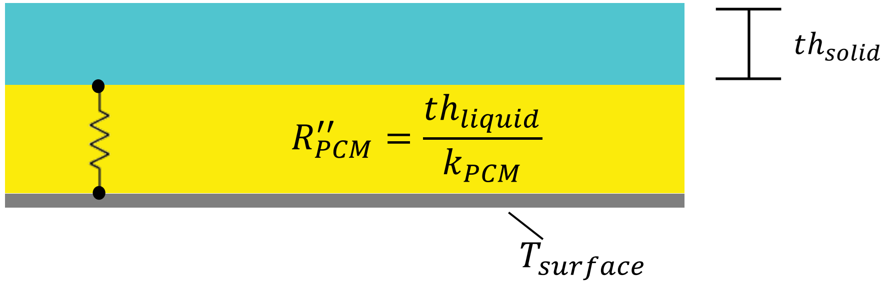
James et al., 2022

Parallel Phase Front Approximation Model

- Assumes that the melting front of the phase change composite is always parallel to the flow direction of the heat transfer fluid

- For a given driving temperature difference (cutoff temperature – Transition temperature) the maximum allowable phase change composite layer thickness needed for full charge utilization can be derived assuming a constant phase change composite thermal conductivity

- An effective charge utilization can be determined from relating the maximum thermal resistance of the PCM layer to the allowable thickness determined by the cutoff temperature for a given power delivery requirement



Target conditions:

$$\dot{Q}_{target} = C_{rate} * Cap$$

Resistance when you reach cutoff:

$$\dot{Q}_{target} = \frac{\bar{T}_{fluid,cutoff} - \bar{T}_t}{R_{conv} + R_{contact} + R_{cutoff}}$$

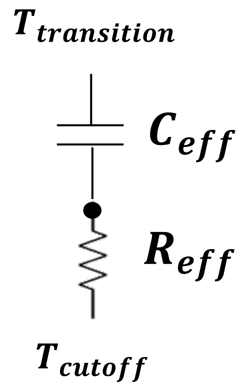
$$SOC_{cutoff} = 1 - \frac{R_{cutoff}}{R_{max}}$$

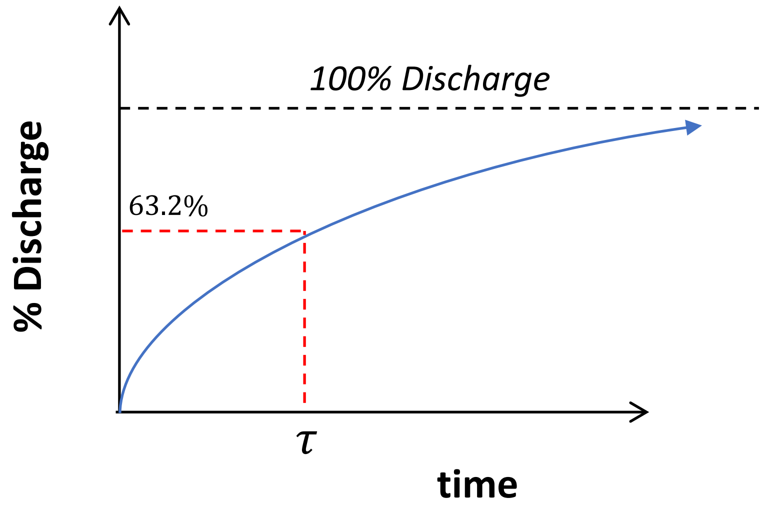
Lumped Mass Approximation Model

- Treats the thermal energy storage as an RC-circuit with an effective resistance and capacitance based on material and geometric properties

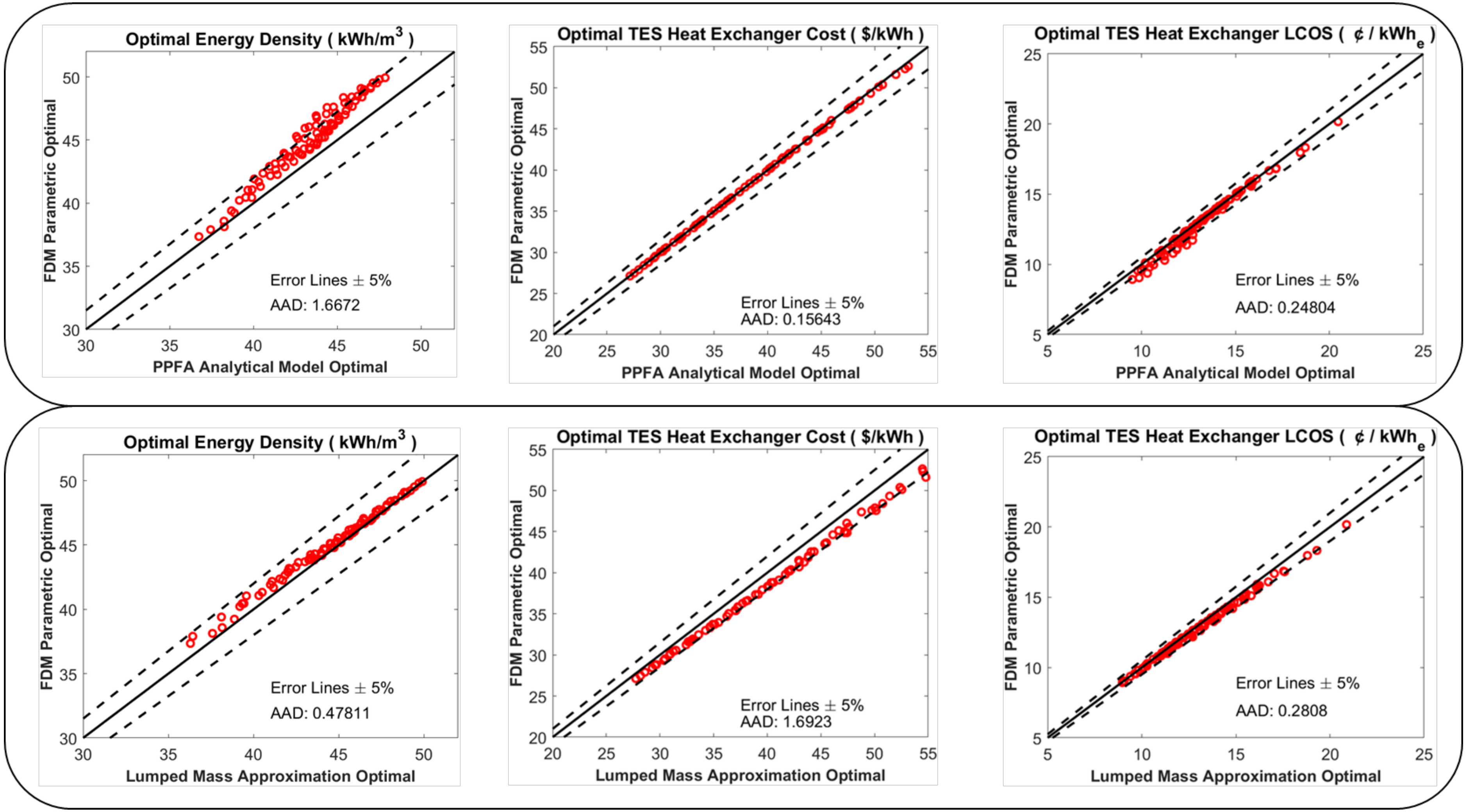
- Defines a time constant capturing the impact of the driving temperature difference

- Relates the time required for a nearly complete discharge (*99%*) to the time required for discharge determined by the target C-rate





Model Comparisons



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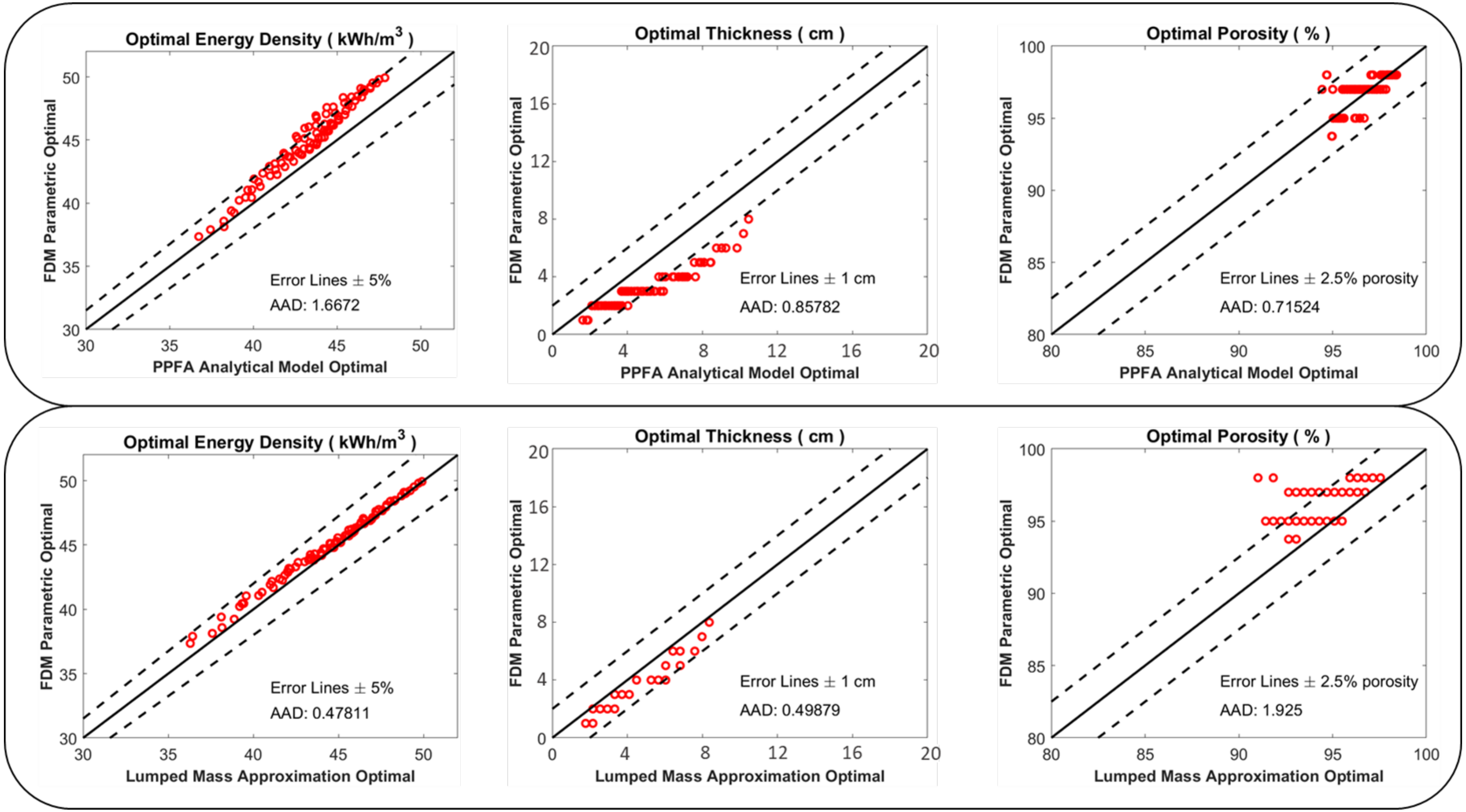

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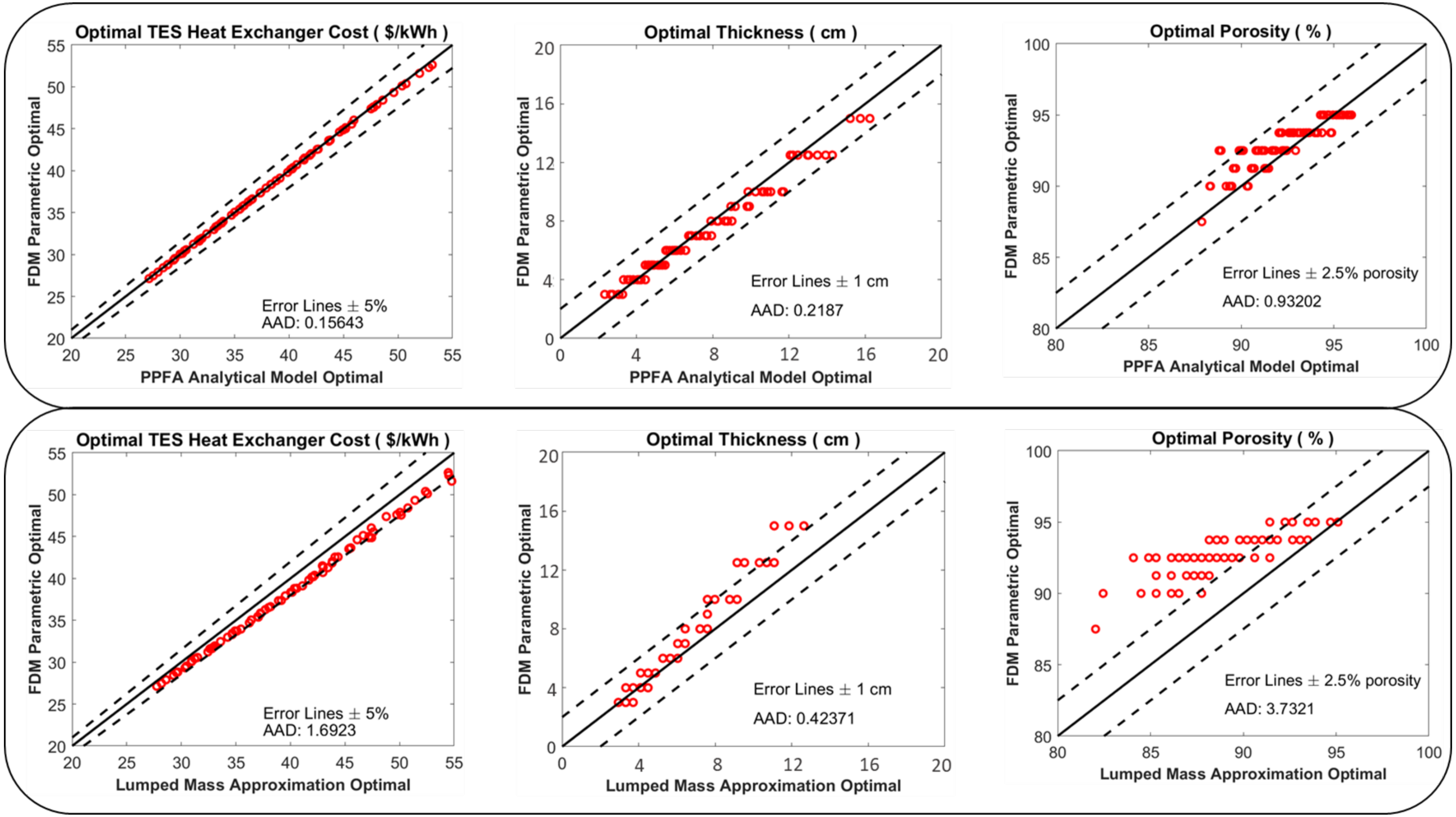

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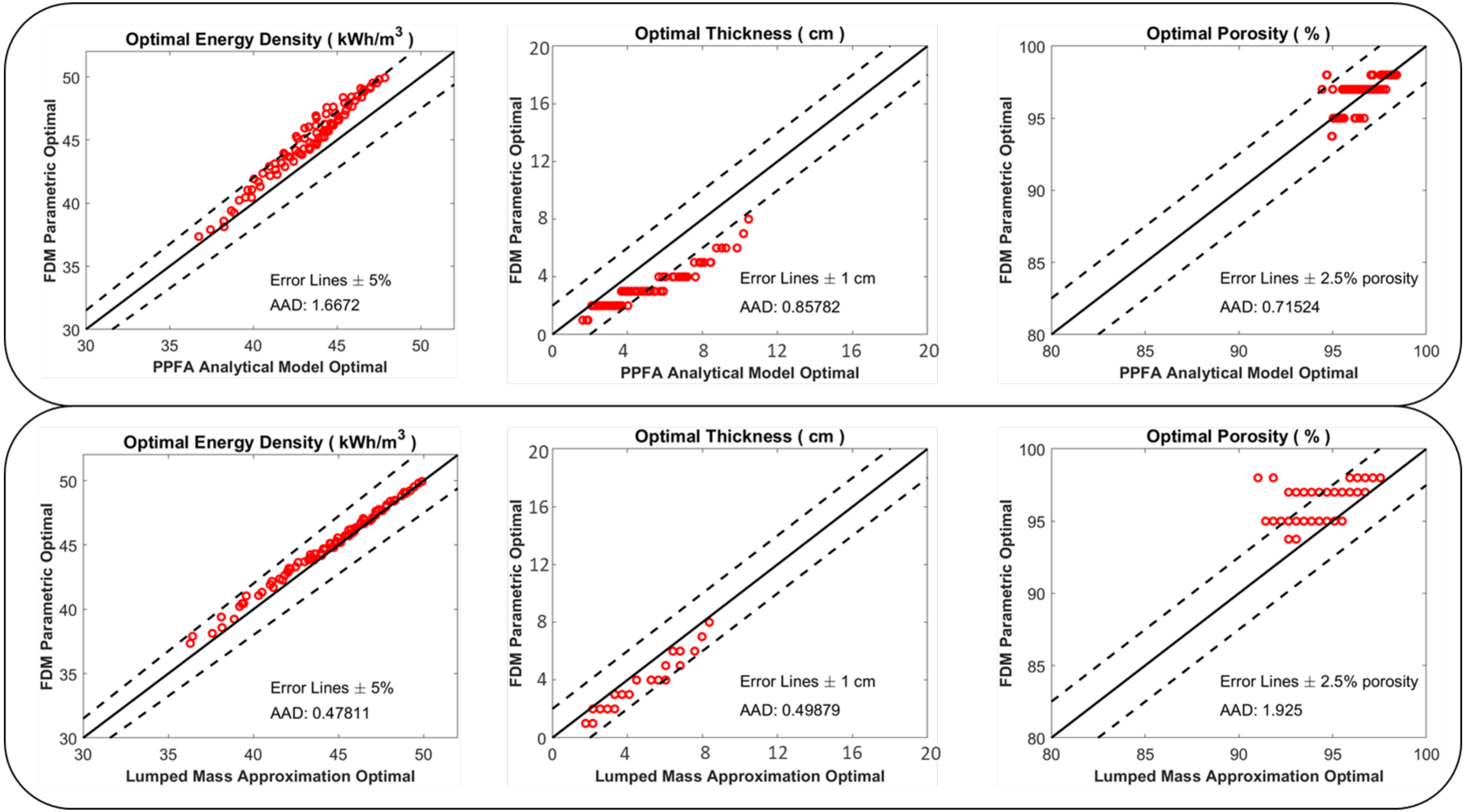
Model Comparisons



James et al., 2022

Conclusions

- As the C-Rate decreases and the driving temperature difference increases, the porosities and thicknesses needed to maximize energy density, minimize cost, or minimize LCOS will both increase
- Higher C-Rates and lower driving temperature differences necessitate thinner PCC layer thicknesses and lower porosity conductivity additives for optimizing thermal storage devices
- For the assumed material cost estimates, minimizing LCOS or energy-specific capital costs requires thicker PCC layers with less conductivity enhancing material compared to those needed to maximize the effective energy density
- Simplified models that incorporate elements of the Ragone framework were presented which can aid in accelerating the evaluation of thermal energy storage heat exchanger designs

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Bibliography

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James et al., Optimizing phase change composite thermal energy storage using the thermal Ragone framework. J. Energy Storage 56, 105875 (2022)

Questions

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