



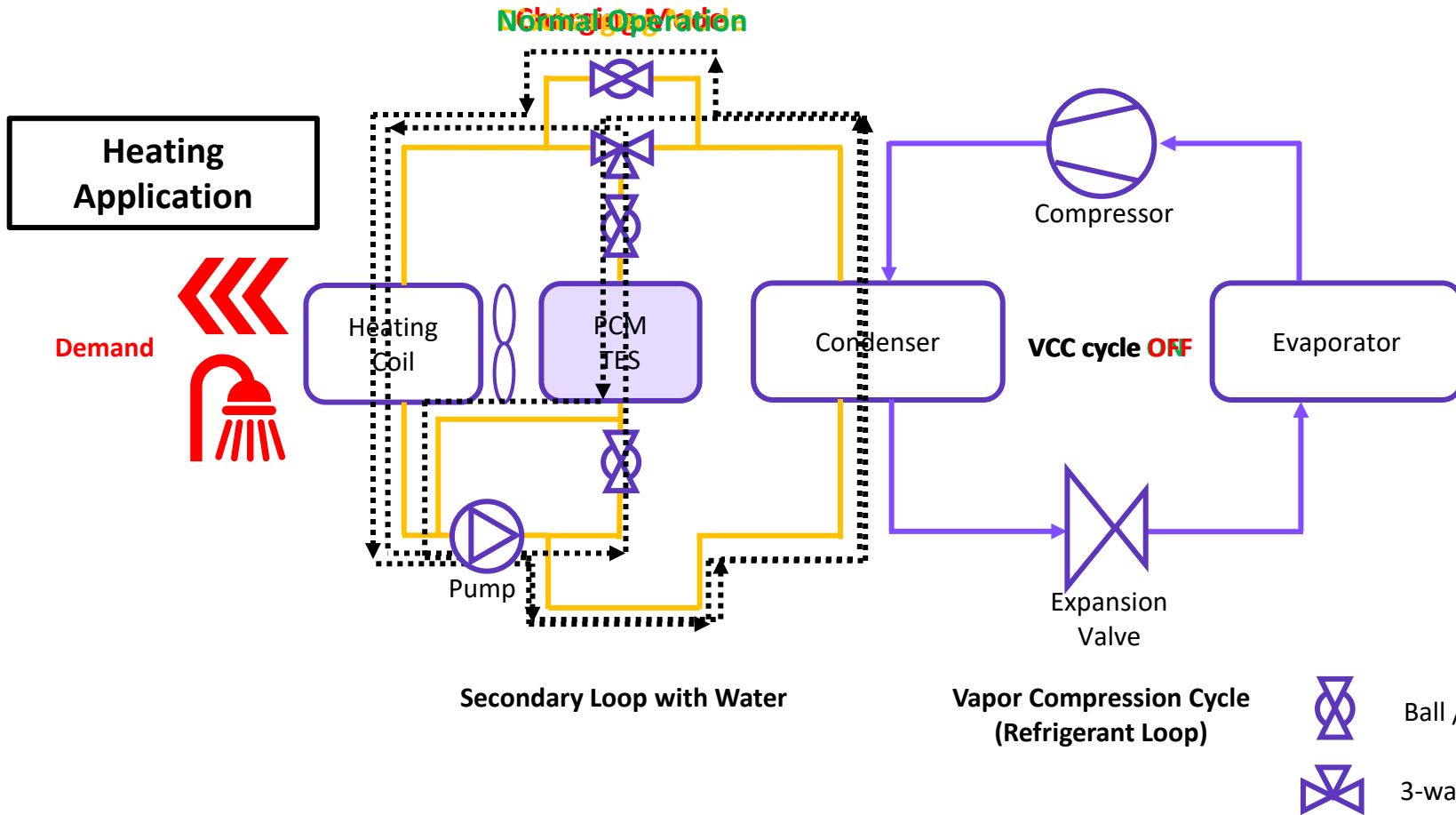
Experimental Investigation of a Phase Change Material Charged Serpentine Heat Exchanger with Louvered Fins

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PCM-TES Application Concept Example – Heating Case



PCM-TES (Thermal Energy Storage) Operation

- Charge during off-peak period
 - Higher COP (occasional)
 - Off-peak electricity cost
- Discharge during peak demand period
 - Only run the pump
- Single-pass TES with secondary loop in this example

First Order Analysis of the PCM-HX Candidates (commercially available options)

Metric	Annular Fin (baseline)	Wire Fins	Crimped Fins	Flat Plate	Serpentine Microchannel	Spine Fin
Compactness $\frac{A_{HT}}{V_C}$ (m ² /m ³)	135.9	105.1 (238.6)	378.2 (414.1)	529.9 (106)	1123.1 (537.6)	636.7
Volume Ratio $\frac{V_{PCM}}{V_C}$ (%)	86.5	91.7 (86.5)	87.4 (86.5)	46.5 (86.8)	80.7 (86.5)	86.5
Material Utilization $\frac{A_{HT}}{V_{HT,mat}}$ (m ² /m ³)	1,212.6	1,263.5 (1,767.7)	2,995.0 (3,067.6)	1,040 (1,001.9)	7,575 (5,992.3)	4,716
Hydraulic Diameter (mm)	9.7	4.8	4.8	3.6	1 x channel #	8.1

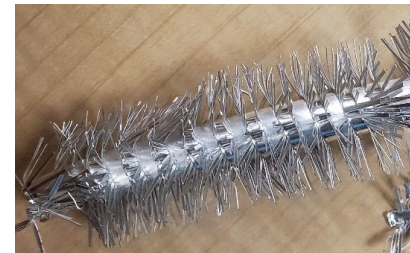
Crimped fin



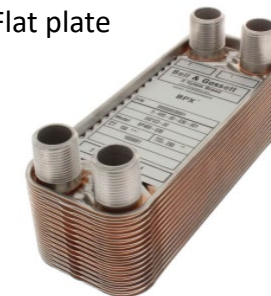
Wire fin



Spine fin



Flat plate



Annular fin



Serpentine microchannel



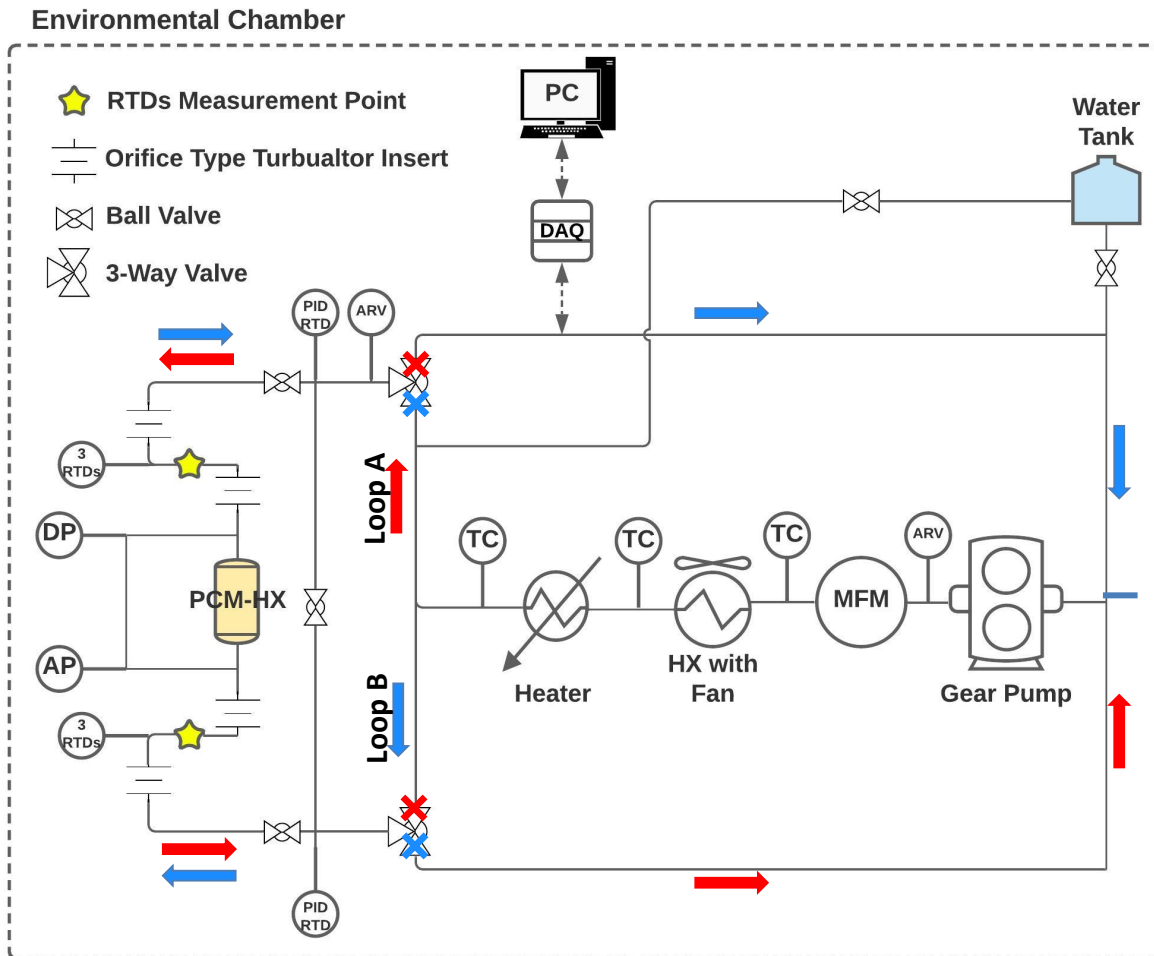
- **Red & bolded values** represent the values when the volume ratio is fixed to 86.5 (annular fin)
 - Fin pitch of each HX was varied to fix the volume ratio



Research Background and Objectives



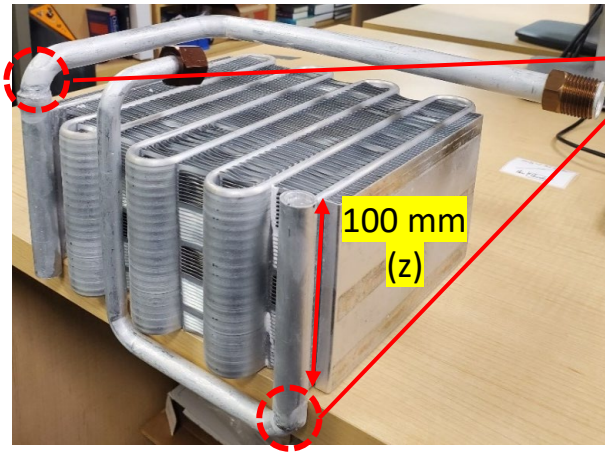
- The experimental study regarding the serpentine tube configuration is scarce in literature (when used as PCM-TES)
- To scrutinize the potential of this HX configuration to be used as a PCM-TES
 - Experimentally investigate a commercially available serpentine tube heat exchanger with louvered fins
 - Conduct a comprehensive thermal performance analysis for full melting and solidification processes
 - Experimentally consider often-neglected visual observation and heat loss and thermal mass calculations



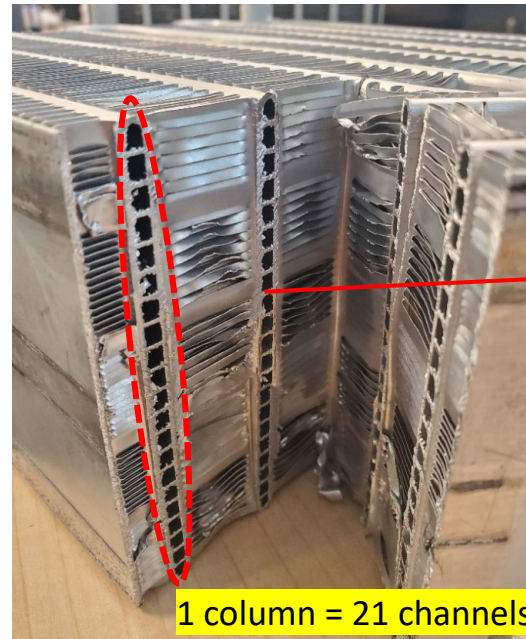
AP	Absolute pressure transducer
ARV	Air release valve
DP	Differential pressure transducer
TC	Thermocouple
RTD	Resistance temperature detector
DAQ	Data acquisition system

- Bi-directional flow (upward / downward)
- High accuracy RTD measurement
 - Turbulator insert
 - Two sets of three RTDs with 3D printed RTD guide
 - 90° turns before the measurement points

Serpentine PCM-HX Configuration



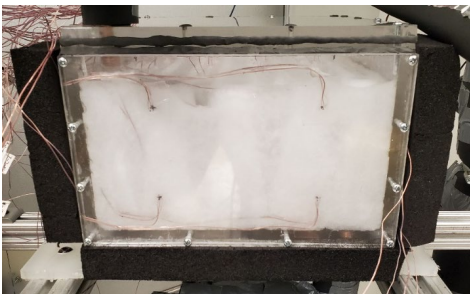
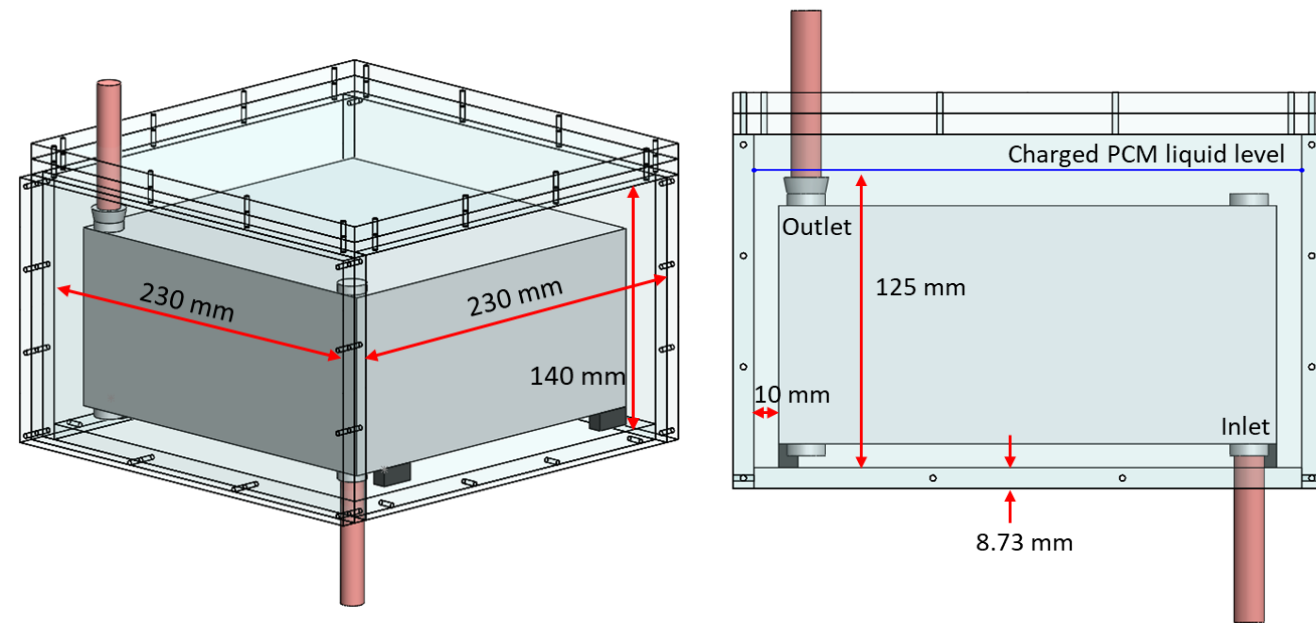
Header-side tubes were later cut and modified



Rectangular channel size:
(3 mm X 4 mm)



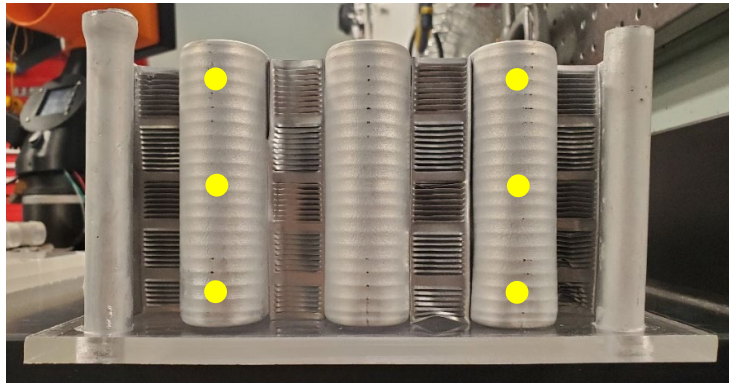
HX Key Dimensions [mm]	
Width x length x height	210 x 210 x 100
Rectangular channel dimension	3 x 4
Number of rectangular channels	21
Header-side tube inner diameter	11.1
Fin thickness	0.15



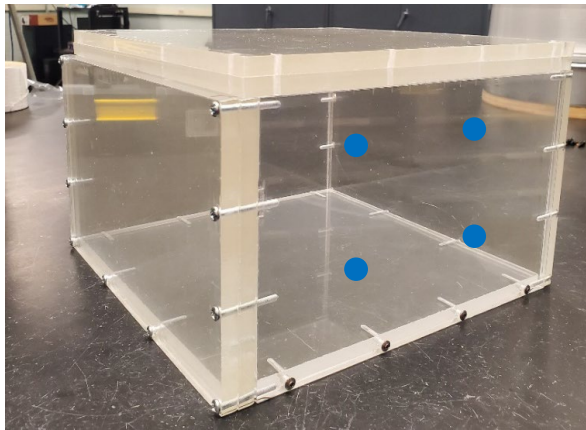
All sides were insulated except for the front and top sides

RT35HC (PCM) Thermophysical Properties and Mass [1]	
Nominal phase change temperature [°C]	35
Density [kg/m ³]	880 [solid], 770 [liquid]
Thermal conductivity [W/m*K]	0.2 [solid], 0.2 [liquid]
Specific heat [kJ/kg*K]	2 [solid], 2 [liquid]
Heat storage capacity (HSC) [kJ/kg] – OEM data (combination of latent and sensible heat in a temperature range of 27 °C to 42 °C)	240 (with ±7.5% accuracy, 222~258)
Charged PCM mass [g]	3,979

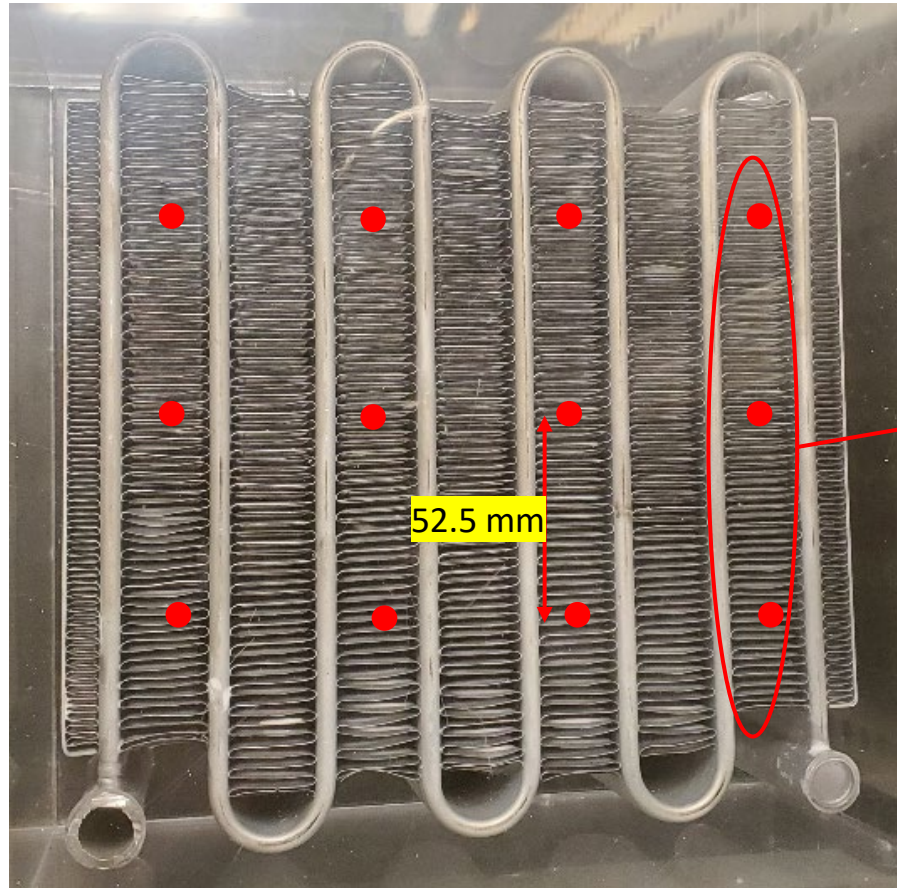
- Front and top sections were double-plated while having no insulation sheets (for visual observation)
- Gaps between the inner walls and the heat exchanger surfaces – front, back, left, right, and bottom: 10 mm
- RT35HC DSC (differential scanning calorimetry) results for HSC values:
 - Melting: 180.6 kJ/kg
 - Solidification: 203.7 kJ/kg



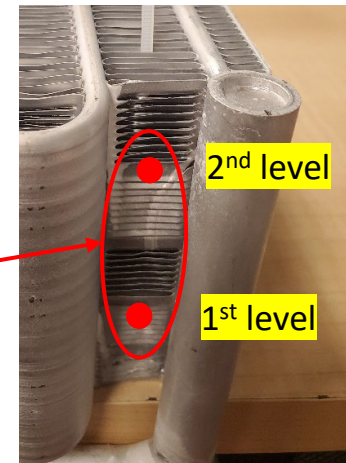
U-bends outer surface thermocouples



Heat loss and thermal mass measurement thermocouples pairs (inner and outer on all 6 surfaces)

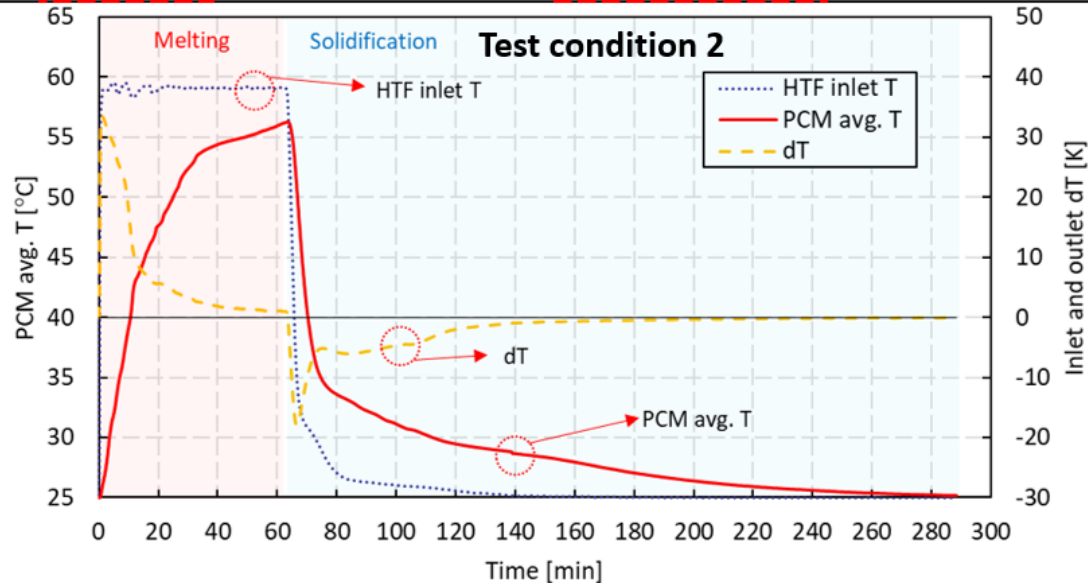


PCM-side thermocouples (2-level)



- U-bend TC
- PCM TC
- Heat loss and thermal mass TC

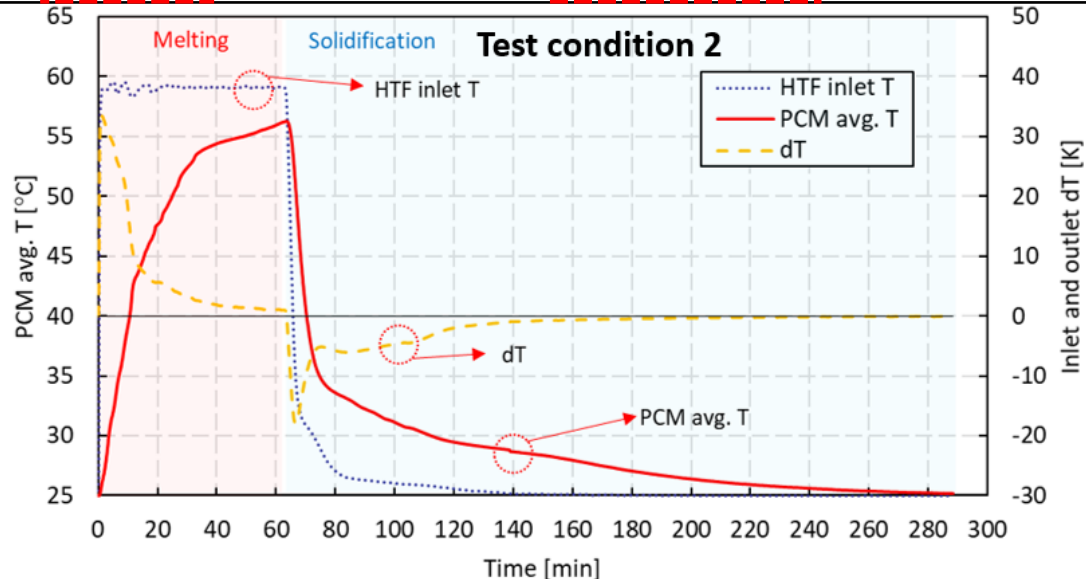
Test	MFR [g/s]	Re for single channel	Avg. Inlet T [°C]	Ste	Test Durations [min]	Avg. Charge/Discharge rates [W]	Energy density [kWh/m ³]
1	5	143.4 [M], 78.4 [S]	58.9 [M], 26.1 [S]	0.215 [M], 0.0802 [S]	73.8 [M], 258.2 [S]	256.7 / 65.8	42.2 [M], 43.1 [S]
2	10	287.3 [M], 155.7 [S]	59.0 [M], 25.8 [S]	0.216 [M], 0.0829 [S]	62.7 [M], 224.7 [S]	299.1 / 74.8	41.8 [M], 42.0 [S]
3	15	431.0 [M], 231.9 [S]	59.0 [M], 25.5 [S]	0.216 [M], 0.0856 [S]	59.0 [M], 213.7 [S]	316.9 / 80.3	41.8 [M], 42.5 [S]
4	5	132.8 [M], 78.2 [S]	54.0 [M], 26.0 [S]	0.171 [M], 0.0811 [S]	90.5 [M], 254.3 [S]	201.6 / 61.5	40.4 [M], 39.7 [S]
5	10	265.7 [M], 156.4 [S]	54.0 [M], 26.0 [S]	0.171 [M], 0.0811 [S]	76.5 [M], 223.5 [S]	231.8 / 72.2	39.3 [M], 40.3 [S]
6	15	398.5 [M], 231.4 [S]	54.0 [M], 25.4 [S]	0.171 [M], 0.0865 [S]	73.2 [M], 212.8 [S]	242.1 / 76.2	39.3 [M], 40.3 [S]



[M] – melting, [S] – solidification

- The ambient temperature for all test conditions was within the range of **25.0~25.1 °C**
- **MFR** and **HTF inlet temperature for melting** were varied
- Test condition 2 was repeated three times
- Thermocouples on inner walls to indicate full melting and solidification

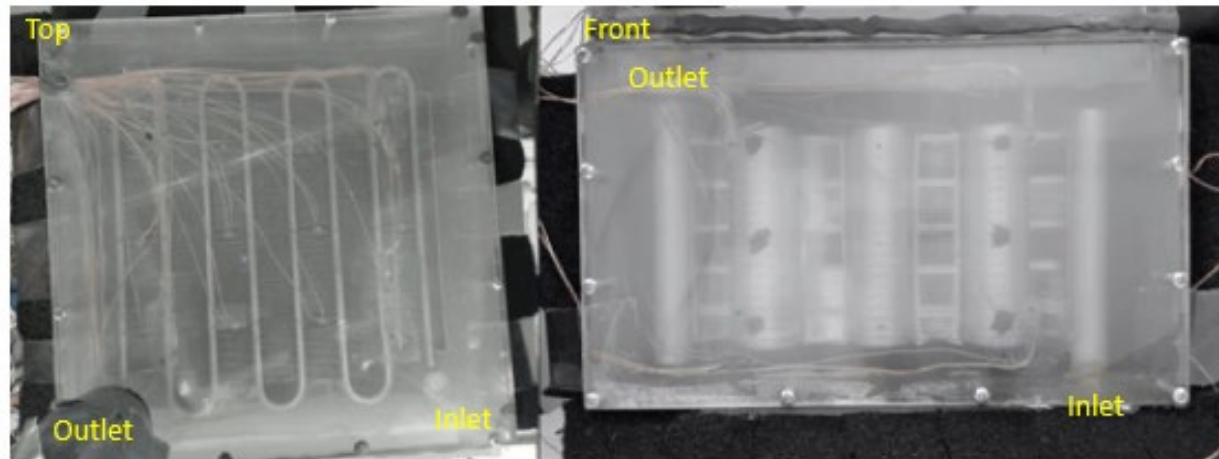
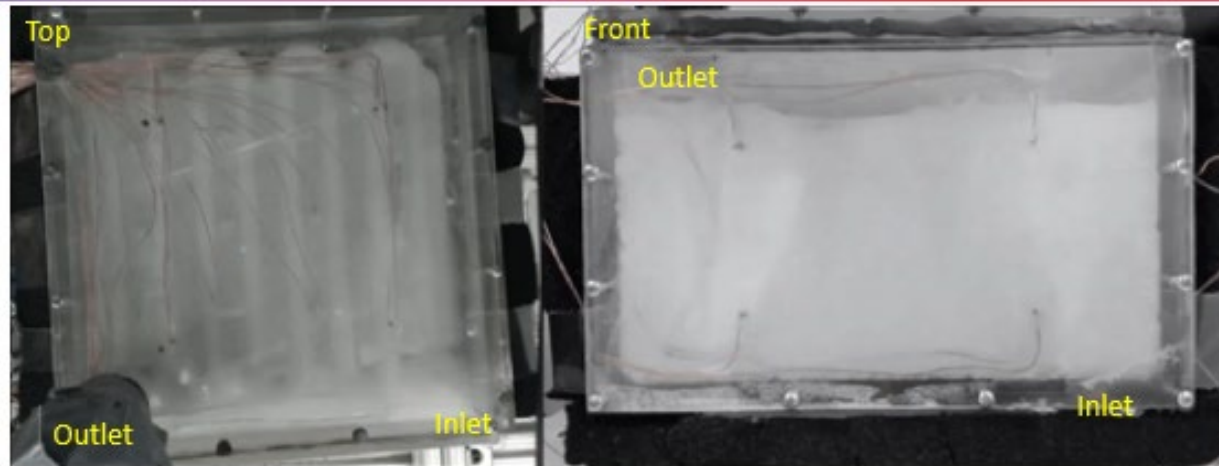
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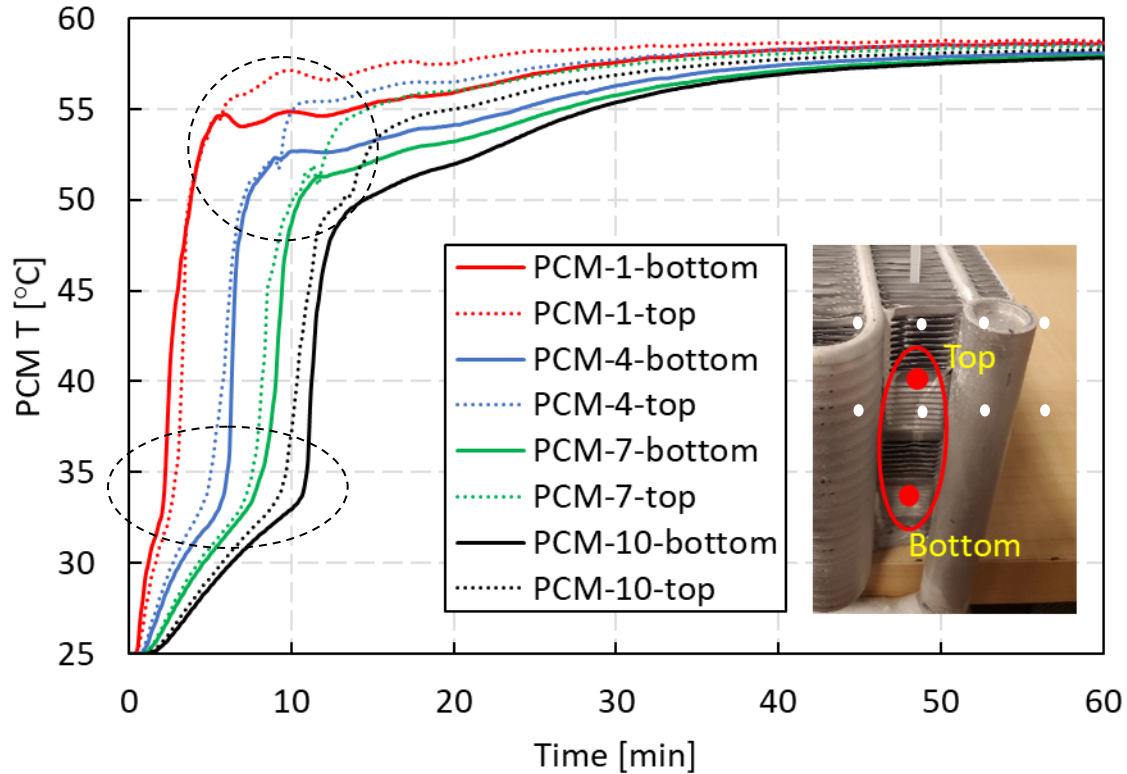
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*Test condition 2

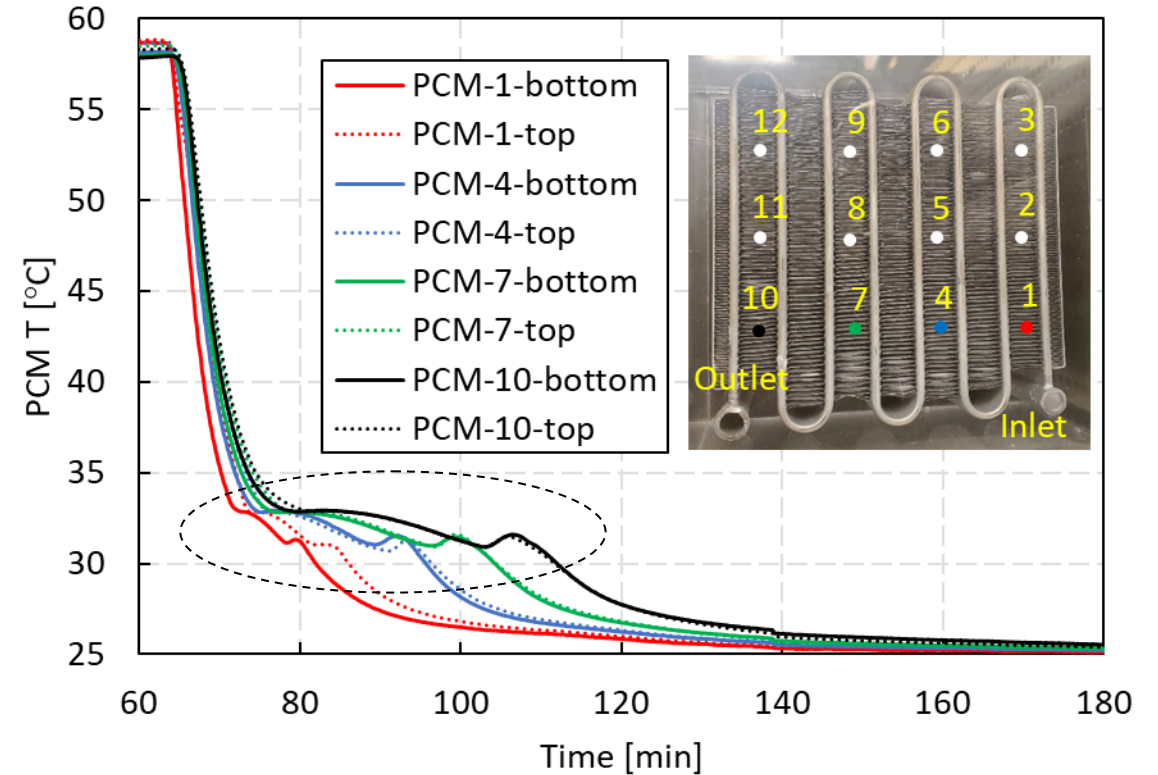


- **Melting** (first 1 hour)
 - MFR: 10 g/s, avg. inlet T: 59 °C
 - Convection and vertical temperature stratification observed
- **Solidification** (first 1 hour)
 - MFR: 10 g/s, avg. inlet T: 25.8 °C
 - More of a uniform solidification pattern in vertical direction observed
- PCM level change clearly observed in both cases
- Melting and solidification pattern captured which followed the HTF direction

*Test condition 2



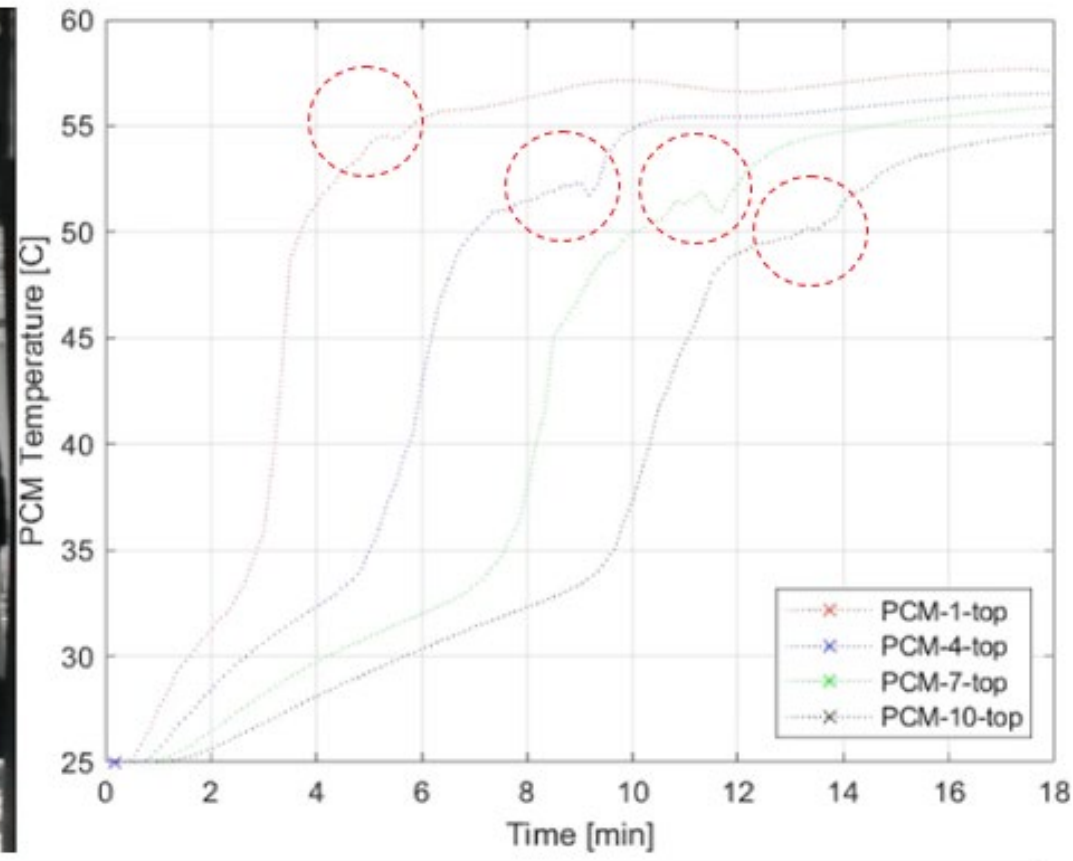
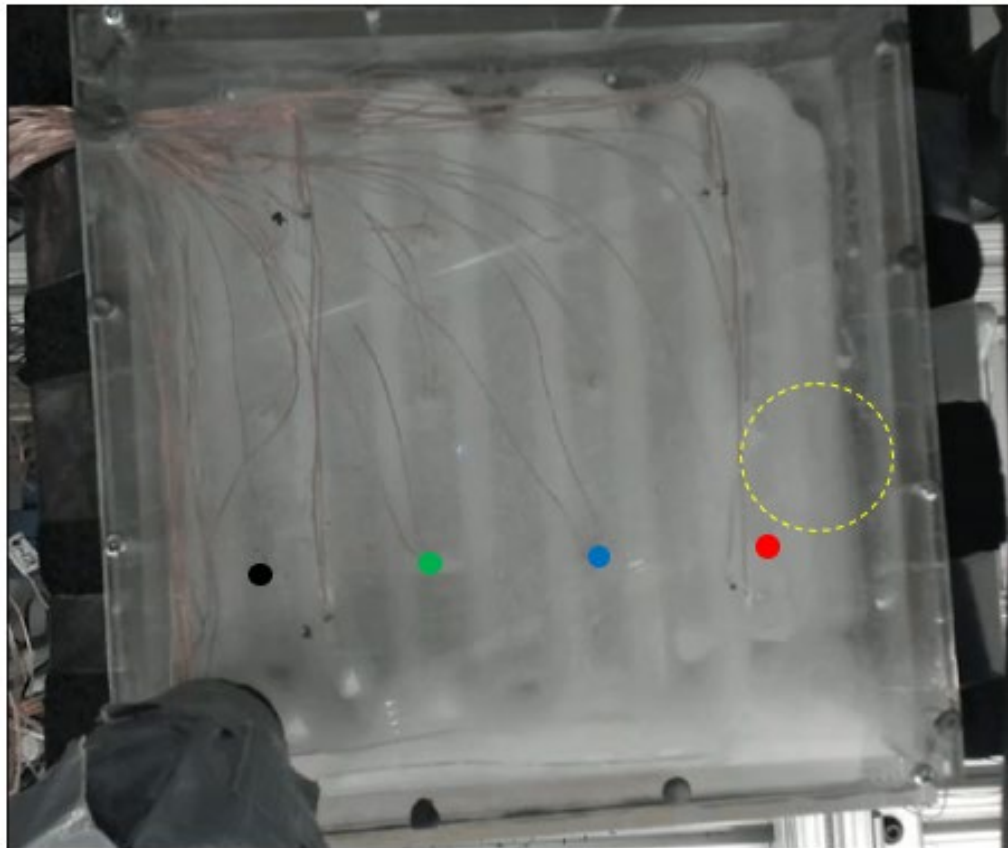
- **Melting**
 - Temperature slope changes were observed
 - Temperature dips were observed on the top TC locations



- **Solidification**
 - Temperature slope changes were observed
 - Suspected supercooling behaviors were observed

Visual Observation with Temperature Profile Progression

*Test condition 2



- PCM liquid hitting the ceiling at the beginning due to volume expansion (pressure buildup)
- Temperature dips matched with the top surface melting timing



Energy Balance Estimation



Test	Q_{water} [kJ]	Theoretical Storage [kJ] w/ DSC HSC values	Theoretical Storage [kJ] w/ -7.5% HSC values	Estimated Actual Charged / Discharged Energy [kJ]	Energy Balance Deviation [%] w/ DSC HSC values	Energy Balance Deviation [%] w/ -7.5% HSC values
1	1140 [M], 1020 [S]	887 [M], 979 [S]	1052 [M], 1052 [S]	1006 [M], 1025 [S]	-13.3 [M], -4.7 [S]	4.4 [M], 2.6 [S]
2	1128 [M], 1009 [S]	896 [M], 986 [S]	1061 [M], 1059 [S]	996 [M], 1000 [S]	-11.1 [M], -1.4 [S]	6.1 [M], 5.5 [S]
3	1126 [M], 1031 [S]	898 [M], 990 [S]	1063 [M], 1063 [S]	996 [M], 1012 [S]	-10.8 [M], -2.2 [S]	6.4 [M], 4.8 [S]
4	1097 [M], 938 [S]	850 [M], 940 [S]	1015 [M], 1013 [S]	961 [M], 945 [S]	-13.0 [M], -0.6 [S]	5.3 [M], 6.7 [S]
5	1067 [M], 969 [S]	854 [M], 946 [S]	1019 [M], 1019 [S]	936 [M], 960 [S]	-9.6 [M], -1.5 [S]	8.1 [M], 5.7 [S]
6	1066 [M], 974 [S]	856 [M], 947 [S]	1022 [M], 1020 [S]	937 [M], 960 [S]	-9.3 [M], -1.3 [S]	8.3 [M], 5.9 [S]

[M] – melting, [S] – solidification

- The systematic uncertainties of the HTF (water) side energy (Q_{water}) for all test conditions
 - Average: $\pm 0.5\%$ [M] and $\pm 1.4\%$ [S]
 - Maximum: $\pm 0.7\%$ [M] and $\pm 2.1\%$ [S]
- The energy balance deviation was calculated by comparing the **theoretical storage** and the **estimated charged/discharged energy** values
- For more accurate energy balance estimation in the future, the DSC test should be conducted with **multiple heat rates** to get the best result as they are highly dependent on different heat rates as well as **the sample size** and **test temperature range**



Conclusions and Practical Considerations



Conclusions

- Increase in both Re and Ste had considerable effects on reducing the test durations while increasing the average charge and discharge rates in a laminar regime
- The energy balance deviations were within $\pm 14\%$ and $\pm 9\%$, respectively when the HSC values from DSC results and the lower bound of the OEM datasheet were used

Practical Considerations

- Pressure build-up in the container
- Changing boundary condition during PCM volume expansion and contraction
- Air cavities and bubbles creation during PCM volume contraction



Future Work



- Expanded test matrix with more MFR and HTF inlet conditions would be helpful to develop meaningful correlations
- Performance comparison with different types of PCM-HX
 - ϵ -NTU method [2-5]
 - Ragone plots [6]
- Experimental result validation with a numerical model
 - Once validated, fin optimization would be possible (fin thickness, shape, pitch, length, angle etc.)
 - E.g. maximize PCM volume and minimize temperature gradient along the PCM-HX domain



Acknowledgements



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