PURDUE UNIVERSITY

Reduced-Order Modeling Of Thermal Energy Storage Modules

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Problem Statement

Composite energy storage (CES) materials have incredible potential to provide optimal energy storage performance under mass and volume constraints.

Current efforts focus on combining new and existing phase change materials (PCMs) with existing heat exchanger (HX) designs. **However, to maximize performance, we propose integrating CES material design with component-level module design.**

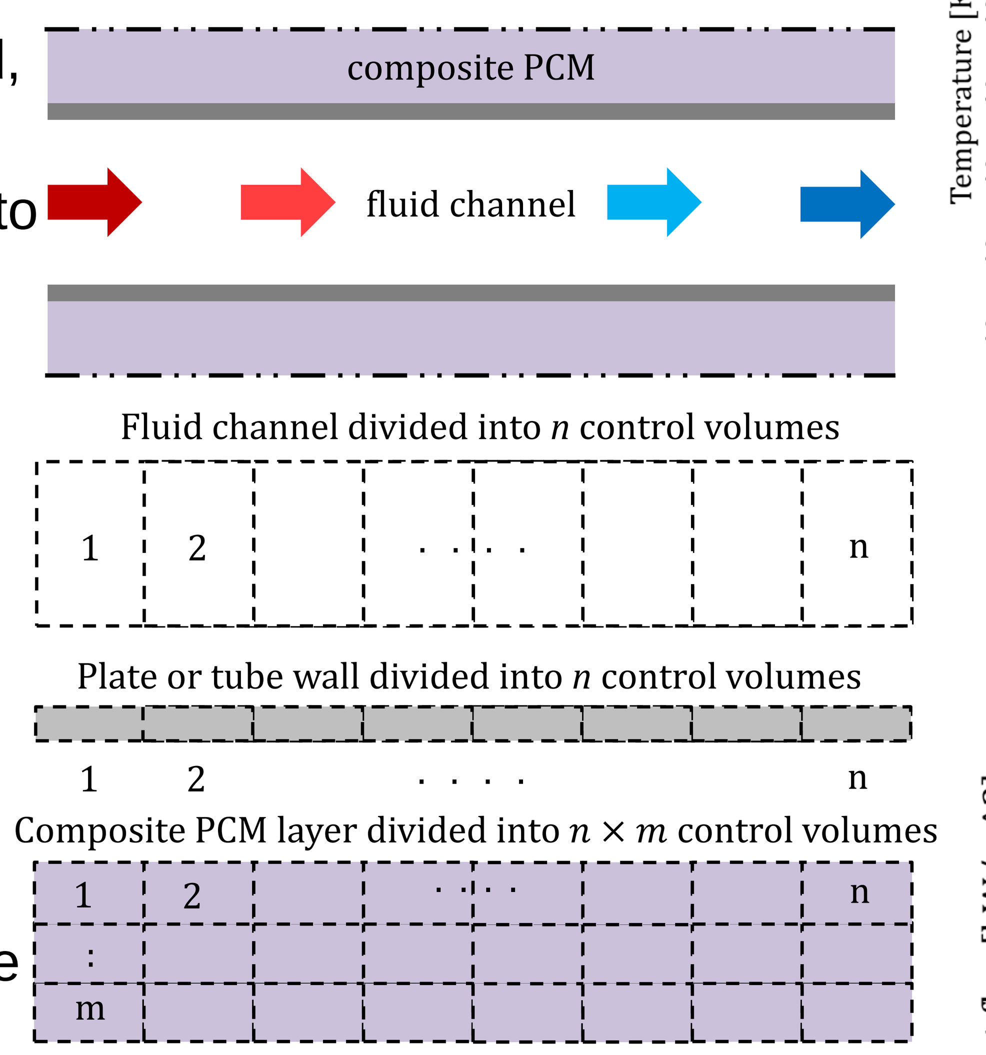
To do this requires

- a reduced-order model, amenable to optimization, that captures the relationship between material performance characteristics and the dynamic behaviour of the component
- validation of the reduced-order model using a higher fidelity modelling tool

With this model, we can then optimally design CES modules to achieve required performance specifications.

Reduced-Order Model

- Using finite-volume method, the fluid channel and metal plate or tube are divided into *n* control volumes, and the composite PCM layer is divided into *n* × *m* control volumes
- Each control volume is assumed to have lumped properties and states
- Properties of fluid and PCM are assumed independent of temperature
- The top boundary of the composite PCM layer, and bottom boundary of the fluid channel in the extended plate geometry have adiabatic boundary conditions



Using the principle of conservation of energy:

fluid channel $$m^f c_p^f \frac{dT_j^f}{dt} = \frac{1}{R^f + R^p}\left(T_j^p - T_j^f\right) + \dot{m} c_p^f\left(T_{j-1}^f - T_j^f\right)$$

metal tube or plate $$m^p c_p^p \frac{dT_j^p}{dt} = \frac{1}{R^f + R^p}\left(T_j^f - T_j^p\right) + \frac{1}{R^p + R^{n1}}\left(T_j^{n1} - T_j^p\right)$$

CPCM layer 1 $$m^{n1} c_p^{n1} \frac{dT_j^{n1}}{dt} = \frac{1}{R^p + R^{n1}}\left(T_j^p - T_j^{n1}\right) + \frac{1}{R^{n1} + R^{n2}}\left(T_j^{n2} - T_j^{n1}\right)$$

CPCM layer 2 $$m^{n2} c_p^{n2} \frac{dT_j^{n2}}{dt} = \frac{1}{R^{n1} + R^{n2}}\left(T_j^{n1} - T_j^{n2}\right) + \frac{1}{R^{n2} + R^{n3}}\left(T_j^{n3} - T_j^{n2}\right)$$

Convection coefficient calculations:

- The convection coefficient at the fluid-metal plate or tube interface is calculated using empirical Nusselt number correlations available in literature

Laminar Flow

$$\overline{Nu} = 3.66 + \frac{0.0668\, Gz_D}{1 + 0.04\, Gz_D^{\frac{2}{3}}}$$

Turbulent Flow (Gnielinski correlation)

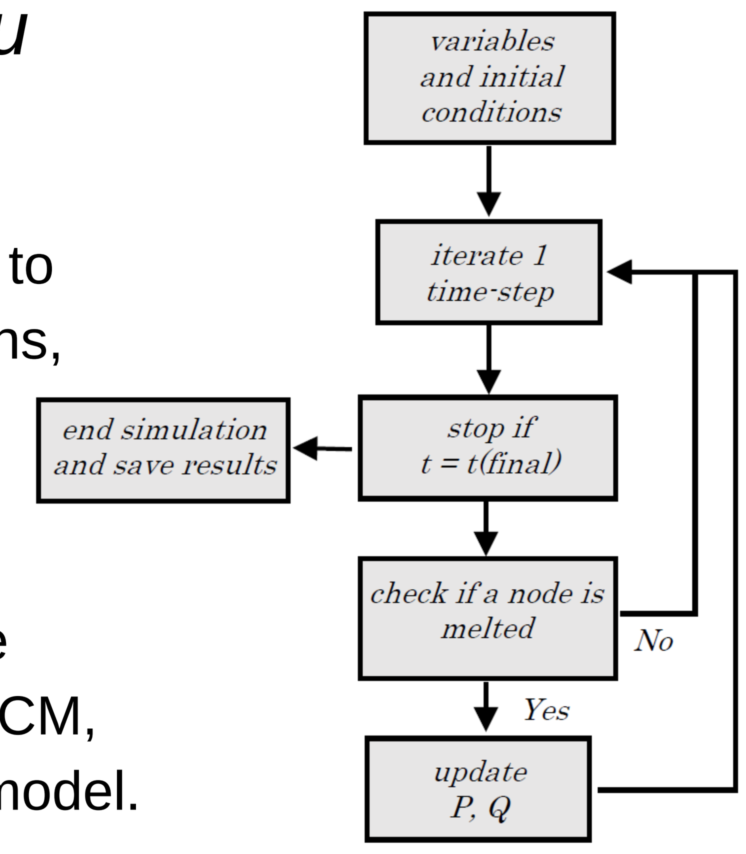
$$Nu = \frac{\left(\frac{f}{8}\right)(Re_D - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}} - 1\right)}$$

Numerical Solution:

The backward Euler method is used to numerically solve the model equations,

$$T(p+1) = \boldsymbol{P}\, T(p) + \boldsymbol{Q}$$

where $\boldsymbol{P}$ and $\boldsymbol{Q}$ are dependent on the properties of the fluid, metal plate, PCM, and the boundary conditions of the model.



Model Validation

The reduced-order model is validated against a high-fidelity computational fluid dynamics (CFD) model made using ANSYS Fluent for both laminar and turbulent fluid flow regimes in extended plate and cylindrical tube geometries.

Cylindrical Tube HX Results (Turbulent Flow Regime)

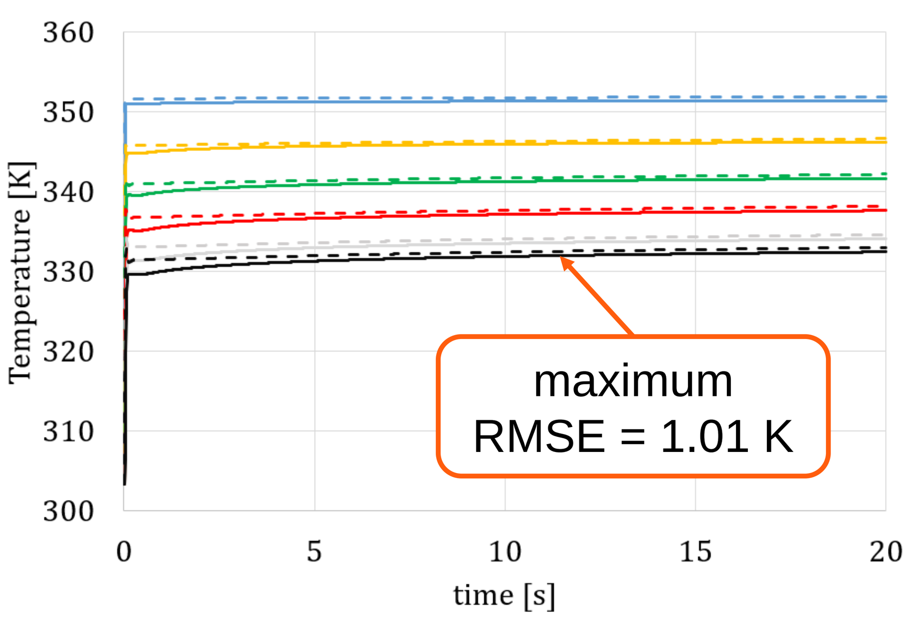


Figure 1: Time evolution of the temperature of different control volumes of fluid.

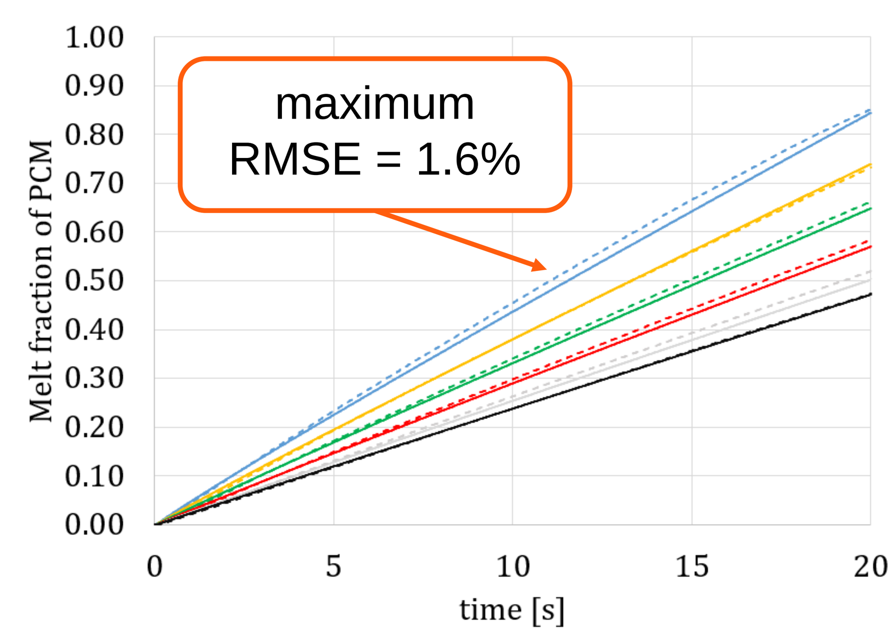


Figure 2: Time evolution of the melt fraction of different sections of composite PCM.

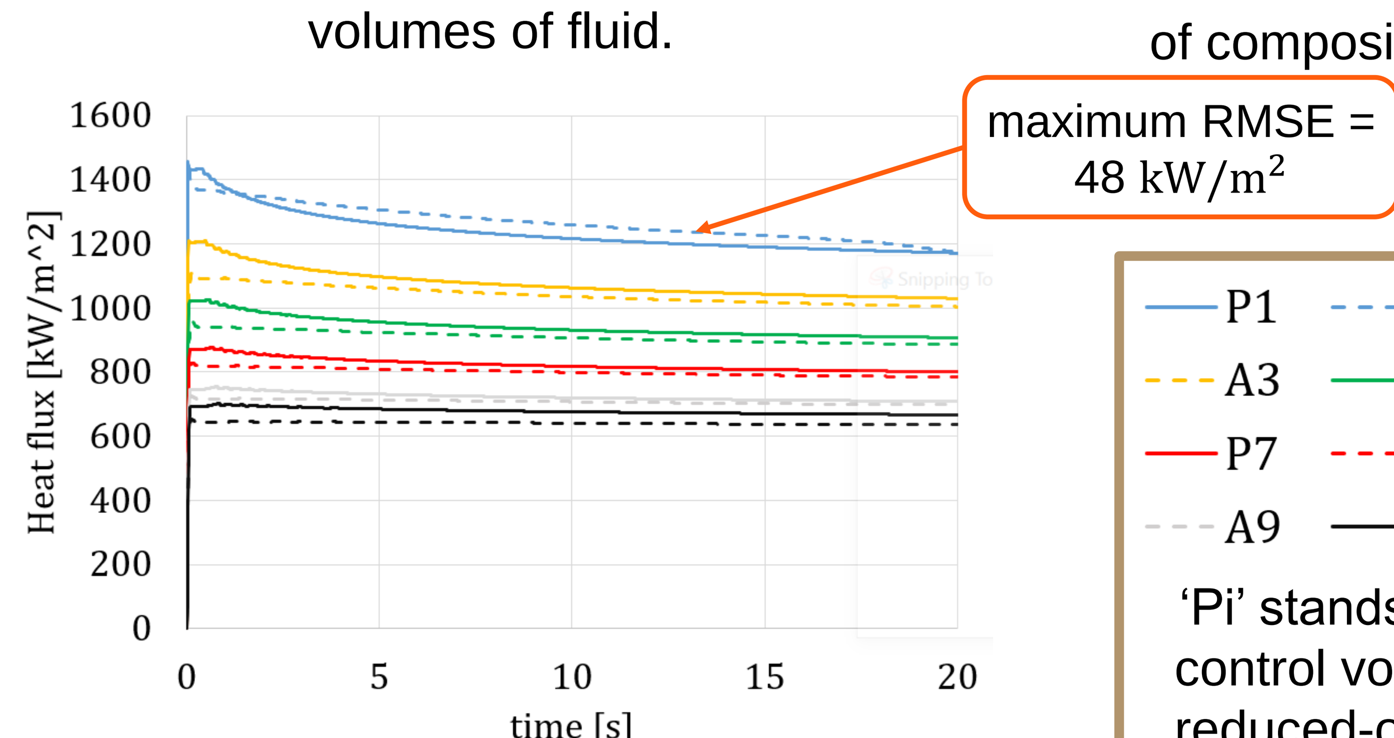
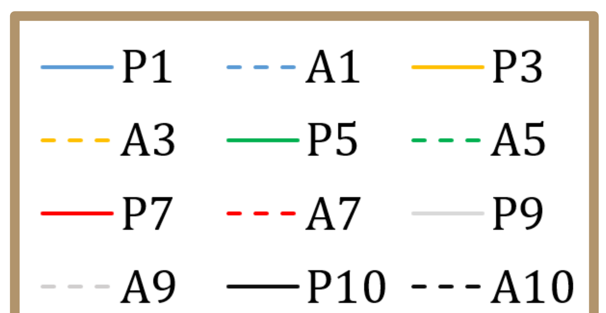


Figure 3: Time evolution of heat flux through the interface between the fluid and metal tube



'Pi' stands for the i^{th} control volume of the reduced-order model and 'Ai' stands for the i^{th} control volume of high-fidelity CFD model

Future Work

1. Sensitivity analysis of reduced-order model to design parameters
2. Formalization and solution of design optimization problem with an emphasis on transient performance objectives

Potential Impact of Research

- Design CES modules such that the heat flux profile along length of the HX evolves in a user-specified manner
- Utilize reduced-order model for both design optimization and control design and synthesis

Acknowledgements

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