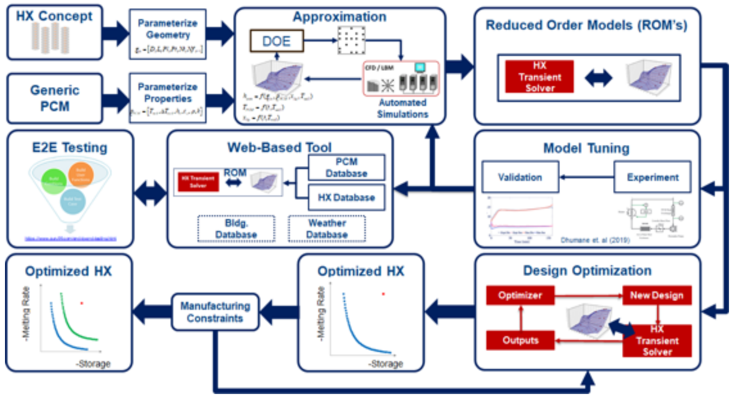
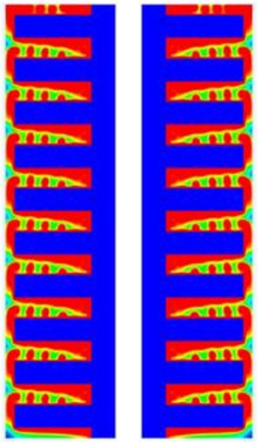
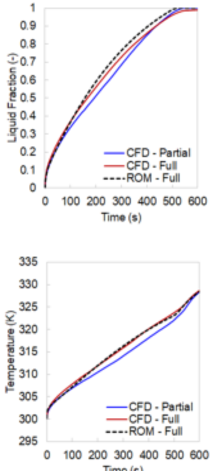
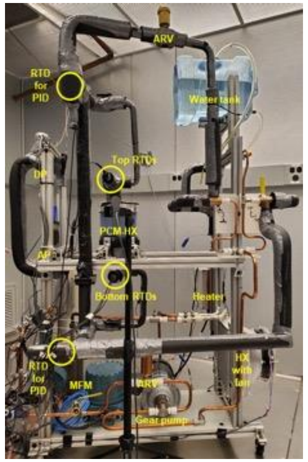
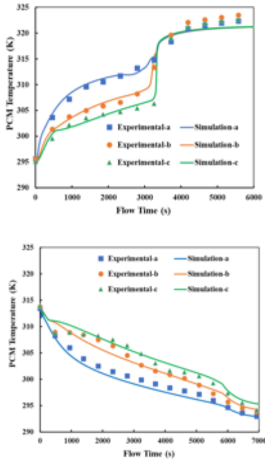
A Novel Framework for Performance Evaluation and Design Optimization of PCM Embedded Heat Exchangers for the Built Environment











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Project Summary

Timeline:

Start date: 04/08/2020

Planned end date: 04/08/2023

Key Milestones

1. Develop a new framework for design optimization; 04/08/2021
2. Develop Web/Desktop UI that incorporates the reduced order models; 04/08/2022
3. Fabricate and test the two PCM-HXs and validate the model; 12/07/2022

Industry Advisors:

Rheem	Active Energy Systems
Carrier	Hussmann
Daikin / Goodman	Johnson Controls
NETenergy	Electrolux
Danfoss	

Budget:

Total Project $ to Date:

- DOE: $460,666
- Cost Share: $117,541

Total Project $:

- DOE: $1,400,000
- Cost Share: $350,000

Project Outcome:

Novel framework for rapid performance evaluation and design optimization of PCM embedded heat exchangers (PCM-HX) designs

An online PCM material database and PCM-HX performance simulation tool to assist the HVAC design community.

Develop and test novel PCM embedded heat exchangers (PCM-HX) achieving DOE’s targets for thermal storage.

Team

- University of Maryland
    - *Expertise*: 30+ years of experience in R&D of heat pumps, refrigerant, HVAC&R components and systems, modeling and optimization software development; system and component test facilities; funded by industry and government
- Heat Transfer Technologies
    - 20+ years of experience in design and mfg. of heat exchangers for pre-production evaluation; development of innovative joining techniques for small diameter tubes and manifolds

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Dr. R. Radermacher
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Dr. J. Ling, Co-PI

J. Muehlbauer

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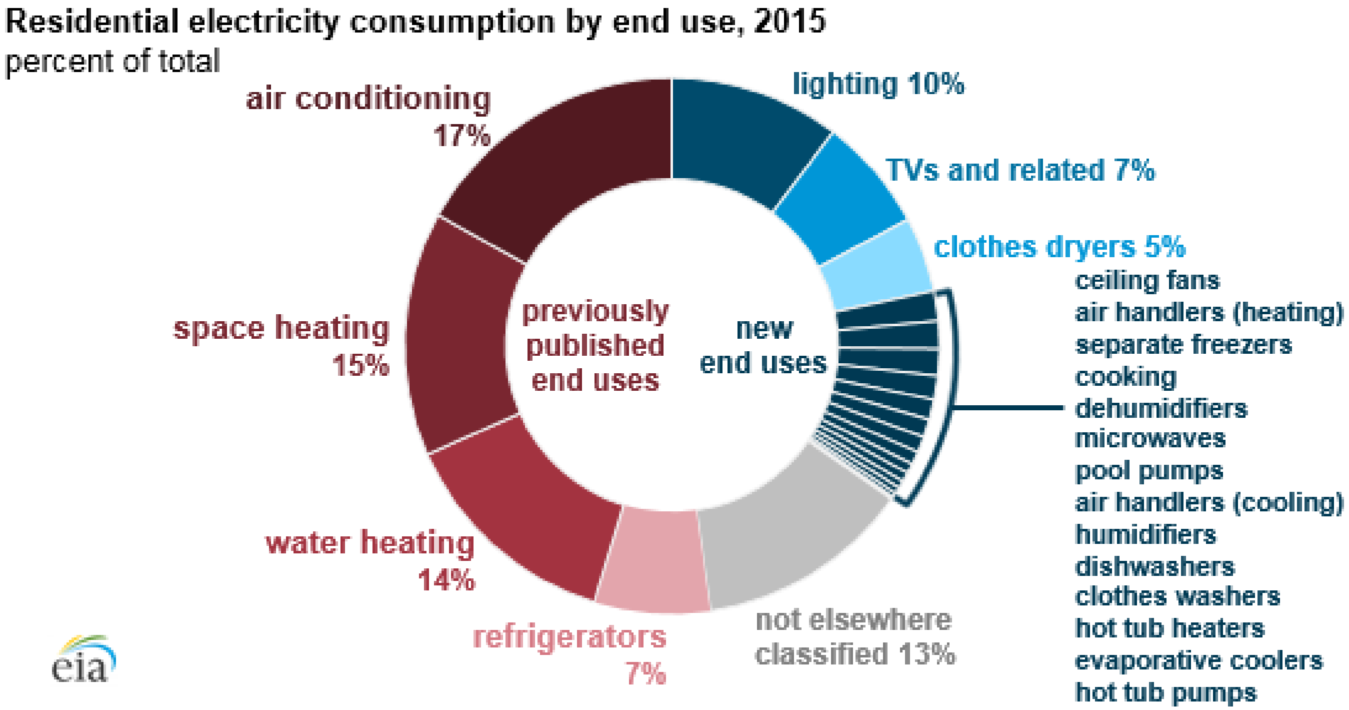
Yoram Shabtay
President, HTT, PI

Dr. John Black
VP, HTT, Co-PI

Challenge

- *Combined average energy consumption of residential and commercial sectors from 2017 to 2020 was 39% while industrial and transportation sectors were 33% and 28%, respectively[a].*
  - *Average total energy consumption: 98 quadrillion BTU*
- *For residential electricity consumption by end use in 2015, the air conditioning, space heating, and water heating took up 46% of the total.*
- *One-third of U.S. households struggles with meeting energy needs[b].*
- *The high demand of air conditioning and heating during peak electricity hours*
  - *Needs for load balancing on electric grids and power plants*
- *Deployment of renewable energy coupled with HVAC systems*



Source: U.S. Energy Information Administration, *2015 Residential Energy Consumption Survey*

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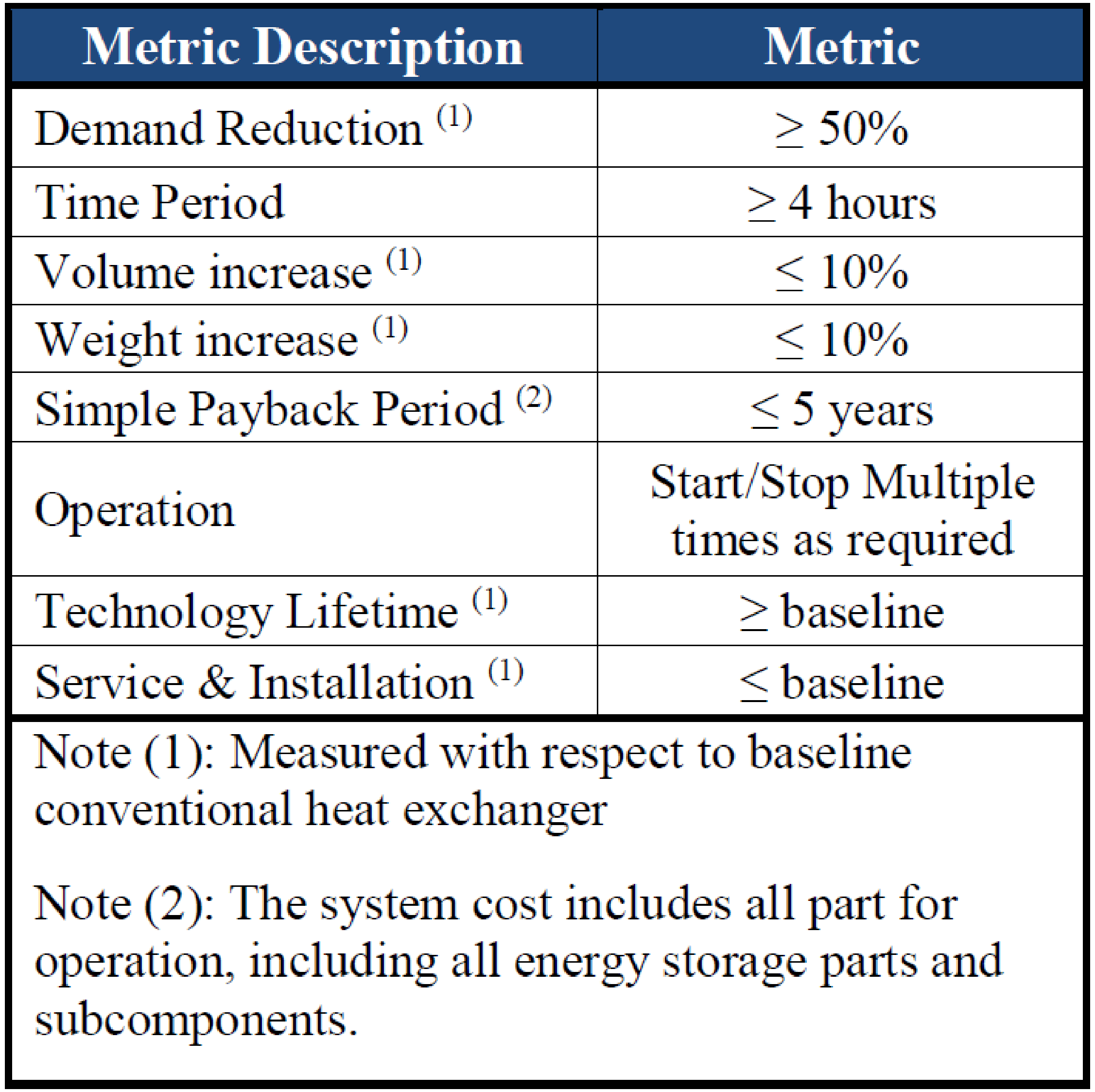
[a] - U.S. Energy Information Administration, Monthly Energy Review – Table 2.1
[b] - U.S. Energy Information Administration, Residential Energy Consumption Survey 2015

Objectives

- *Develop a novel framework for performance evaluation and design optimization of PCM-embedded heat exchangers (PCM-HX)*
- *Develop and test a PCM embedded heat exchangers (PCM-HX)*
- *Develop an online PCM material database and PCM-HX performance simulation tool to assist the design community on common use-cases such as Single/multiple flow path(s) fluid-to-PCM configuration and air-to-fluid-to-PCM configuration*

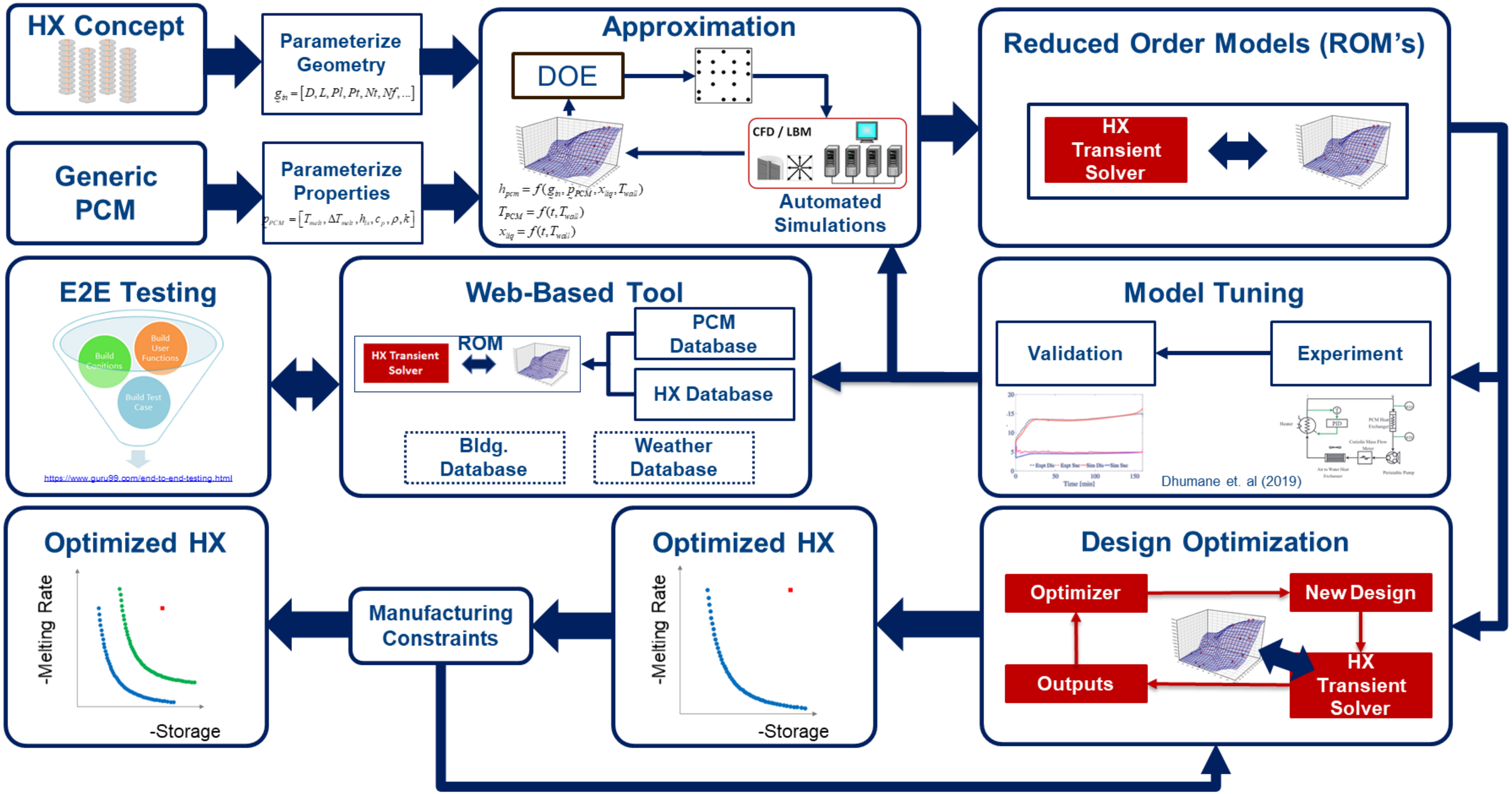


Metric Description	Metric
Demand Reduction (1)	$\geq$ 50%
Time Period	$\geq$ 4 hours
Volume increase (1)	$\leq$ 10%
Weight increase (1)	$\leq$ 10%
Simple Payback Period (2)	$\leq$ 5 years
Operation	Start/Stop Multiple times as required
Technology Lifetime (1)	$\geq$ baseline
Service & Installation (1)	$\leq$ baseline

Note (1): Measured with respect to baseline conventional heat exchanger

Note (2): The system cost includes all part for operation, including all energy storage parts and subcomponents.

Approach – Framework



HX Concept

Parameterize Geometry

$g_{in} = [D, L, Pl, Pt, Nt, Nf, \ldots]$

Generic PCM

Parameterize Properties

$p_{PCM} = [T_{melt}, \Delta T_{melt}, h_{ls}, c_p, \rho, k]$

Approximation

DOE

$h_{pcm} = f(g_{in}, p_{PCM}, x_{liq}, T_{wall})$

$T_{PCM} = f(t, T_{wall})$

$x_{liq} = f(t, T_{wall})$

CFD / LBM

Automated Simulations

Reduced Order Models (ROM's)

HX Transient Solver

E2E Testing

https://www.guru99.com/end-to-end-testing.html

Web-Based Tool

HX Transient Solver

ROM

PCM Database

HX Database

Bldg. Database

Weather Database

Model Tuning

Validation

Experiment

Dhumane et. al (2019)

Optimized HX

Manufacturing Constraints

Optimized HX

Design Optimization

Optimizer

New Design

Outputs

HX Transient Solver

Approach

Year-1: Develop the PCM-HX Design and Optimization Framework

COMPLETE

- *Extensive **literature review** on PCM-HXs and modeling techniques*
- *Construction of commercially available **PCM property database***
- *Development of a **new framework** for PCM-HX design optimization for built environment applications*
- *Fabricate and test **simple PCM-HX geometries** for fundamental control volume validation*
- *Establish **applications of interest***

Year-2: Design, Fabricate and Test Heat Exchangers Resulting from Exercising the Framework

- *Design, fabricate, and test the **PCM-HX prototypes***
- *Develop **Web/Desktop UI** that incorporates the reduced order models*
- *Update **framework**, generate **reduced order performance map** and test the integration in building simulation tools*

Year-3: Validate and Improve the Design and Optimization Framework

- *Fabricate and test the PCM-HXs and **validate the model***
- *Conduct a **second round** of performance map generation and integrate these with UI*
- ***Final framework** and documentation delivery*

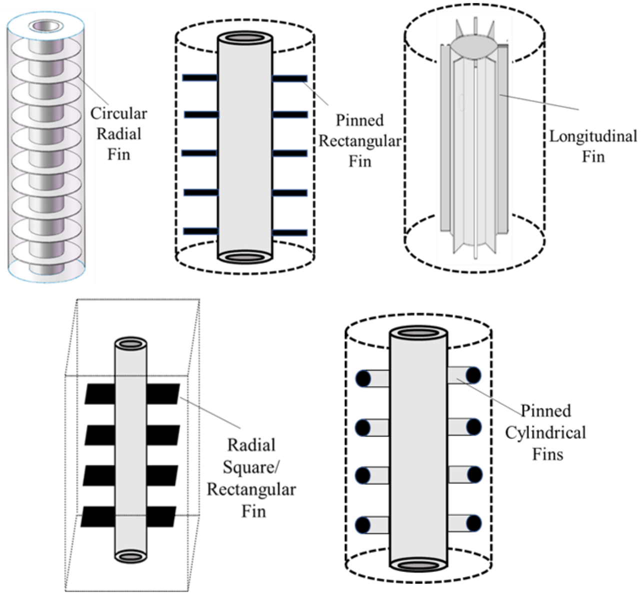
Impact

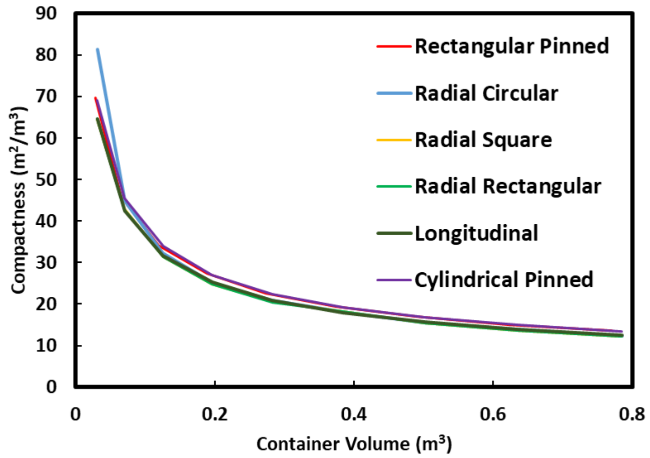
- **Design community impact**
  - Easy to use online simulation tool for design engineers
- **Advancement of PCM-HX design, testing and modeling technology**
- **Large scale financial savings and efficient energy distribution when widely employed**
  - In 2015, the energy consumption for residential sector was 21 quad BTU[a]
  - Air conditioning and water heating : 31% (6.5 quad BTU) [b]
  - If employed in half of the residential sector, with 50% demand reduction, the yearly energy savings will be 1.6 quad BTU
- **Next-generation fully optimized PCM-HX obtained from the framework**
  - Capable of 50% demand reduction with less than 10% volume and 20% weight increase

[a] - U.S. Energy Information Administration, Monthly Energy Review – Table 2.1
[b] - U.S. Energy Information Administration, *2015 Residential Energy Consumption Survey*

Literature Review Summary

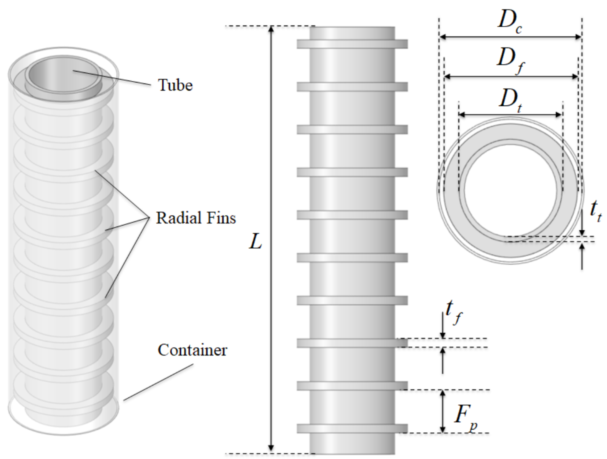
- **PCM-HX configurations and HT enhancement**
  - Fins and conductive particle embedded enhanced PCMs are the most widely used HT enhancement techniques (can reduce charge/discharge time by up to 50%)
  - Trade-off between charge/discharge time and energy storage capacity can be considered by opting for designs with high compactness
  - First order analysis shows that radial circular fins have higher compactness
  - Combining fins with particle enhanced PCM-HX, non-uniform arrangement of fins, and topology optimization can lead to more compact promising designs
- **PCM-HX modeling techniques**
  - Analytical and simple iterative numerical models
    - Advantage - Fast
    - Disadvantage- Not very accurate and becomes complicated when applied to multidimensional problem
  - CFD based models
    - Advantage- More reliable, accurate, can be applied to complicated geometries
    - Disadvantage- Computationally expensive, requires expensive setup
  - Resistance-Capacitance based model
    - An approximate method problem which can be implemented easily to estimate charge/discharge time (2-D implementation will improve accuracy)
    - Accurate prediction of PCM internal temperature is less important in practical case

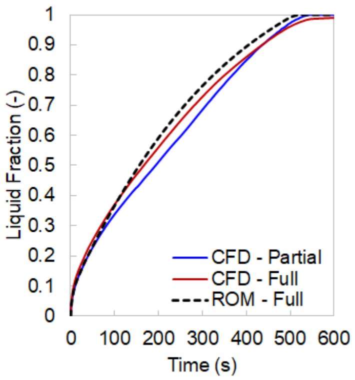


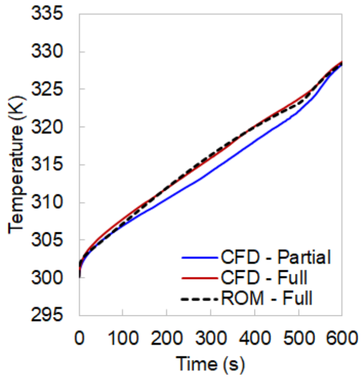


Year-1 Accomplishments

Reduced Order Model (ROM)

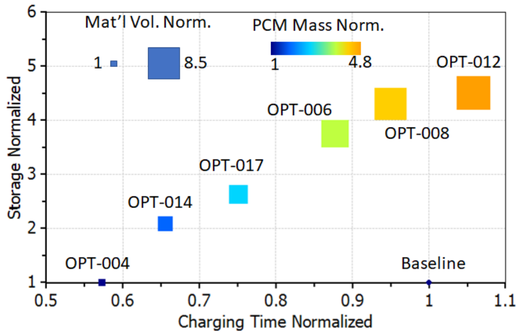


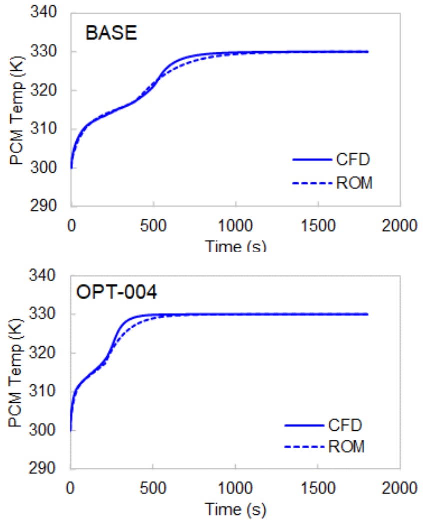




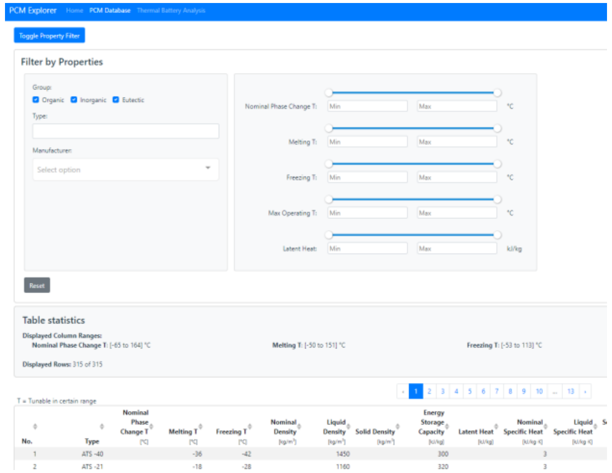
Optimization

Run Time (s)	CFD	ROM	Speed Increase
Training Set	3,300,000	5.67	580,000
Cross-Validation Set	330,000	0.77	430,000
Test Set	86,000	0.36	240,000
Total	3,700,000	6.80	540,000





Web-based tool



Filter by Properties

Group: ☑ Organic ☑ Inorganic ☑ Eutectic

Type:

Manufacturer: Select option

Nominal Phase Change T: Min Max °C

Melting T: Min Max °C

Freezing T: Min Max °C

Max Operating T: Min Max °C

Latent Heat: Min Max kJ/kg

Table statistics

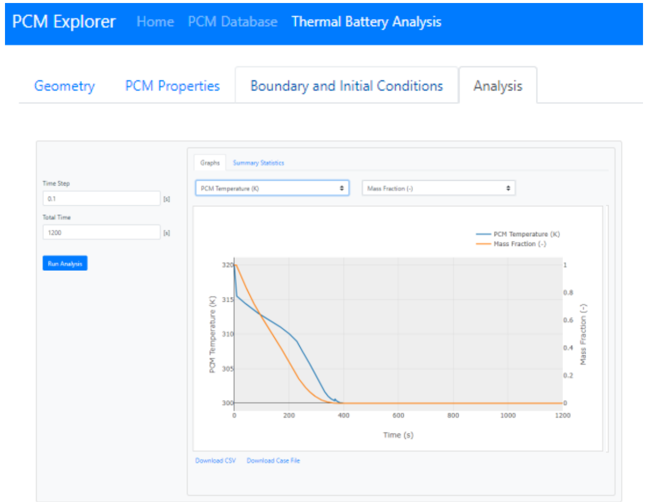
Displayed Column Ranges:
Nominal Phase Change T: [-65 to 164] °C
Melting T: [-50 to 151] °C
Freezing T: [-53 to 113] °C

Displayed Rows: 315 of 315

‹ 1 2 3 4 5 6 7 8 9 10 ... 13 ›

T = Tunable in certain range

No.	Type	Nominal Phase Change T [°C]	Melting T [°C]	Freezing T [°C]	Nominal Density [kg/m³]	Liquid Density [kg/m³]	Solid Density [kg/m³]	Energy Storage Capacity [kJ/kg]	Latent Heat [kJ/kg]	Nominal Specific Heat [kJ/kg·K]	Liquid Specific Heat [kJ/kg·K]
1	ATS -40		-36	-42		1450		300		3	
2	ATS -21		-18	-28		1160		320		3	



Time Step: 0.1 [s]

Total Time: 1200 [s]

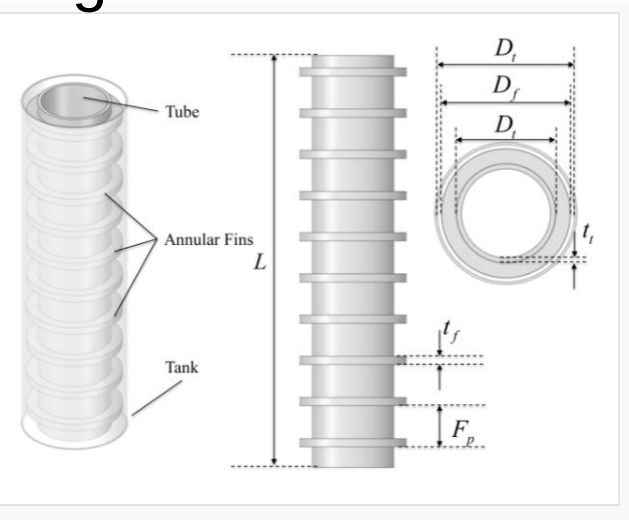
PCM Temperature (K)

Mass Fraction (-)

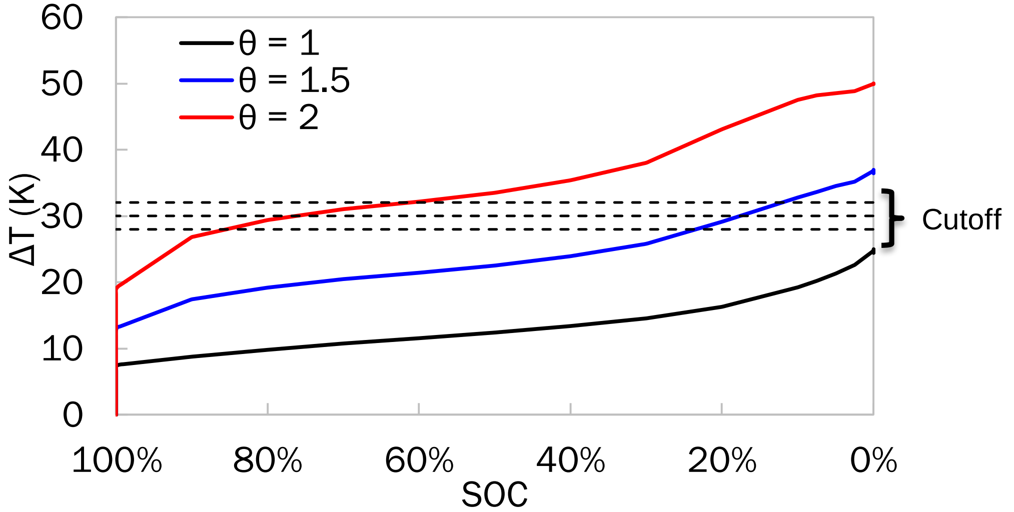
Year-1 Accomplishments (cont'd)

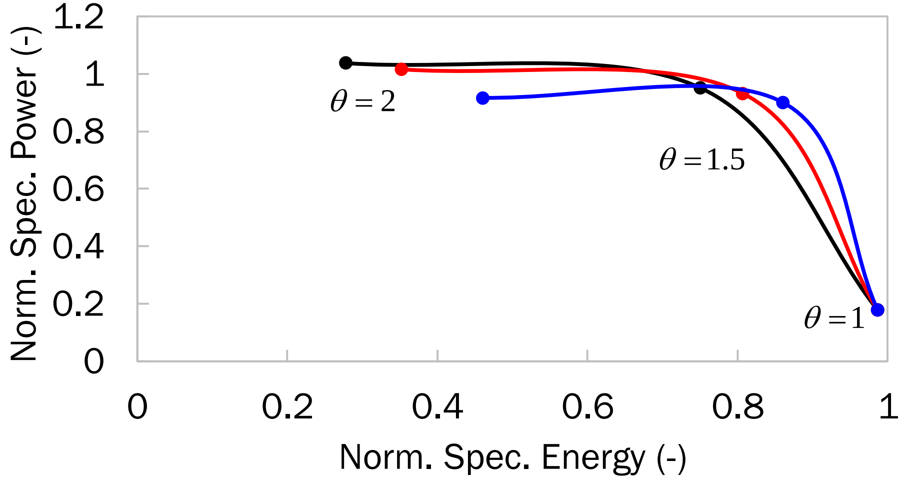
ROM enables quick generation of the thermal battery Ragone plots[1]

E.g.



Dimension	Unit	Value
Tube diam.	mm	5
Tube length	mm	100
Fin diam.	mm	25.4
Fin thick.	mm	0.25
Fin pitch	mm	5
Tank diam.	mm	25.9
PCM	-	RT35





$$\Delta T = T_{wall} - T(t)[K] \leftrightarrow \Delta U[V]$$

$$\theta = \frac{UA\cdot\Delta T}{UA\cdot\Delta T_o}\left[\frac{W}{W}\right] \leftrightarrow \frac{i}{i_{\Delta V_o}}\left[\frac{A}{A}\right]$$

$$se = 1 - \frac{h_{\Delta T=\Delta T_{cutoff}}}{h_o}; h : enthalpy$$

$$sp = \frac{se\cdot h_o}{t_{\Delta T=\Delta T_{cutoff}} - t_o}$$

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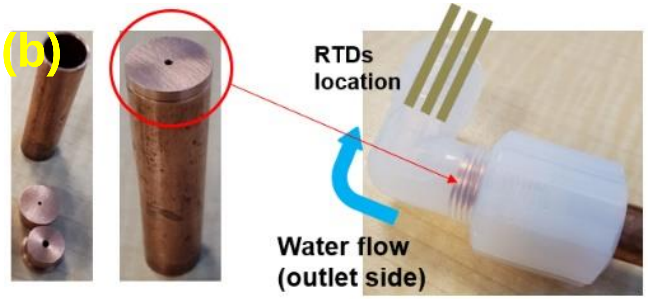
[1] Jason Woods, Allison Mahvi, Anurag Goyal, Eric Kozubal, Adewale Odukomaiya and Roderick Jackson. Rate capability and Ragone plots for phase change thermal energy storage. Nature Energy, 6, (2021), pp. 295-302

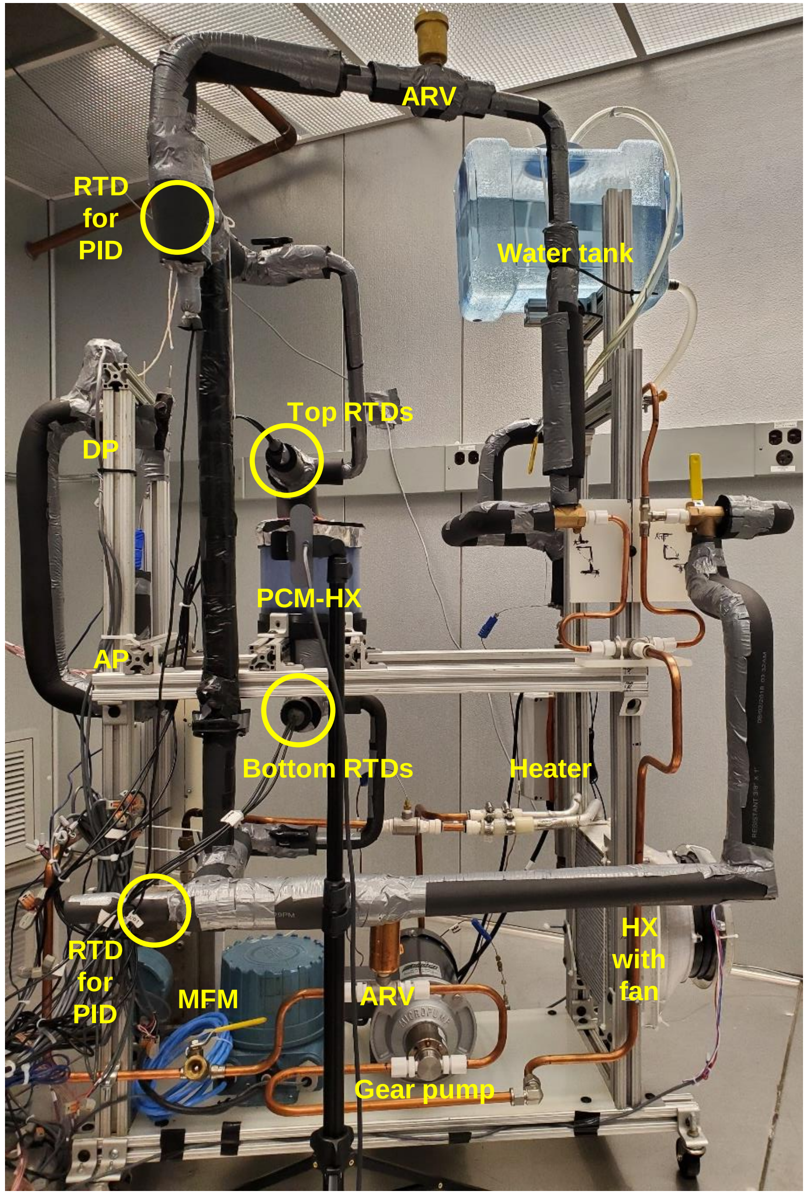
Year-1 Assessment

- *In need of extensive PCM data gathering and performance testing of PCM-HXs based on simple geometries, using the in-house test facility*
- *Actions*
  - *Construction of PCM database:*
    - *Surveyed 12 OEMs, collected property data for 300+ commercially available PCM products*
  - *Water-to-PCM test facility construction*
    - *Construction of test facility capable of testing different PCM-HX configurations*
    - *Accessory components for accurate water-side measurement: 3D printed RTD guides, turbulator inserts*
  - *Simple geometry PCM-HX fabrication and experiment*
    - *Successfully fabricated and tested the straight and helix tube PCM-HXs*

3D printed RTD guides



Orifice type turbulator inserts



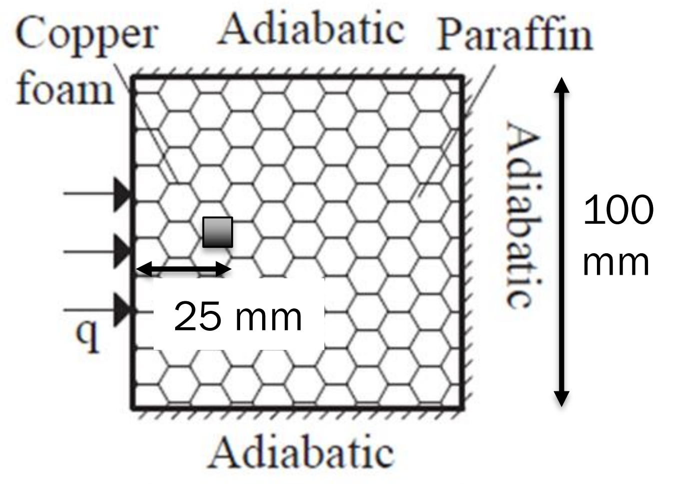
Year-1 Assessment (cont'd)

- **PCM-HX configurations and HT enhancement**
  - Annular PCM-HX are one of the most investigated configurations
  - Fins and conductive particle embedded enhanced PCMs are the most widely used HT enhancement techniques
  - Trade-off between melting rate and energy storage capacity exists
  - Optimization is necessary but not straightforward
- **PCM-HX modeling techniques**
  - Analytical and simple iterative numerical models are fast but often not very accurate
  - CFD based models are more reliable and accurate but computationally expensive
  - Alternative methods like Lattice Boltzmann may provide some computational cost advantages but developing optimization framework can be difficult
  - Minimizing natural convection and focusing on conduction dominated modeling is necessary to reduce computational cost

Year-1 Assessment (cont'd)

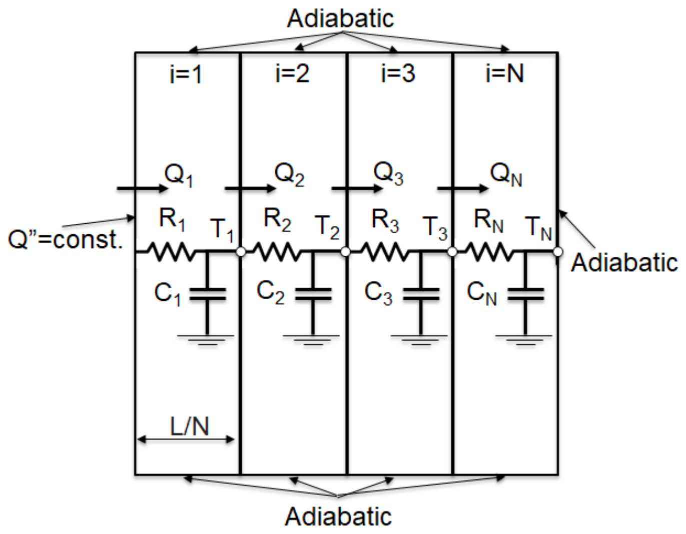
- **CFD is still computationally too expensive for this project, despite the speed gains achieved in the first year**
- **Future analyses require another breakthrough in speed increase**
- **Actions:**
  - Focus on diffusion-dominated problems that minimize natural convection (e.g., enhanced PCM's with metal foam or graphite, high fin density)
    - Motion of liquid PCM is physically complex and computationally intensive
    - Enhanced PCM's typically result in better heat transfer performance, albeit at the cost of reduced storage volume
  - Develop a hybrid lightweight solver (Resistance-Capacitance-Based)
  - Explore shape & topology optimization for novel surface structures

Progress – Year-2 (Mid.)



Zheng et al. (2018)[1]

1-D Resistance-Capacitance Model (RBM)[2]



Explicit time-marching formulation:

$$\frac{dT_{i,t+1}}{dt} = \frac{\dot{Q}_{i-1,t} - \dot{Q}_{i,t}}{C_{i,t}} \qquad \dot{Q}_{i,t} = \dot{Q}''\cdot L; i = 1$$

$$T_{i,t+\Delta t} = T_{i,t} + \frac{dT_i}{dt}\cdot \Delta t \qquad \dot{Q}_{i,t} = \frac{T_{i-1,t} - T_{i,t}}{R_{i-1,t}}; i \geq 2$$

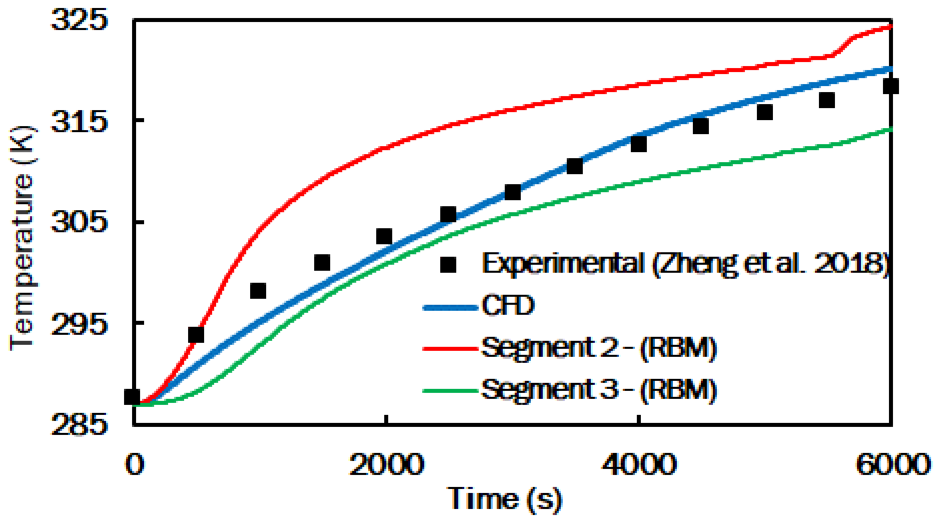
$$R_{i,t} \approx R_{cond} = \frac{L/N}{k_{eff}\cdot A}; R_{nat\_conv} \ll R_{cond}$$

$$C_{PCM} = \begin{cases} C_s; & T \leq T_s \\ \dfrac{C_s\left(T_s - T_{ref}\right) + h_{sl}\cdot f}{T - T_{ref}}; & T_s \leq T \leq T_l \\ \dfrac{C_s\left(T_s - T_{ref}\right) + h_{sl} + C_s\left(T - T_l\right)}{T - T_{ref}}; & T > T_l \end{cases}$$

$$C_{i,t} = \left(1-\gamma\right)C_{PCM} + \gamma C_{FOAM}$$

f = liquid mass fraction

γ = foam porosity



Model	Size	Run time (h)
CFD	10K elements (2D)	29
RCM	10 segments (1D)	0.7

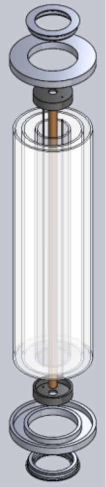
~40x

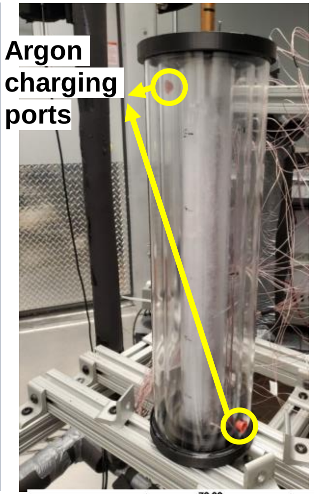
[1] Huanpei Zheng, Changhong Wanga, Qingming Liu, Zhongxuan Tian, Xianbo Fan. Thermal performance of copper foam/paraffin composite phase change material. Energy Conversion and Management 157 (2018), pp. 372–381.

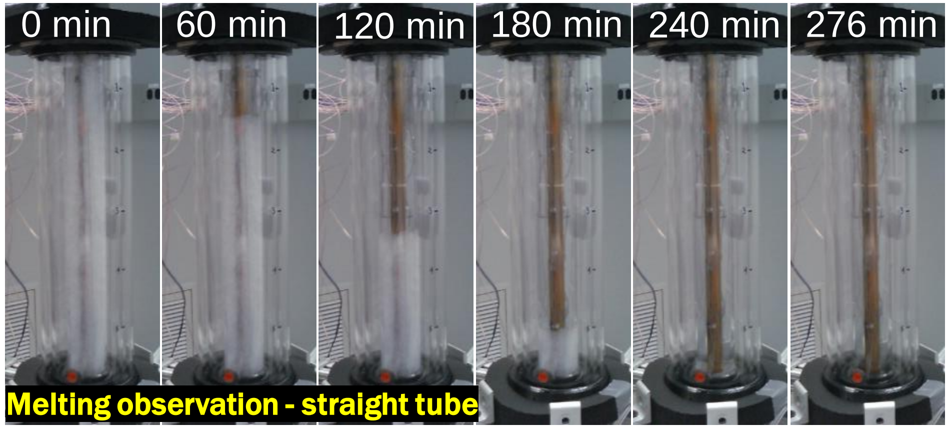
[2] V. Madhav, Karthik G. M., V. Raghavendra, P. Kumar, A. Ambirajan. "Thermal Resistance-Capacitance Network Model for a PCM Coupled Heat Pipe", 20th IEEE ITHERM Conference, 2021.

Progress – Year-2 (Mid.) (cont'd)

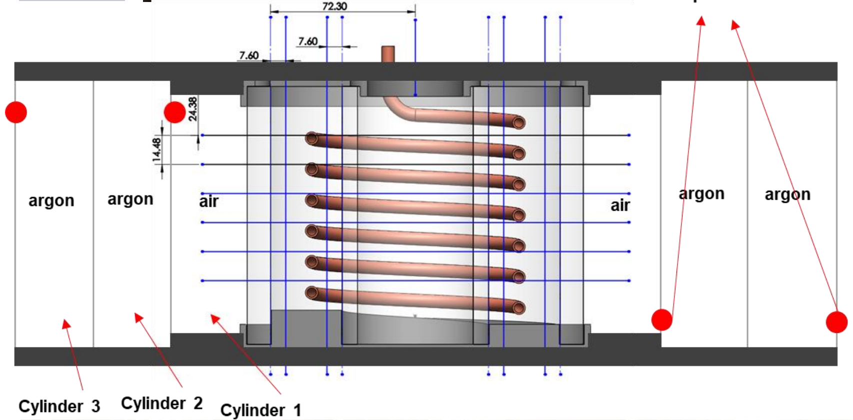
- *Straight & helix tube PCM-HX fabrication and experiments*
  - *Implementation of air and argon cylinders for improved insulation*
  - *Visualization of phase change processes*
  - *Laminar and turbulent flow tests with upward and downward water flow directions*
  - *Repeatability tests*
  - *Heat loss estimation with thermocouple pairs, thermocouple arrays inside the PCM-HX*
  - *Energy balance analysis for each melting and solidification process: maximum discrepancy under 6% (straight laminar), 8% (helix laminar), 17% (helix turbulent)*
  - *Water-side uncertainty in heat transfer:*
    - *Straight: laminar - ±2% [M] and ±4% [S]*
    - *Helix: laminar - ±1% [M] and ±2% [S], turbulent – ±2% [M] and ±6% [S]*

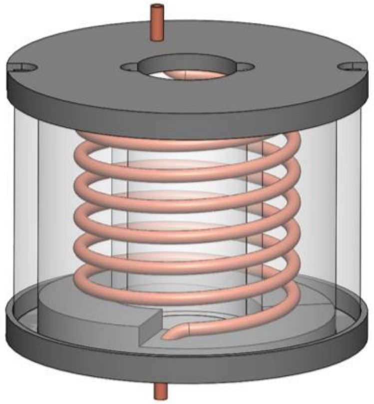


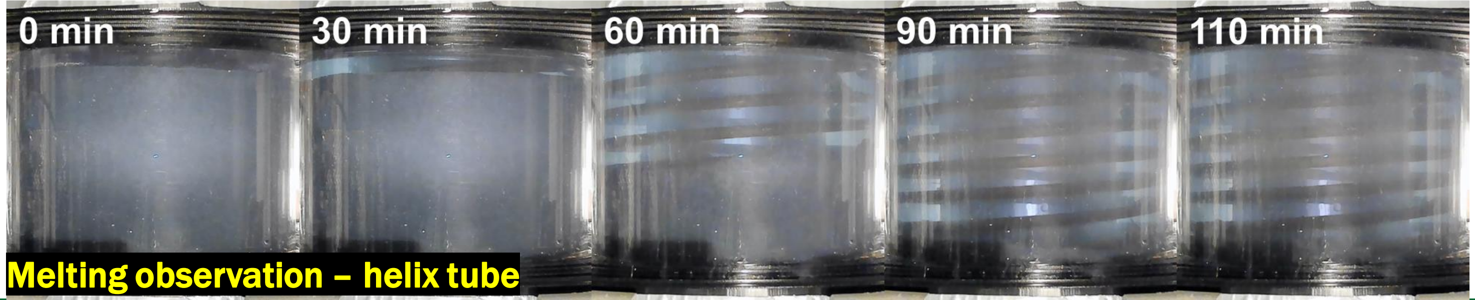




Melting observation - straight tube

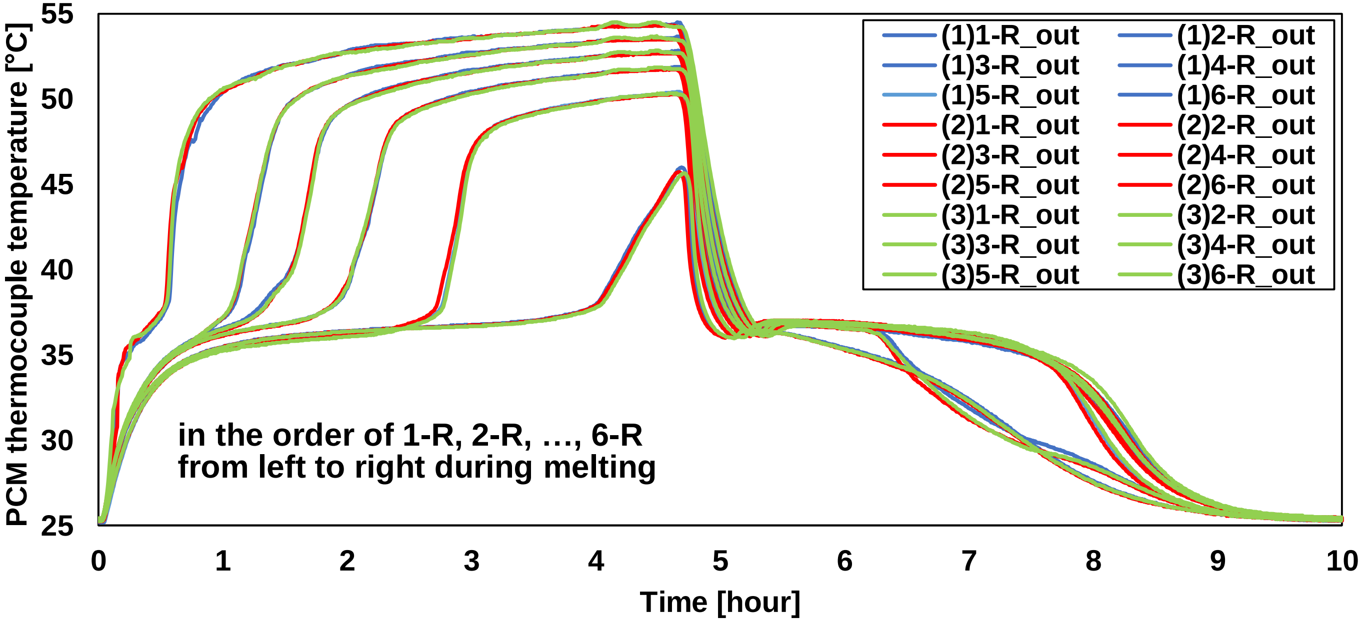




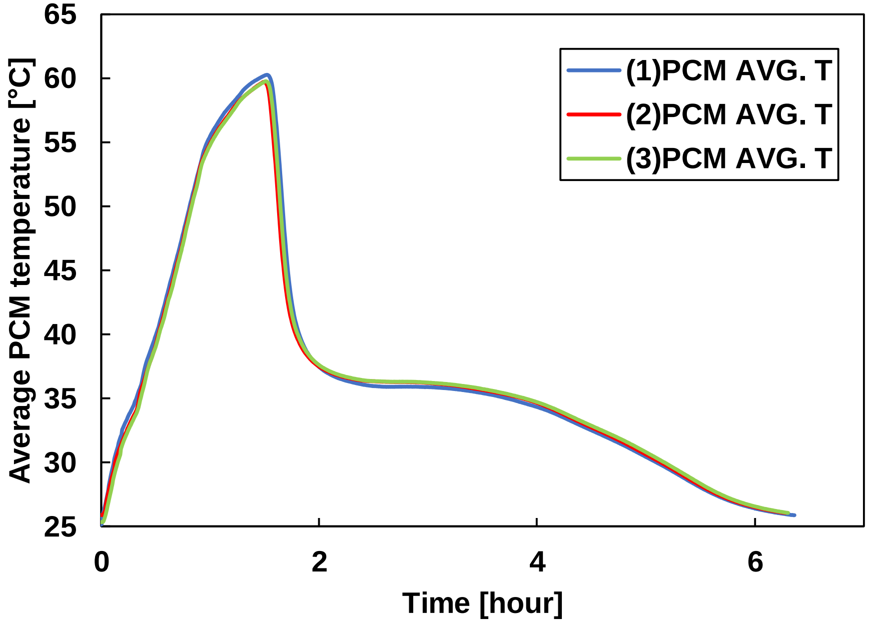


Melting observation – helix tube

Progress – Year-2 (Mid.) (cont'd)



Straight tube PCM-HX repeatability tests – PCM temperature distribution by layers

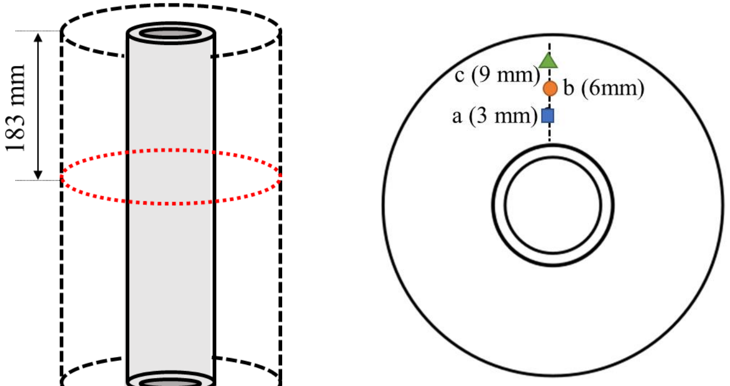


Helix tube PCM-HX repeatability tests – PCM average temperatures

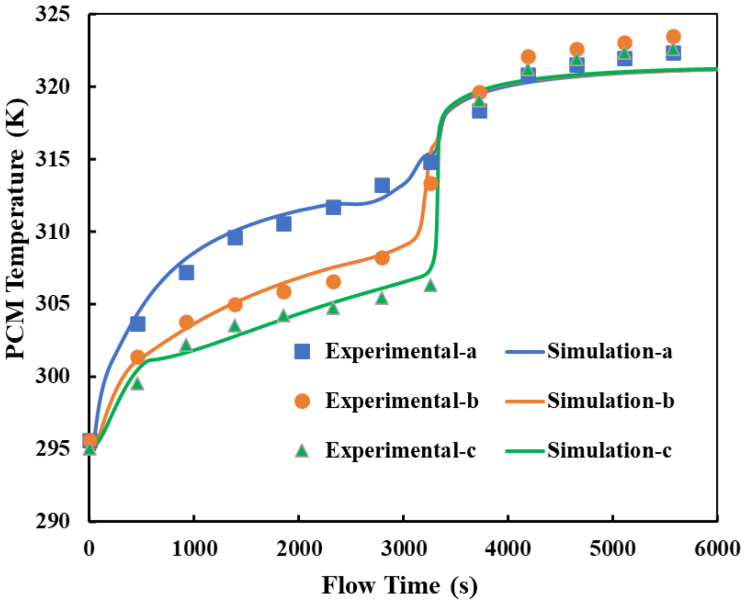
- *Both straight and helix tube PCM-HXs were cycled three times to verify the repeatability*
- *For the straight tube plots, the outer right hand side thermocouples from each layer was plotted for simplicity*
  - *(#-R_out), #: layer number, R: right hand side, out: outer*
  - *Layers 1 to 6 are evenly spaced out from the top to bottom of the PCM-HX*
- *For the helix tube plots, the average of the PCM temperatures were plotted for simplicity*

Progress – Year-2 (Mid.) (cont'd)

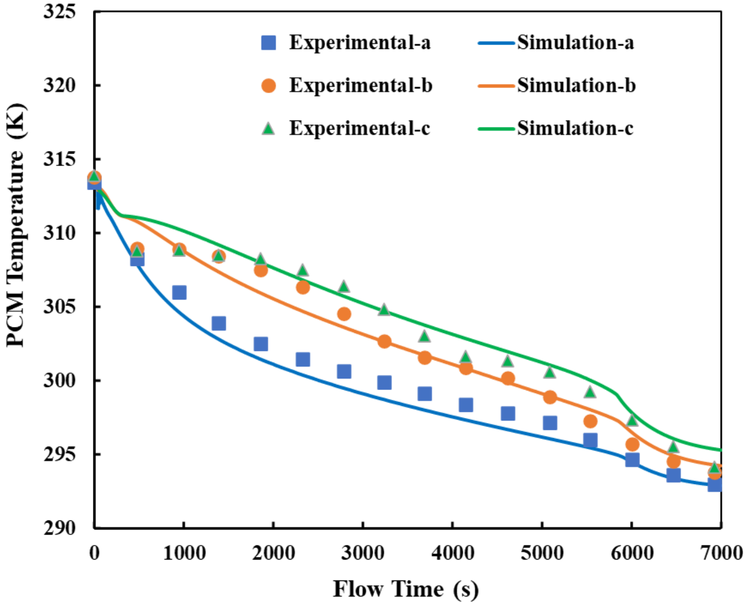
Model Validation from Literature



Ref: Longeon et al. (2013)



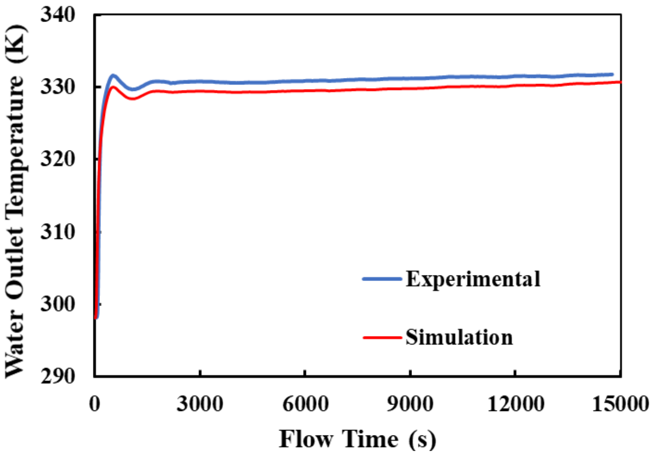
Melting



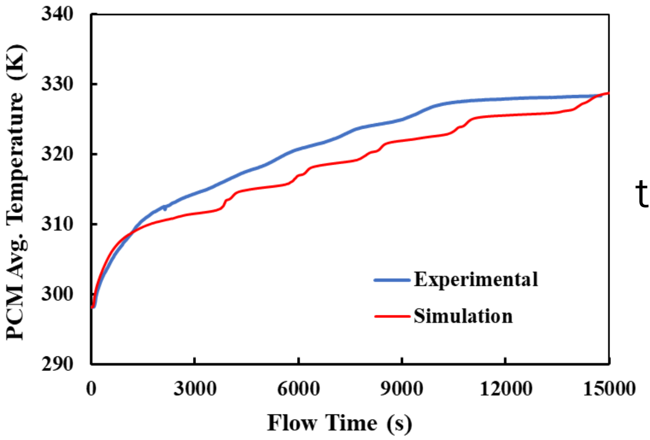
Solidification

Model Validation from In-house Data

- All necessary thermophysical properties of PT37 were not confirmed
- Thermal expansion coefficient can significantly impact effects of natural convection [1]



Water Outlet Temperature



PCM Average Temperature

Maximum water outlet temperature difference is ≈1° C

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[1] Alam et al. (2021)

Stakeholder Engagement

- Stakeholders: BTO, HVAC and TES OEMs, PCM material developers and suppliers, building energy modelers
- First semi-annual industry partner meeting was held on Apr. 23, 2021
- Participants: Rheem, Carrier, Daikin/Goodman, NETenergy, Active Energy Systems, Hussmann, Johnson Controls, Electrolux and Danfoss
- Plan: 4+ Annual meetings

- Reaching out to PCM manufacturers, to improve the database of material characteristics, potentially undertake material testing
- Collaboration Opportunities
  - Performers focusing on novel materials
  - Performers focusing on integrating PCM-HX in HVAC equipment

Remaining Project Work

Immediate Future Work

- *Experimental*
  - *Finned-tube PCM-HX design and fabrication*
  - *Performance test of the finned-tube PCM-HX*
  - *Enhanced PCM-HX with copper foam/ graphite shavings*
- *Simulation*
  - *Development of resistance-capacitance-based model for enhanced PCM-HX*
  - *Development of reduced order model*
  - *Web-based tool*
  - *Use topology optimization to develop novel fin/surface structures*
- *Overall*
  - *Design of new PCM-HX prototypes for air conditioning and water heating application*

Remaining Future Work

- *Design and fabricate the final versions of PCM-HXs for performance testing and validation*

Thank You

Performing Organization(s): University of Maryland, Heat Transfer Technologies LLC.

PI: Dr. Vikrant Aute, Research Scientist

301-405-8726; vikrant@umd.edu

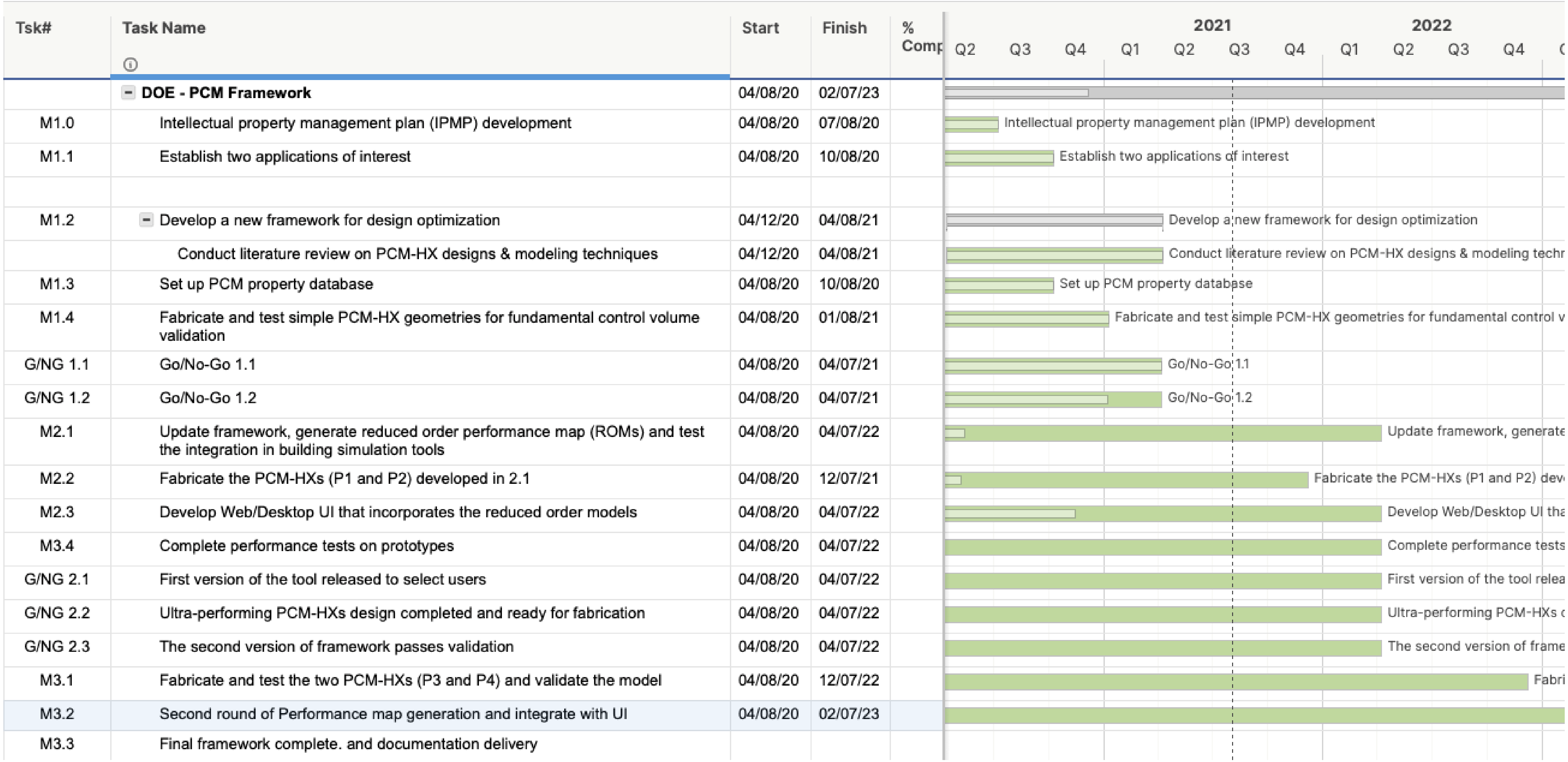
REFERENCE SLIDES

Project Budget

Project Budget: 1,750,000 (including cost share)
Variances: NA
Cost to Date: $578,207 (including cost share)
Additional Funding: None

Budget History					
4/8/2020 – FY 2020 (past)		FY 2021 (current, cumulative)		FY 2022 – 4/7/2023 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$336,555	$86,508	$460,666	$117,541	$939,334	$232,459

Project Plan and Schedule



Tsk#	Task Name	Start	Finish	% Comp
	DOE - PCM Framework	04/08/20	02/07/23	
M1.0	Intellectual property management plan (IPMP) development	04/08/20	07/08/20	
M1.1	Establish two applications of interest	04/08/20	10/08/20	
M1.2	Develop a new framework for design optimization	04/12/20	04/08/21	
	Conduct literature review on PCM-HX designs & modeling techniques	04/12/20	04/08/21	
M1.3	Set up PCM property database	04/08/20	10/08/20	
M1.4	Fabricate and test simple PCM-HX geometries for fundamental control volume validation	04/08/20	01/08/21	
G/NG 1.1	Go/No-Go 1.1	04/08/20	04/07/21	
G/NG 1.2	Go/No-Go 1.2	04/08/20	04/07/21	
M2.1	Update framework, generate reduced order performance map (ROMs) and test the integration in building simulation tools	04/08/20	04/07/22	
M2.2	Fabricate the PCM-HXs (P1 and P2) developed in 2.1	04/08/20	12/07/21	
M2.3	Develop Web/Desktop UI that incorporates the reduced order models	04/08/20	04/07/22	
M3.4	Complete performance tests on prototypes	04/08/20	04/07/22	
G/NG 2.1	First version of the tool released to select users	04/08/20	04/07/22	
G/NG 2.2	Ultra-performing PCM-HXs design completed and ready for fabrication	04/08/20	04/07/22	
G/NG 2.3	The second version of framework passes validation	04/08/20	04/07/22	
M3.1	Fabricate and test the two PCM-HXs (P3 and P4) and validate the model	04/08/20	12/07/22	
M3.2	Second round of Performance map generation and integrate with UI	04/08/20	02/07/23	
M3.3	Final framework complete. and documentation delivery			

Approach – Barriers and Risks

PCM's Thermophysical Properties

- *Limited published/readily available information*[1]
- *Extremely low thermal conductivity*
- *Volume change*
- *Thermal and chemical stability*

→

- *Proper PCM selection with industry partners*
- *PCM thermal conductivity enhancement*

System Size, Cost and Complexity

- *Increasing weight, volume, and cost upon integration*
- *Integration/retrofit concern with existing HVAC applications*

→

- *Novel PCM-HX design for compactness*

Computational Cost[2]

- *CFD modeling is computationally expensive*

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- *Reduced order models*

[1] Alam, Tanjebul; Bacellar, Daniel; Ling, Jiazhen; Aute, Vikrant. Effect of thermal expansion coefficient, viscosity and melting range in simulation of PCM embedded heat exchangers with and without fins. Proceedings of the ASME 2021 International Mechanical Engineering Congress and Exposition IMECE2021, November 1-5, 2021 *(Accepted Manuscript)*

[2] Bacellar, Daniel; Alam, Tanjebul; Ling, Jiazhen; Aute, Vikrant. A Study on Computational Cost Reduction of Simulations of Phase-Change Material (PCM) Embedded Heat Exchangers. 18th International Refrigeration and Air Conditioning Conference at Purdue, May 24-28, 2021