Integrated Heat Exchanger-Phase Change Material Thermal Energy Storage System

Applied Materials Division

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by
D. Singh, W. Yu, and D. France
Applied Materials Division, Argonne National Laboratory

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Principal Investigator	Dileep Singh, Group Leader/Argonne Distinguished Fellow, dsingh@anl.gov, 1-630-252-5009	
Business Contact	Judy Janovyak, Financial Business Partner, jjanovyak@anl.gov, 1-630-252-4998	
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- Executive Summary:** The purpose of this study is to experimentally investigate the thermal performance of an innovative thermal energy storage (TES) system that combines the advantages of the phase-change material (PCM)/graphite foam latent-heat TES medium developed at Argonne National Laboratory (Argonne) and the internally supported plate-fin (ISPE) cell architecture heat transfer fluid (HTF) flow

channels developed at Brayton Energy (Brayton). Several essential tasks were accomplished:

- *Thermal property characterization.* Thermal properties of the graphite foam were characterized, providing necessary data for experimental result analysis and numerical simulation.
- *Design and optimization of lab-scale test module.* Based on Brayton's full-scale heat exchanger (HX)-TES system, the experimental test module was designed, optimized, and fabricated.
- *Thermal performance testing and data analysis.* Five cycle tests were successfully conducted—including one with approximately 3.5 psig of pressure applied to the diaphragms—to investigate the thermal performance of the experimental test module for charging and discharging. Temperature profiles were generated for each charging test and discharging test as a function of time. The temperature profiles clearly show three TES stages: sensible heat (temperature increase), latent heat (melting), and sensible heat (temperature increase) for the charging process. Similarly, the temperature profiles clearly show three thermal energy release stages: sensible heat (temperature decrease), latent heat (solidification), and sensible heat (temperature decrease).

Melting and solidification of the PCM generally occurred in relatively narrow temperature ranges, indicated by the flattened temperature regions in the temperature profiles. These phase changes ranged approximately 3°C for melting and 3.5°C for solidification. The charging and discharging temperature profiles were similar for similar experimental parameter tests whether or not pressure was applied to the diaphragm to eliminate the gap between the HX surface and the TES subsystem. This indicates that the effect of a small gap between the HX surface and the TES subsystem is insignificant for charging and discharging.

- *Comparison of experimental data and simulation results.* We compared the experimental data to the numerical simulation results. Numerical simulations were conducted by using the ANSYS FLUENT 2019 R3 commercial computational fluid dynamics software. The predicted phase-change times agreed reasonably well with those from the experimental data. In most cases, the estimated time differences between the relative phase changes were within 16%. The predicted start and end times for the charging process agreed well with those from the experimental data. However, the simulation results showed earlier start and end times than the experimental data for the discharging process. Overall, the experimental data and its comparison with the simulation predictions verified the technical viability of the integrated ISPF HX-PCM/graphite foam latent-heat TES system.

4. Table of Contents:

1. Acknowledgement.....	1
2. Disclaimer	1
3. Executive Summary	1
4. Table of Contents.....	3
5. Background.....	3
6. Project Objectives	5
7. Project Results and Discussion.....	8
7.1. Design and Optimization of Experimental Test Module	8
7.2. Thermal Property Characterization of Graphite Foam	10
7.3. Fabrication of MgCl ₂ /Graphite Foam and Assembly of Test Module.....	13
7.4. Moisture and Impurity Removal of MgCl ₂ /Graphite Foam Composite.....	15
7.5. Modifications to Argonne's Existing Test Loop	15
7.6. Prototype Testing and Data Analysis.....	15
8. Significant Accomplishments and Conclusions.....	21
9. Budget and Schedule.....	22
10.Path Forward	23
11.Inventions, Patents, Publications, and Other Results	23
12.References	23

5. **Background:** The TES system is a key component in concentrating solar-thermal power (CSP) plants. It allows CSP plants to continuously operate when the sun is not shining, which levels grid electricity supply, improves overall plant efficiency, and reduces the levelized cost of electricity. The thermal performance of the TES system is essential to making CSP a renewable energy option that is competitive with conventional technologies for electric power generation.

Two recent development trends for CSP plants and TES systems have introduced further challenges to the thermal performance of TES systems. The first challenge is using the PCM as the TES medium, and therefore storing thermal energy based on the latent heat of fusion instead of sensible heat. The PCM latent-heat TES system greatly increases the storage energy density, resulting in a smaller storage size. The PCM latent-heat TES system also allows a narrower operation temperature range around the melting/solidification temperature of the PCM, which results in the potential for a high exergy efficiency [1]. However, heat transfer in the PCM storage

medium is poor due to the low thermal conductivities of PCMs, usually <1 W/mK for PCMs (such as chloride salts and their eutectic or non-eutectic mixtures) that are applicable to the TES system for a CSP plant [2].

The second challenge is using a supercritical carbon dioxide ($s\text{CO}_2$) Brayton cycle instead of a steam cycle for electricity generation, making the power cycle more efficient [3]. However, the $s\text{CO}_2$ power cycle operates at a very high pressure; in addition, the $s\text{CO}_2$ gas, due to its poor heat transfer characteristics, adversely affects heat transfer in the HTF side of the TES system. Both trends lead to a low heat transfer rate between the HTF and the storage medium and could potentially require many HTF channels for charging and discharging the TES system.

Several technologies have been proposed and developed to improve the overall heat transfer rate between the storage medium and the HTF to achieve a short charging/discharging period for the storage medium. These technologies aim to reduce thermal resistances in the storage medium, between the storage medium and the HTF, and in the HTF. Composite storage media with enhanced effective thermal conductivities have been proposed, including particle-dispersed storage media [4], metal foam/PCM storage media [5-8], and graphite foam/PCM storage media [9-13]. Finned HTF tubes [14-16] and heat pipes [17,18] have also been proposed to enhance the heat transfer between the PCM storage medium and the HTF. Their combined use has also been investigated [19,20].

To reduce the thermal resistance from the HTF side, passive heat transfer enhancement techniques—such as coated surfaces, rough surfaces, extended surfaces, displaced inserts, swirl flows, coiled tubes, surface tensions, and additives for fluids—are generally used because they have no additional power requirement [21,22]. Various high-efficiency HXs have been developed to increase the volumetric heat transfer surface and therefore the volumetric power density. These HXs generally have compact plate-fin structures [23-25]. Among them, the diffusion-bonded, printed-circuit HX, with a very high power density, can operate at high pressures and high temperatures [26]. These high-efficiency HX approaches can generally be adopted for TES system applications.

In previous SunShot projects, Argonne has developed and demonstrated the latent heat-based TES system that uses salt PCMs (MgCl_2 or NaCl-KCl) infiltrated into a high-thermal-conductivity graphite foam. Brayton demonstrated a HX design that uses HTF flow channels with ISPE cell architecture (shown in Figure 5-1) and high-temperature mechanical reliability. By combining the two technologies, it is possible to deliver a TES system that provides efficient performance with minimal thermal transients. The key advantage of the integrated HX-TES system will be the enhanced gas-side heat transfer and the ability to perform thermal transport at temperatures compatible with the $s\text{CO}_2$ power cycle and TES capability.

Figure 5-1. ISPE cell architecture HTF flow channels

6. **Project Objectives:** The project goal is to develop and demonstrate an integrated HX-TES system. It has enhanced heat transfer from both the heat transfer gas side by using the ISPF cell architecture, and the storage medium side by using graphite foam/PCM composite.

The project work scope includes: (a) optimize the design of the lab-scale prototype of the proposed HX-TES system with the desired storage capacity and operational temperature; (b) perform charging and discharging testing of the storage medium within the required time frame and validate the modeling results; and (c) conduct long-term testing to ensure stable performance. In addition, this work will quantify the interfacial heat transfer between the HX and TES subsystems that results from any gaps and/or degradation from corrosion.

To achieve the project goal, we will use both modeling and experimental approaches. Statistical analysis of the experimental data will validate our experimental results. We will conduct multiple charging and discharging tests to evaluate any redistribution effects of the PCM inside the graphite foam/PCM composite. The experimental data will be compared to the predicted results to assess and, if necessary, refine the simulation models.

The integrated HX-TES system we demonstrate will be applicable to the sCO₂ power cycle. It will eliminate the independent HX, thereby reducing the overall plant cost. Results from this work will allow Brayton to build a scaled-up, integrated HX-TES system and validate its performance.

A summary of the tasks is presented below.

Task 1. Argonne will provide support for Brayton to design an integrated heat exchanger-TES (ITES)

Task Description: Brayton will develop an optimum design for an integrated HX-TES full-scale system. Argonne will support Brayton in developing a design for the lab-scale unit cell prototype. Insulation layers will be employed to minimize the boundary and heat loss effects on the test module.

Some key considerations for the test module design are: (a) a test module structure whose thermal performance data of charging and discharging processes can be used to predict the thermal performance of the full-scale HX-TES system, (b) an appropriate test module size that can represent the proposed HX-TES system, (c) a reasonable TES capacity that can be tested in the Argonne's existing experimental test loop, (d) design to apply force on the TES and HX interface, and (e) circular tube ends that can easily be connected to the Argonne's existing experimental test loop. We will place thermocouples in the storage medium (graphite foam/PCM composite) of the test module, along both the melting front movement direction and the heat transfer gas flow direction. Temperature measurements from these thermocouples will be used to record the temperature profile and the melting front movement inside the storage medium as functions of the time. This activity will be conducted in collaboration with Brayton.

Milestone 1: The optimized design of the laboratory-scale prototype will be completed, including design parameters, geometric dimensions, and material property requirements.

Task 2. Fabricate and characterize infiltrated graphite foam/PCM blocks for ITES unit cells

Task Description: Using the results from Task 1, Brayton will fabricate test module frames including heat transfer gas flow channels and end connectors. The size of each unit cell will be such that it fits within Argonne's existing test loop. Argonne will provide panels of graphite foam infiltrated with PCM (NaCl-KCl or MgCl_2) of the appropriate size, as determined from Task 1. To accurately determine the infiltration rate, the infiltration process will be closely monitored and the weights of graphite foams will be measured prior to and post the infiltration process.

Milestone 2: Argonne will confirm infiltration of PCM to full capacity.

Task 3. Insert PCM/foam into the unit cell prototype

Task Description: Brayton will provide a partially built unit cell for the ITES. Argonne will assemble fabricated components into a prototype module. The major steps of the assembly process are as follows: (a) attach ports (tubes) that connect the storage medium chambers to the outside of the test module to purify the PCM, (b) insert the graphite foam/PCM panels into the test module frame, (c) attach thermocouple connectors to the side panels, (d) seal-weld the side panels to the test module frame, (e) drill thermocouple holes into the graphite foam/PCM panels at the designed positions and depths, and (f) install thermocouples into the test module.

Multiple approaches will be investigated to ensure that the graphite foam and the HX plate are in full contact with each other. In addition, we will evaluate trial sections of PCM/graphite foam and HX plate using thermal diffusivity measurements to ensure that they are in uniform contact. Assembly of the prototype will be done in close collaboration with personnel from Brayton.

Milestone 3: The fabrication of a fully functional prototype will be completed.

Task 4. Develop a process to remove moisture and oxygen

Task Description: The assembled HX-TES module will undergo a rigorous heating and flushing process designed to remove any bound and absorbed moisture in the PCM salt, and to remove oxygen from the system. This step is necessary to mitigate corrosion of the metal components that are in contact with the PCM salt. Subsequent to the cleaning process, the TES module will be back filled with an inert gas and the vacuum port will be sealed.

Milestone 4: The corrosion mitigation of the prototype will be completed, and the prototype will be ready for thermal performance testing.

Task 5. Modify Argonne's existing test loop

Task Description: The fabricated test module will be integrated into the experimental test loop at Argonne. The experimental test facility consists mainly of an air-flow pump, an air heater, a furnace, and a ventilation hood with operation temperatures up to 900°C. Heated air is used as the HTF. Sensors are provided to measure the temperature, pressure, and air flowrate. To integrate the prototype, some modifications to the piping and furnace will be needed. In addition, the prototype will be thermally insulated.

Milestone 5: The test loop will be operational for thermal performance testing of the prototype under desired conditions.

Task 6. Test the prototype and analyze the data

Task Description: Experimental testing will be conducted at Argonne for charging and discharging the storage media in the test module. During a typical experiment, the test module will be held at a fixed furnace temperature. The charging and discharging are conducted by maintaining the flowing air at appropriate temperatures. Temperatures will be continuously monitored and recorded in various locations of the storage media during experiment testing. Pressure drops over the course of the test will be recorded. Based on the measurements taken during the experiment, medium temperature profiles, melting fronts, and solidification fronts will be recorded as functions of the time for related parameters such as heat transfer air inlet temperature and flowrate. Repeating charging and discharging tests will be performed for each test module to evaluate any redistribution effects of the PCM inside the graphite foam/PCM composite. Further, efficiencies of the TES component will be estimated.

Milestone 6: The thermal performance of the integrated HX-TES system will be established through the testing results of the lab-scale prototype.

Go/NO GO Decision Point 1: Completion of Milestones 1-6.

Task 7. Test the long-term performance of the prototype

Task Description: Performance testing will be conducted for the prototype post long-term high-temperature exposure. After the performance testing described in Task 6, the selected prototype will be heated above the melting point of the PCM for a long period of time. Exposure time will range up to several hundred hours. After the long-term exposure, we will test the prototype's performance again in the test loop as per Task 6. To ensure that there are no degradation effects due to the long-term hold, the performance of the prototype should be within $\pm 10\%$ of the results obtained prior to the exposure testing. If deviations or degradation in the prototype performance are observed, then the prototype will be sectioned to identify the corrosion depth.

Milestone 7: The long-term performance and feasibility of the HX-TES system will be demonstrated.

Task 8. Report and disseminate the results

Task Description: Reports will be prepared on the design parameters, fabrication and assembly processes, and performance data of the integrated HX-TES system. In addition, journal and conference papers will be prepared and submitted.

Milestone 8: Final report and published journal and conference papers.

7. Project Results and Discussion:

7.1. Designing and Optimizing the Experimental Test Module

The experimental test module is designed and optimized based on the full-scale HX-TES system and the requirements of the experimental test loop. The following are some of the key criteria of the experimental test module:

- Dimensions of HTF channels and TES unit are appropriate to represent the HX-TES system, and environmental conditions (such as temperatures) of the experimental test module are maintained uniform during testing by setting up the test module inside the test furnace.
- The TES capacity is reasonable for charging and discharging the test module in several hours.
- Inlet and outlet port sizes and arrangements of the experimental test module are suitable for the pressure drop and uniform distribution of the HTF, and for easy connection of the test module to the experimental test loop.

- Thermocouples are distributed along and perpendicular to the HTF direction for monitoring the melting/solidification front movements.

A schematic overview of the resulted design of the experimental test module is shown in Figure 7-1.

Figure 7-1. Design of experimental test module

The key design features of the experimental test module are as follows:

- The test module is of ISPF cell architecture HTF flow channels with manifolds and properly sized connection tubes on both ends to be connected to the experimental test loop.
- On one side of the flow channels, there are a welded enclosure for housing the PCM/graphite foam composite, a MgCl_2 /graphite foam composite placed inside the enclosure for storing or releasing thermal energy during charging or discharging processes, a diaphragm for applying a desired pressure to maintain the contact of the MgCl_2 /graphite foam composite and the surface of the flow channels, and a top plate welded to the enclosure to seal the MgCl_2 /graphite foam composite.
- On another side of the flow channels, there are a mica insulation layer held in place by the base plate for reducing heat losses or gains during the charging or discharging processes and a second diaphragm between the HX cell and the mica to apply equal pressure on both sides of the cell.

- Four thermocouple probes are attached through Swagelok fittings on the enclosure for measuring temperatures during experimental testing.

7.2. Characterizing the Thermal Properties of Graphite Foam

It was necessary to characterize the thermal properties of graphite foam to generate data for experimental test result analysis and numerical simulation. Figure 7-2 shows the graphite foam sample block used to characterize the properties of graphite foam. Visual inspection showed the blocks are uniform in porosity, but slightly different on the top and the bottom.

Figure 7-2. Graphite foam block for thermal property characterization

The density, porosity, thermal diffusivity, and thermal conductivity of the graphite foam were characterized. The density and the porosity were characterized for two types of samples. First, the density and porosity were determined through the measured dimensions and weight of the sample. The results show an average density of approximately 412 kg/m³ and an average porosity of approximately 81.8%.

Next, the densities and porosities were calculated from the measured diameters, thicknesses, and masses of six samples used for thermal diffusivity measurements. To reflect the material property and structure differences in the planar direction and in the direction perpendicular to the planar direction (the top-bottom direction), as well as the distance from the center of the graphite foam, the samples were cut in both directions and at different distances from the center of the graphite foam, as shown in Figure 7-3. The cutout samples are illustrated in Figure 7-4. The results are listed in Table 7-1. The average density is 471 kg/m³ and the average porosity is 79.2%.

Figure 7-3. Samples extracted from various locations

Figure 7-4. Samples for thermal diffusivity measurements

Table 7-1. Density measurements on thermal diffusivity measurement samples

Sample	Diameter (mm)	Thickness (mm)	Volume (mm ³)	Mass (g)	Density (kg/m ³)	Porosity (%)
xy1	12.53	8.01	988.11	0.4959	501.90	0.778
xy2	12.44	8.07	981.38	0.4413	449.64	0.801
xy3	12.35	8.09	968.19	0.4087	422.16	0.813
z1	12.33	8.04	959.09	0.4946	515.73	0.772
z2	12.32	8.05	959.24	0.4669	486.74	0.785
z3	12.39	7.94	958.23	0.4282	446.83	0.802

We used the Discovery Xenon Flash System from TA Instruments to measure the thermal diffusivities of the six samples. Three measurements were taken for each sample. The thermal conductivities and their deviations were calculated from the thermal diffusivity data. The results are summarized in Table 7-2. The table shows that (a) standard deviations for all measurements are generally small, indicating that they are reliable; (b) changes along the distance from the center are generally insignificant; and (c) thermal diffusivities and thermal conductivities are much higher along the top-bottom direction than along the planar direction. These results indicate that the graphite foam fabrication process is repeatable and reliable.

Table 7-2. Experimental thermal diffusivities and calculated thermal conductivities

Sample	Density (kg/m ³)	Specific heat (kJ/kgK)	Porosity	Thermal diffusivity (cm ² /s)		Thermal conductivity (W/mK)	
				Average	Deviation	Average	Deviation
xy1 (23°C)	501.90	0.737	0.778	1.8110	0.0075	68.62	0.284
xy2 (23°C)	449.64	0.737	0.801	1.7112	0.0025	58.14	0.084
xy3 (23°C)	422.16	0.737	0.813	1.8613	0.0104	59.41	0.332
z1 (27°C)	515.73	0.753	0.772	3.6693	0.0049	145.90	0.196
z2 (27°C)	486.74	0.753	0.785	3.2365	0.0241	121.51	0.904
z3 (27°C)	446.83	0.753	0.802	4.0515	0.0315	139.73	1.088

In addition, we measured thermal diffusivities as functions of temperature for the six samples. The measured thermal diffusivity results and the calculated thermal conductivity results are plotted in Figure 7-5. The figure shows that thermal diffusivity and thermal conductivity decrease as the temperature increases. However, they decrease more slowly with the temperature and level out at high temperatures.

Figure 7-5. Thermal diffusivity and thermal conductivity as functions of temperature

7.3. Fabricating MgCl_2 /Graphite Foam Composite and Assembling the Test Module

Due to the overall layout of the experimental test module, it is very difficult for MgCl_2 to directly infiltrate the graphite foam inside the enclosure of the experimental test module without contaminating other components. Therefore, we fabricated the MgCl_2 /graphite foam composite with an infiltration mold, which was essentially a box without a top, whose internal dimensions were large enough to machine out the required MgCl_2 /graphite foam composite for the experimental test module with enough space above the graphite foam for MgCl_2 powders to ensure full infiltration of the graphite foam. Figure 7-6 shows the procedures of infiltrating and machining the MgCl_2 /graphite foam composite.

Figure 7-6. MgCl_2 /graphite foam composite

The dimensions and weights were measured for the graphite foam and the MgCl_2 /graphite foam composite before and after infiltration to determine the MgCl_2 infiltration rate.

The test module was assembled through the following steps. First, the trimmed MgCl_2 /graphite foam composite was integrated into the enclosure of the experimental test module and the enclosure top plate was welded to the enclosure for sealing the MgCl_2 /graphite foam composite, as shown in Figure 7-7(a). Second, the enclosure top edges were trimmed to the level of the enclosure top plate to maintain an even clamp force, as shown in Figure 7-7(b). Third, four thermocouple

probes were installed into the experimental test module, using Swagelok fittings to measure temperatures during charging and discharging tests, as shown in Figure 7-7(c). Finally, the test module was insulated to reduce heat losses or gains during charging or discharging tests, as shown in Figure 7-7(d).

(a) Seal-welded enclosure

(b) Trimmed enclosure

(c) Thermocouple installation

(d) Insulated test module

Figure 7-7. Experimental test module assembly

Figure 7-8. Test module dimensions and thermocouple locations

The thermocouples were positioned in various locations along three axial directions of the test module to monitor the temperatures of the MgCl_2 /graphite foam composite. The details are shown in Figure 7-8.

7.4. Removing Moisture and Impurities from the MgCl_2 /Graphite Foam Composite

In order to remove any moisture and impurities absorbed in MgCl_2 during the fabrication of the test module, we conducted a moisture removal procedure for the MgCl_2 /graphite foam composite. This involved a combination of furnace heating and pump evacuation. The test module was heated to $\sim 600^\circ\text{C}$. It was then maintained at that temperature for several hours, and the enclosure for the MgCl_2 /graphite foam composite was periodically evacuated to remove moisture and impurities from the MgCl_2 /graphite foam composite. After the removal of moisture and impurities, the test module was pressurized with argon to approximately 10 psig and then evacuated to approximately 500 mTorr five times to create an argon environment for the MgCl_2 /graphite foam composite.

7.5. Modifying Argonne's Existing Test Loop

Air temperatures and flowrates for both charging and discharging influence the responses (temperature profiles and melting/solidification front movements) of the HX-TES system. The air temperature is controlled by setting the heater at an appropriate heating level. In order to control the air flowrate, modifications were made to the test loop. A flow-control device with an adjustable valve was added to the section between the air pump and the heater. With this added feature, the laboratory-scale HX-TES module can be tested in the experimental test loop at a desired air flowrate or at different air flowrates.

7.6. Testing the Prototype and Analyzing the Data

Experimental testing was conducted in Argonne's testing loop. The detailed experimental test setup is shown in Figure 7-9. Five charging and discharging cycles—including one (Cycle 5) with approximately 3.5 psig of pressure applied to the diaphragms—were performed for the test module. Charging and discharging were generally conducted in a single cycle following these main steps (as shown in Figure 7-10): (a) preheat the test module to 660°C ; (b) run the air pump and switch on the air heater controller, then wait for approximately 2 hours to reach an equilibrium state; (c) increase the air heater controller setting for charging; (d) preheat the test module to 735°C and wait for approximately 1 hour to reach an equilibrium state; and (e) decrease the air heater controller setting for discharging.

Figure 7-9. Experimental test setup

Figure 7-10. Furnace and air settings during charging and discharging

The experimental parameters for the charging and discharging tests are summarized in Table 7-3. During each charging process or discharging process, the air flowrate was not adjusted; however, some fluctuations existed due to air temperature changes. All readings from various sensors including the thermocouples, the air flowmeter, and the air pressure transducer were automatically logged into the data acquisition computer in a predetermined time interval of approximately 6 seconds.

Table 7-3. Experimental parameters for charging and discharging tests*

Cycle		Air flowrate (kg/s)	Initial PCM/graphite foam temperature (°C)	Insulation outside temperature (°C)	Phase-change range (°C)
1	Charging	0.002151	700.1	707	714.5–717.5
	Discharging	0.002198	752.0	780	716.5–713.0
2	Charging	0.001465	685.5	706	714.5–717.5
	Discharging	0.001648	740.2	780	716.5–713.0
3	Charging	0.001390	678.5	706	714.5–717.5
	Discharging	0.001339	746.4	781	716.5–713.0
4	Charging	0.001234	682.1	706	714.5–717.5
	Discharging	0.001332	749.7	781	716.5–713.0
5	Charging	0.001312	684.6	707	714.5–717.5
	Discharging	0.001330	751.6	781	716.5–713.0

* Approximately a 3.5-psig pressure was applied to the diaphragms during Cycle 5 testing.

Temperature profiles were generated for all tests. Figure 7-11 shows the measurements from Thermocouple 1 (TC1). The figure shows that the MgCl_2 went through three TES stages during charging: sensible heat energy storage seen as temperature increase, latent heat energy storage at near-constant temperature due to melting, and sensible heat energy storage seen as temperature increase after complete melting. The MgCl_2 also went through three thermal energy release stages during discharging: sensible heat energy release seen as temperature decrease,

latent heat energy release at near-constant temperature due to solidification, and sensible heat energy release seen as temperature decrease after complete solidification.

The experimental results showed that melting and solidification of MgCl_2 generally occurred in relatively narrow temperature ranges, indicated by the flat temperature regions in the temperature profiles. These phase-change ranges were approximately 3°C for melting and 3.5°C for solidification. Although it was difficult to directly compare temperature profiles of a test without a diaphragm pressure and a test with a diaphragm pressure due to different experimental parameters, the results indicated that the effect of a small gap between the MgCl_2 /graphite foam composite and the surface of the flow channels was not significant for charging and discharging. This condition is evident from the very similar temperature profiles between Cycle 4 (without diaphragm pressure) and Cycle 5 (with a 3.5-psig diaphragm pressure) under similar experimental parameters.

Figure 7-11. Temperature as a function of time

Numerical simulations were conducted by using the ANSYS FLUENT 2019 R3 commercial computational fluid dynamics software with 8.7 million polyhedral cells. The average and minimum orthogonal qualities of the mesh were 0.96 and 0.36, respectively, with a maximum aspect ratio of 4.94. Various material properties and test conditions for the simulation, such as the graphite foam porosity, MgCl_2 infiltration rate, thermal conductivity of the MgCl_2 /graphite composite, and air inlet temperature, were based on experimentally measured results. An example of comparisons of the experimental data and the simulation results is illustrated in Figure 7-12 for the charging and discharging processes. The figure shows that the experimental data and the simulation results generally had similar temperature increase and decrease trends. The comparisons showed that the experimental and simulated phase-change times agreed reasonably well with deviations (calculated as $(t_{\text{simulated}} - t_{\text{experimental}})/[(t_{\text{simulated}} + t_{\text{experimental}})/2]$), generally <15% for the melting process and <16% for the solidification process (as shown in Table 7-4). The experimental phase-change time, $t_{\text{experimental}}$, was determined from the corresponding temperature profile, and the simulated phase-change time, $t_{\text{simulated}}$, was determined by using the liquid fraction of the PCM, which was recorded, along with the temperature, during the analysis. The start and end times for the melting process agreed quite well; however, the simulation showed earlier start and end times for the solidification process. In addition, after completion of the phase changes, the simulation showed higher temperatures for the melting process and lower temperatures for the solidification process. These last two deviations were well before or after the most important results of this study, namely PCM melting and solidification.

Figure 7-12. Comparison of experimental data and simulation results

Table 7-4. Phase-change time comparison

Cycle	Thermocouple number	Relative phase-change time difference (%)	
		Charging	Discharging
1	TC1	-24	15
	TC3	-3	-6
2	TC1	13	16
	TC3	15	-16
3	TC1	7	-5
	TC3	-2	-14
4	TC1	10	-9
	TC3	-5	-22
5	TC1	13	-9
	TC3	2	-23

8. Significant Accomplishments and Conclusions:

The significant accomplishments and conclusions of this project include:

- Thermal properties of the graphite foam were characterized, providing necessary data for experimental result analysis and numerical simulation.
- Based on Brayton's full-scale HX-TES system, the experimental test module was designed, optimized, and fabricated.
- Five cycle tests—including one with approximately a 3.5-psig pressure applied to the diaphragms—of the thermal performance of the experimental test module for charging and discharging processes were successfully conducted.
- Temperature profiles were generated for each charging testing and discharging test as a function of time.
- The experimental data and the numerical simulation results were compared.
- The temperature profiles clearly showed three TES stages of sensible heat (temperature increase), latent heat (melting), and sensible heat (temperature increase) for the charging process. Similarly, the temperature profiles clearly showed three thermal energy release stages of sensible heat (temperature decrease), latent heat (solidification), and sensible heat (temperature decrease).
- Melting and solidification of the PCM generally occurred in relatively narrow temperature ranges, indicated by the flat temperature regions in the temperature profiles. These phase-change ranges were approximately 3°C for melting and 3.5°C for solidification.
- The charging and discharging temperature profiles are similar for similar experimental parameter tests with or without a pressure applied to the diaphragm to eliminate the gap between the HX surface and the TES subsystem. This indicates that the effect of a small gap between the HX surface and the TES subsystem is not significant for charging and discharging.

- Numerical simulations were conducted using the ANSYS FLUENT 2019 R3 commercial computational fluid dynamics software. The predicted phase-change times agreed reasonably well with those from the experimental data. In most cases, the estimated relative phase-change time differences were within 16%. The predicted start and end times for the charging process agreed well with those from the experimental data. However, the simulation results showed earlier start and end times than the experimental data for the discharging process.
- Overall, the experimental data and its comparison with the simulation predictions verified the technical viability of the integrated ISPF HX-PCM/graphite foam latent-heat TES system.

9. Path Forward: Major tasks of the project have been successfully completed. The results show promising of the integrated HX-TES system for solar applications. The following future research and development will be useful for commercialization of the technology:

- Long-term performance testing of the prototype needs to be conducted to verify the reliability of the integrated HX-TES system with limited deviations or degradation.
- Further refining on the simulation models is necessary to better predict the experimental data.
- Potential use of other foam types (such as copper foam) is worthy of investigation.

10. Inventions, Patents, Publications, and Other Results:

- [1] W. Yu, D. Singh, D. M. France, S. Bhatta, and J. Nash, Investigation of MgCl_2 /Graphite Foam Thermal Energy Storage System with Internally Supported Plate-Fin Flow Channels, SolarPaces 2020, poster presentation, September 28–October 2, 2020.
- [2] W. Yu, D. Singh, D. M. France, S. Bhatta, and J. Nash, Investigation of MgCl_2 /Graphite Foam Thermal Energy Storage System with Internally Supported Plate-Fin Flow Channels, SolarPaces 2020, conference paper, September 28–October 2, 2020.

11. References:

- [1] S. Jegadheeswaran, S. D. Pohekar, and T. Kousksou, Exergy Based Performance Evaluation of Latent Heat Thermal Storage System: A Review, *Renew. Sust. Energ. Rev.*, vol. 14, pp. 2580–2595, 2010.
- [2] B. Zalba, J. M. Marin, L. F. Cabeza, and H. Mehling, Review on Thermal Energy Storage with Phase Change: Materials, Heat Transfer Analysis and Applications, *Appl. Therm. Eng.*, vol. 23, pp. 251–283, 2003.

- [3] Y. Ahn, S. J. Bae, M. Kim, S. K. Cho, S. Baik, J. I. Lee, and J. E. Cha, Review of Supercritical CO₂ Power Cycle Technology and Current Status of Research and Development, *Nucl. Eng. Technol.*, vol. 47, pp. 647–661, 2015.
- [4] R. Siegel, Solidification of Low Conductivity Material Containing Dispersed High Conductivity Particles, *Int. J. Heat Mass Tran.*, vol. 20, pp. 1087–1089, 1977.
- [5] S. Krishnan, J. Y. Murthy, and S. V. Garimella, A Two-Temperature Model for Solid-Liquid Phase Change in Metal Foams, *J Heat Trans.-T. ASME*, vol. 127, pp. 995–1004, 2005.
- [6] S. T. Hong and D. R. Herling, Open-Cell Aluminum Foams Filled with Phase Change Materials as Compact Heat Sinks, *Scr. Mater.*, vol. 55, pp. 887–890, 2006.
- [7] A. Siahpush, J. O'Brien, and J. Crepeau, Phase Change Heat Transfer Enhancement Using Copper Porous Foam, *J Heat Trans.-T. ASME*, vol. 130, 082301, 2008.
- [8] C. Y. Zhao and Z. G. Wu, Heat Transfer Enhancement of High Temperature Thermal Energy Storage Using Metal Foams and Expanded Graphite, *Sol. Energy Mater Sol. Cells*, vol. 95, pp. 636–643, 2011.
- [9] T. Kim, D. M. France, W. Yu, W. Zhao, and D. Singh, Heat Transfer Analysis of a Latent Heat Thermal Energy Storage System Using Graphite Foam for Concentrated Solar Power, *Sol. Energy*, vol. 103, pp. 438–447, 2014.
- [10] W. Zhao, D. M. France, W. Yu, T. Kim, and D. Singh, Phase Change Material with Graphite Foam for Applications in High-Temperature Latent Heat Storage Systems of Concentrated Solar Power Plants, *Renew. Energy*, vol. 69, pp. 134–146, 2014.
- [11] D. Singh, W. Zhao, W. Yu, D. M. France, and T. Kim, Analysis of a Graphite Foam-NaCl Latent Heat Storage System for Supercritical CO₂ Power Cycles for Concentrated Solar Power, *Sol. Energy*, vol. 118, pp. 232–242, 2015.
- [12] D. Singh, T. Kim, W. Zhao, W. Yu, and D. M. France, Development of Graphite Foam Infiltrated with MgCl₂ for a Latent Heat Based Thermal Energy Storage (LHTES) System, *Renew. Energy*, vol. 94, pp. 660–667, 2016.
- [13] D. Singh, W. Yu, W. Zhao, T. Kim, D. M. France, and Roger K. Smith, Development and Prototype Testing of MgCl₂/Graphite Foam Latent Heat Thermal Energy Storage System, *Sol. Energy*, vol. 159, pp. 270–282, 2018.
- [14] M. Lacroix, Study of the Heat Transfer Behavior of a Latent Heat Thermal Energy Storage Unit with a Finned Tube, *Int. J. Heat Mass Tran.*, vol. 36, pp. 2083–2092, 1993.
- [15] R. Velraj, R. V. Seeniraj, B. Hafner, C. Faber, and K. Schwarzer, Experimental Analysis and Numerical Modelling of Inward Solidification on a Finned Vertical Tube for a Latent Heat Storage Unit, *Sol. Energy*, vol. 60, pp. 281–290, 1997.
- [16] A. Miliozzi, R. Liberatore, T. Crescenzi, and E. Veca, Experimental Analysis of Heat Transfer in Passive Latent Heat Thermal Energy Storage Systems for CSP Plants, *Energy Procedia*, vol. 82, pp. 730–736, 2015.
- [17] H. Shabgard, T. L. Bergman, N. Sharifi, and A. Faghri, High Temperature Latent Heat Thermal Energy Storage Using Heat Pipes, *Int. J. Heat Mass Tran.*, vol. 53, pp. 2979–2988, 2010.

- [18] C. W. Robak, T. L. Bergman, and A. Faghri, Enhancement of Latent Heat Energy Storage Using Embedded Heat Pipes, *Int. J. Heat Mass Tran.*, vol. 54, pp. 3476–3484, 2011.
- [19] K. Nithyanandam and R. Pitchumani, Design and Analysis of Metal Foam Enhanced Latent Thermal Energy Storage with Embedded Heat Pipes for Concentrating Solar Power Plants, in *Proceedings of ASME 2013 7th International Conference on Energy Sustainability and 11th Fuel Cell Science*, 2013.
- [20] K. Nithyanandam and R. Pitchumani, Computational Studies on Metal Foam and Heat Pipe Enhanced Latent Thermal Energy Storage, *J Heat Trans.-T. ASME*, vol. 136, 051503, Paper No: HT-13-1278, 2014.
- [21] K. M. Stone, Review of Literature on Heat Transfer Enhancement in Compact Heat Exchangers, ACRC TR-105, University of Illinois, 1996.
- [22] M. Siddique, A.-R. A. Khaled, N. I. Abdulhafiz, and A. Y. Boukhary, Recent Advances in Heat Transfer Enhancements: A Review Report, *Int. J. Chem. Eng.*, vol. 2010, Article ID 106461, 2010.
- [23] J. E. Hesselgreaves, R. Law, and D. Reay, *Compact Heat Exchangers: Selection, Design and Operation*, Butterworth-Heinemann, Oxford UK, 2016.
- [24] M. A. Taylor, *Plate-Fin Heat Exchangers: Guide to Their Specification and Use*, Harwell, Oxfordshire, UK, 1987.
- [25] S. J. Dewson and C. Grady, Heatric™ Workshop at MIT, Cambridge, MA, October 2, 2003.
- [26] D. Ranjan, Fundamental Study of Key Issues Related to Advanced sCO₂ Brayton Cycle: Prototypic HX Development and Cavitation, Final report for NEUP project 14-6670, 2018.

Applied Materials Division

Argonne National Laboratory
9700 South Cass Avenue, Bldg. 212
Lemont, IL 60439-4832

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