Purdue University

Purdue e-Pubs

International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2022

Experimental Results Of Density Controlled Phase Change Material Capsules For Increased First Hour Rating For Heat Pump Water Heaters

Joseph Rendall

Kashif Nawaz

Will Asher

Jamieson Brechtl

Ahmed Elatar

See next page for additional authors

Follow this and additional works at: https://docs.lib.purdue.edu/iracc

Rendall, Joseph; Nawaz, Kashif; Asher, Will; Brechtl, Jamieson; Elatar, Ahmed; Li, Kai; Yang, Cheng-Min; Sun, Jian; and Gehl, Tony, "Experimental Results Of Density Controlled Phase Change Material Capsules For Increased First Hour Rating For Heat Pump Water Heaters" (2022). *International Refrigeration and Air Conditioning Conference.* Paper 2346.
https://docs.lib.purdue.edu/iracc/2346

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.
Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at https://engineering.purdue.edu/Herrick/Events/orderlit.html

Authors
Joseph Rendall, Kashif Nawaz, Will Asher, Jamieson Brechtl, Ahmed Elatar, Kai Li, Cheng-Min Yang, Jian Sun, and Tony Gehl

This conference paper is available at Purdue e-Pubs: https://docs.lib.purdue.edu/iracc/2346

Experimental Results of Density Controlled Phase Change Material Capsules for Increased First Hour Rating for Heat Pump Water Heaters (Case Study)

Joseph RENDALL[1], Kashif NAWAZ[1*], Will ASHER[2], Jamieson BRECHTL[1], Ahmed ELATAR[1], Kai LI[1], Cheng-Min YANG[1], Jian SUN [1], Tony GEHL [1]

[1]Multifunctional Equipment Integration Group, Oak Ridge National Laboratory, Oak Ridge, TN, USA
Contact Information (865-241-0972, nawazk@ornl.gov)
[2]Gas Technology Institute, San Jose, California, USA

ABSTRACT

To improve the capacity of heat pump water heaters, which nominally perform similar to electric resistance water heaters, high energy density PCM was included in a HPWH prototype. Initial results indicate that over a small temperature difference the PCM energy can effective be exchanged to increase the capacity of hot water above a desired cut-off temperature. This increases the amount of water hot enough for mixing at the location of use by the consumer. An industry standard capacity-based test was conducted showing an average of 27.7% increase in capacity of a wrapped heat pump water heater when novel capsules were filled with phase change material an added inside a secondary tank. The substantial increase in capacity was two-fold, firstly, the design of the capsules allowed for high utilization of the high energy density phase change storage and secondly the additional tank has a nominal volume. Food grade paraffin's were selected as appropriate for use in domestic hot water heating. The novel encapsulation design attacked the deficiencies of paraffin based PCMs increasing the effective conductivity inside and outside of the capsule.

1. INTRODUCTION

Typical water heaters are thermal energy storage tank-type electric or gas-fired heaters. Holding a small market is the water heating sector are heat pump water heaters (HPWH). The HPWH takes energy from the environment and puts it into a water stored in a tank often through a vapor compression cycle. A wrapped heat pump water heater (W-HPWH) places the condenser coil of the vapor compression cycle wrapped tightly around the tank under insulation. When comparing HPWHs to traditional gas and electric storage tank heaters by industry standard performance test methods the HPWH outperforms the traditional heaters significantly in the Unified Energy Factor (UEF) but is nominally better than electric tanks in First Hour Rating (FHR) and far behind in FHR than a traditional gas storage tank. To increase the FHR of HPWHs a secondary tank was partially filled with novel phase change material (PCM) capsules.

PCM's have high energy density and can deliver significant amount of heat when solidifying when the conduction in the PCM doesn't limit the total heating power. Heat transfer performance of PCMs is quite low, limiting the applications in which they can be used. A secondary problem is that electric utilities face an infrastructure problem due to ever-increasing electric demands. Hot-water heating by electric resistance heaters causes significant peaking issues for the utilities as the demand for hot water usually occurs early in the morning and in the evening. Thermal storage can help alleviate the peaking issued for utilities.

1.2 Review of literature

The solidification temperature of PCM in a heating system is critical to the performance, and even the careful experiments by Kenisarin et al. do not fully replicate the conditions of previous models (Kenisarin et al. 2020). Thus, original experimental work was required to characterize the performance of the novel PCM encapsulation method called density controlled PCM (D-PCM). Correlations exist for heat transfer and phase fraction and are

Notice: This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the US Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department
of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

reported as a function of nondimensional numbers based on cylindrical geometry orientation and spherical geometry (Mallya and Haussener 2021). These nondimensional correlations should model a wide range of PCMs but a critical review of PCMs encapsulated in spheres was recently published by Kenisarin et al., in which correlations from the literature were compared against the solidification fraction of the PCM over time inside a sphere. The correlations were found to be not accurate due to delayed onset of solidification (Kenisarin et al. 2020). For heating applications, the solidification point is most critical in system performance as subcooling the PCM results in adverse heat transfer gradients to the intended direction of heat flow.

1.3 Review of state of art technologies

A patent has been awarded for heating water with refrigerant and phase change material where the configurations have PCM in direct contact with the refrigerant coil (Trant and Zhang 2019). A very broad and unawarded patent where the refrigerant coil is in contact with many different temperature PCMs (Field and Bissell 2020). Suresh and Saini 2020 studied spheres with PCM in different diameter and location in the tank (Suresh and Saini 2020). Kenisarin 2020 wrote a critical review of PCM spheres performance and their work included a technology with internal methods of conduction via rods placed through the encapsulated PCM (Kenisarin et al. 2020). The patents of (Trant and Zhang 2019) and (Field and Bissell 2020) are in direct contact with the refrigerant coils. The papers by (Suresh and Saini 2020) and (Kenisarin et al. 2020) studied the heat transfer performance of PCM encapsulated in water.

1.4 Description of technology

Taking advantage of the density change of the material, the heating power from the PCM during solidification can be utilized near the outlet of the hot water tank at the temperature desired by the user. Inside a hot-water tank that is stratified, the PCM capsules are designed to be neutrally buoyant at the desired delivery temperature. In this initial case, the D-PCM thermally charges and floats above the outlet location (Figure 1A). As cold water enters the bottom of the tank, the water that was stratified at a neutrally buoyant temperature for the D-PCM start giving off phase change energy to maintain the desired outlet temperature (Figure 1B). When discharged, the capsule sinks below the outlet to not further decrease the outlet temperature (Figure 1C). Finally, when recharging, the spheres float back to the top of the tank (Figure 1D).

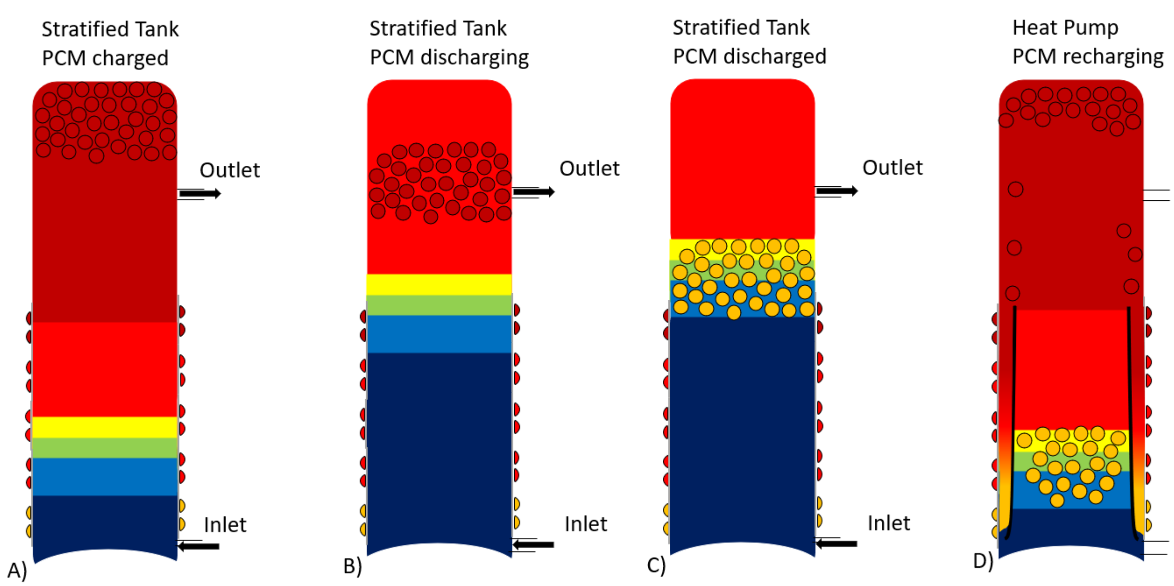

Figure 1 Conceptual design of the D-PCM spheres inside a standard wrapped heat pump water heater during the charge and discharge of the PCM (A to D).

When recharged, the spheres remain ready for the next discharge cycle. This conceptual design was not fully realized in the experimental work. A secondary tank was deployed for ease of testing and will be described in the experimental section.

In the conceptual design, the materiality and size of the spheres is critical to the heat transfer performance. For example, high heat transfer rates are required to reach 450 watts of heating power from the PCM spheres. Large storage capacity is required to sustain the heat transfer which suggests larger diameter spheres. Finally, the forces on the sphere due to the flow condition and gravity need balancing to insure the correct location of the sphere to deliver its heat. The experimental setup and results of the first experimental deployment are discussed in the rest of this paper.

1.5 Design improvements

The D-PCM technology was designed to reduce the issues found in the literature review and surpass the state-of-art technologies found in the patent search. The list of improvements by this study is below:

- The buoyancy-controlled configuration allows for heat transfer to be local in a stratified tank and will only heat the water needed for delivery.
- The coil inside the sphere increases the surface area for heat transfer inside the sphere.
- The external fin increases the external heat transfer on the outside of the sphere to the inside of sphere where the PCM is located.
- The free-floating nature of the encapsulated PCM allows for shocking of the subcooled PCM into the solid state by bouncing around in the tank.

2. Experimental Section

The conceptual design was difficult to implement in the first prototype due to lack of control of the electric elements. Thus the PCM was contained in a secondary tank of nominally 6 gallons and located at the outlet of the hot water tank. A recirculation line was added to integrate the tank holding the PCM spheres with the HPWH. The recirculation pump integrates the secondary storage into the first tank and the similar behavior of the conceptual design describe earlier can be realized (Figure 2).

2.1 Schematic of D-PCM system

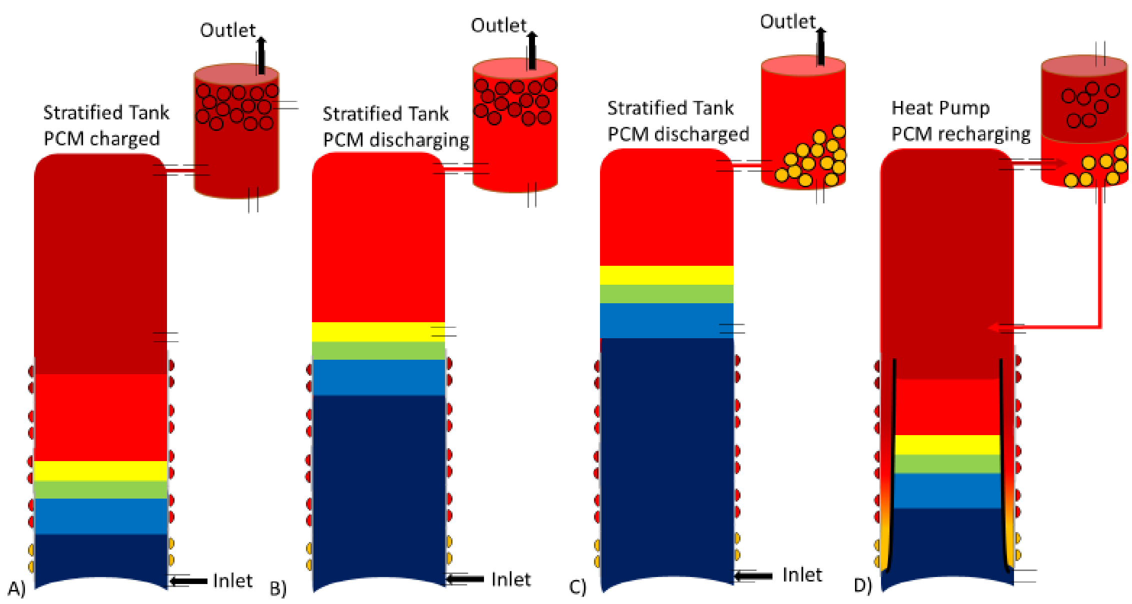

Figure 2 Experimentally built deployment of the D-PCM spheres inside an auxiliary tank attached to a wrapped heat pump water heater during the charge and discharge of the PCM (A to D).

In A, the tank and PCM are fully charged and the PCM spheres should float at the top of the tank. Typically, after water has been drawn from a stratified tank the temperature will drop off significantly. In B, the tank temperature has dropped, although the PCM is still charged and this is where the PCM discharges it's heat to the water. In C, after a larger amount of hot water has been delivered than typical the PCM will be fully discharged and will sink out of the flow path of the water. Dropping below the flow path of the water allows for the heat pump to start recharging the tank. D) depicts recharging of the primary tank water and water is pumped between the two tanks. The PCM will start floating again as it is charged.

2.2. PCM Capsules

To realize the functionality of the density control and increased heat transfer plastic spheres that softened when heater were used to encapsulate food-grade PCM. The heat transfer process was enhanced by adding internal and external coils of wires (Figure 3). Spheres capsules were created using the method listed below. The method insures low air infiltration into the sphere for maximum thermal energy storage in each capsule. To encapsulate about 125 spheres at a time, the following procedure can be used:

1. Ensure that there are holes on both sides of the empty sphere
2. Twist wire into a coil
3. Insert wire into the empty sphere
4. Melt the PCM
5. Put PCM assembly into a chamber that contains melted PCM
6. Close chamber and pull vacuum in chamber that contains the assembly and melted PCM
7. Mix the chamber gently while under vacuum
8. Remove PCM sphere from chamber and shock the PCM sphere by placing in water bath until solid throughout
9. Rewarm the outside of the sphere to melt excess wax
10. Clean sphere to remove excess PCM and then place into water bath
11. Remove sphere from water and apply silicone sealant to hole created for wire

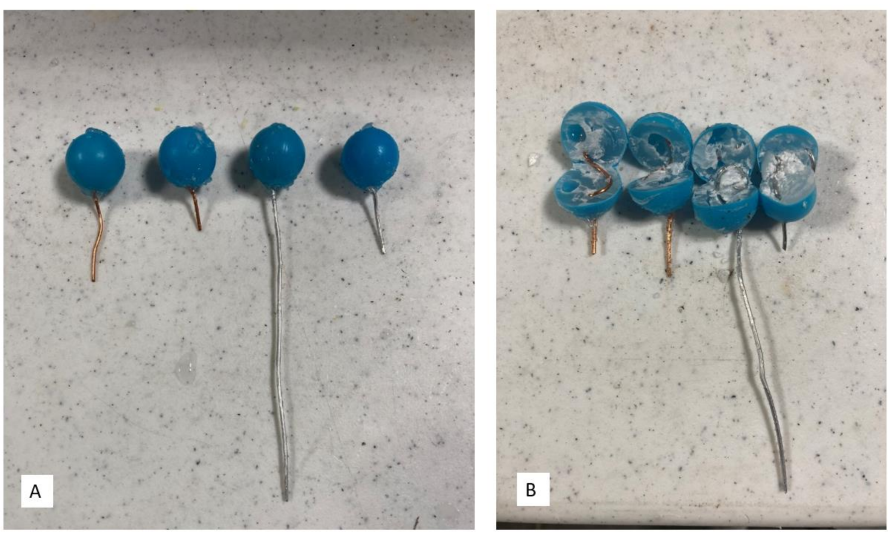

Figure 3 As-built PCM capsules with copper or aluminum fins and coils. One fin extends outside the capsule to increase external heat transfer. The coil on the inside of the capsule increases the surface area for heat transfer. B) As-build capsules cut showing the internal coil, PCM and air void. Note: although 1 extruded fin is easiest to seal, other embodiments of the IP include multiple internal and external fin designs.

942 spheres were placed inside a 6-gallon tank at the outlet of a wrapped heat pump water heater to test the feasibility of the concept (Figure 2). The majority of the spheres were of the short aluminum type (far right in Figure 3) with 795 being of this type (Table 1). The estimated density calculations suggested copper was too dense to create a significant fin outside the capsule. Since the conductivity of copper is much better than aluminum some we created anyways. Ten random samples of the constructed PCM spheres were weighed to determine the mass of the PCM.

Four metal wire samples were also weighed. The total mass of the spheres with wires put into the 6 gallon hot-water tank was 3.403 ± 0.0002 kg, as weighed on a Mettler Toledo ICS425 scale.

Table 1. Sphere type and mass of components that were placed into the 6-gallon tank.

PCM Sphere by wire length	Number of spheres	Mass of metal for length (g)	Mass of constructed sphere (g)	Mass of PCM (g)	Notes
6 cm copper wire	30	0.8940	4.2	99.21	Floats in 46.1°C
8 cm copper wire	81	0.5148	4.8	347.1	Sinks in 46.1°C
8 cm aluminum wire	795	0.2702	3.4	2487	Floats in 46.1°C
15 cm aluminum wire	42	0.6206	4.2	150.3	Floats in 46.1°C

Unfortunately, due to the air inside the sphere, no significant number of PCM spheres were neutrally buoyant at the desired temperature of 46.1°C. It was determined that the total PCM mass by calculation for the wire and plastic samples were 3.084 kg with 0.309 kg, respectively. This result suggests that a very small amount of the spheres had air in them (e.g. < 0.3% by mass). This finding is corroborated with the results for the randomly sampled spheres that were dissected, which shows approximately 1-3% air by volume.

2.3. Apparatus and Measurement

An extensively instrumented 50-gallon heat pump water heater was used to test the FHR for baseline and prototype HPWHs. Figure 4 presents a detailed schematic of the heat pump system with the corresponding measurement instrumentation. Pressure transducers (Omega PX309) with a reading accuracy of 0.25% were installed in the refrigerant line at the compressor and electronic expansion valve inlet and outlet locations. Externally insulated T-type thermocouples were attached to the refrigerant lines in the same locations. Additionally, six thermocouples were installed uniformly throughout the height of the water tank. Thermocouples were also installed at the water heater inlet and outlet. A MicroMotion CMF025 Coriolis mass flow meter was installed between the condenser coil and the expansion valve. The temperature measurement uncertainty is 0.5 °C, and for an energy balance of the water inflow and outflow, the combined uncertainties propagate to less than 3% relative error in terms of energy consumption.

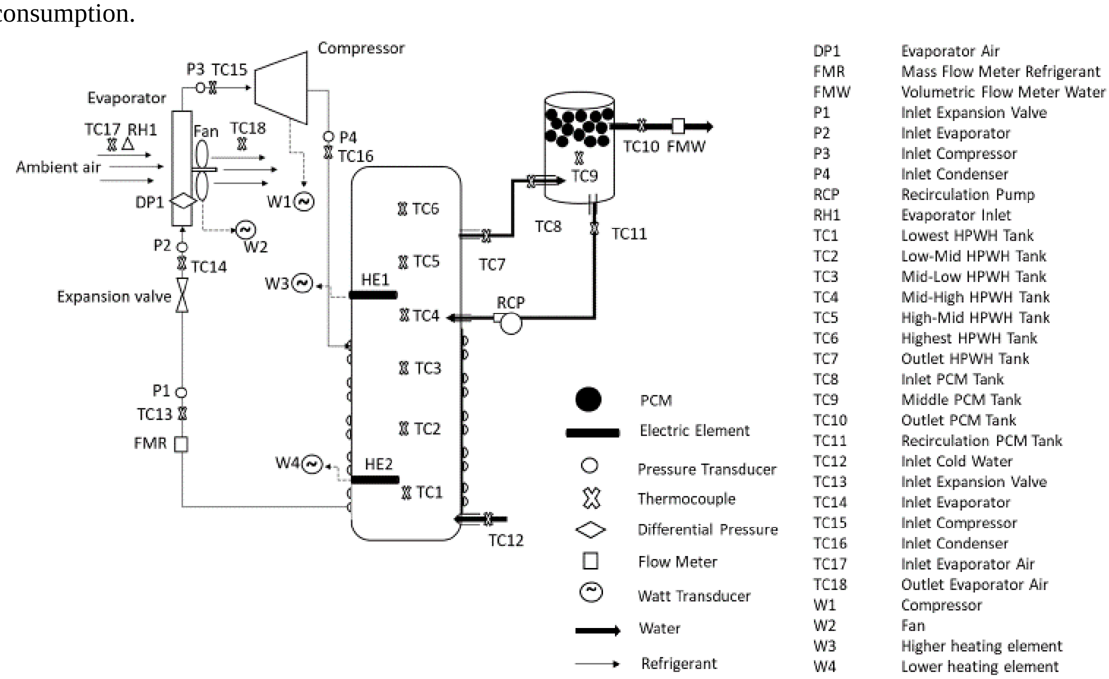

Figure 4 Schematic of the heat pump, hot water tank, PCM tank, and sensor locations.

2.4 Experimental Procedure

The experimental procedure for a FHR test, which quantifies the capacity of a hot water heater at standard conditions, is listed in Ref. (Energy 2017). The FHR test mimics heavy usage of the tank, such as 3 successive high-flow showers were 10 minutes long with about 12 minutes between each shower. The test nominally takes 1 hour where hot water is drawn from a tank at 3 GPM, a typical high-efficiency shower head draws water at a rate of 1.7 GPM. The tank is allowed to recover after the initial temperature drops 8.3°C below the initial temperature of 51.7°C. The completion of the recovery process is denoted by the HPWH turning off the compressor or the upper heating element after hot water is produced in the upper regions of the tank. A second draw then commences until the outlet temperature drops 8.3°C below the hot water temperature of the first recovery. Third draws by the same criteria are common and commence near the end of the 1-hour test. The inlet temperature is prescribed to be 14.4 ± 2.8°C during this test. The performance evaluation experiment was conducted at 23.8 ± 0.41°C. Since the majority of the heating for the FHR occurs in the top of the tank, the impact of this increased temperature may not have a significant impact on the FHR when compared to other technologies. To baseline the system, a test at an average inlet temperature of 22.8 ± 0.11°C was conducted. Both the baseline and performance test had an average flowrate of 2.98 GPM with less than 1% standard deviation in these readings. A third baseline test was conducted at the prescribed 14.4 ± 2.8°C of the baseline unit to determine the effect of the nonstandard inlet temperature. Also, a fourth baseline test was conducted to test the difference between the voltage supplied to the unit 208 V and 240 V. These impacts are discussed in the results section in Table 2.

2.5. Data Recording and Analysis

The data was recorded throughout the FHR testing was recorded every 1 to 2 seconds. A sample of the data for the temperatures leaving the HPWH and entering the PCM tank during the 3 GPM draws is shown in Figure 5. TC7 and TC8 represent the water temperature leaving the HPWH and entering the PCM tank from the HPWH with minimal heat loss. These two temperatures first lead and then lag TC9 and TC10 which show the PCM tank temperature and outlet temperature, respectively. Critically, TC9 and TC10 show the secondary tank to be well mixed as their temperatures are not significantly different and a simple energy balance can be applied to determine the heat energy entering the PCM while TC7/TC8 lead TC9/TC10 and heat leaving the PCM when TC7/TC8 lag TC9/TC10.

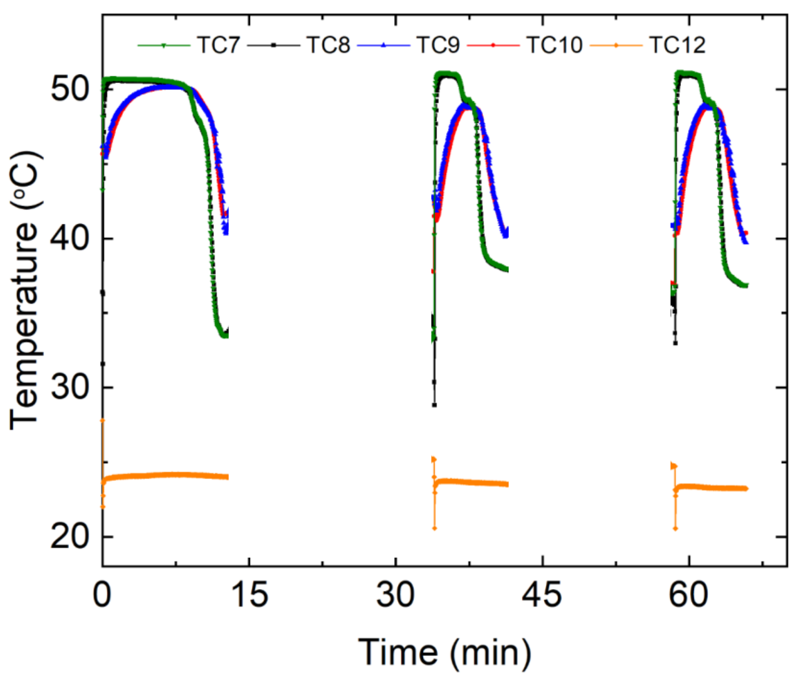

Figure 5 The temperatures leaving the hot-water tank (TC7) and entering the tank with PCM (TC8), the temperature in the middle of the tank with PCM (TC9), temperature leaving the tank with PCM (TC10), and water entering the hot-water tank (TC12).

The properties of the PCM are critical to determine the utilization of the heat in the PCM via the simple energy balance. Thusly, the specific heat capacity of the PCM used in this experiment was determined using a TA Instruments DSC 2500 model following the ASTM E1269 standard (ASTM International 2011). More specifically, an empty pan, Sapphire reference, and samples were heated from -50 to 100°C using a ramp rate of 20 °C/min under a nitrogen atmosphere. Then the specific heat capacity was calculated using Trios software (TA Instruments 2021). The values at 20°C and 80°C was taken for the solid and liquid specific heat capacity, respectively. For latent heat measurements, the PCM was heated from -50 to 100°C and then cooled from 100 to -50°C using a ramp rate of 20°C/min under a nitrogen atmosphere. The properties of the PCM were determined to be 1.74 kJ/kg°C in the solid phase, 2.03 kJ/kg°C in the liquid phase, and a specific heat of 201 kJ/kg.

3. RESULTS AND DISCUSSION

The goal of these experiments was to increase the capacity (FHR) of the system over the baseline test. Since an additional 6-gallon tank was added to the baseline system, the volume of water storage increased by 4 gallons of water (approx. 2 gallons were PCM spheres). This initial condition will increase the FHR by at least these 4 gallons on the first draw as the water is prewarmed before the test starts. The increase in FHR due to the nonstandard inlet temperature was minimum (e.g., 0.9 gallons) as can be seen in Table 2 when comparing the two baseline runs at 3,600 nominal wattages. The FHR of the baseline unit when run at 240 Volts increased the FHR by 8.4 gallons. Due to intensive investigation (e.g., disassembly) of the prototype unit, the impact of running at 240 volts can only be estimated and is compared to average hot water heaters on the market with the nominal heating capacity in watts (Table 3).

Table 2. Comparison of HPWH baseline tests to prototype test.

Hot water heater technology	Nominal Storage (Gallons)	FHR Rating
Baselined HPWH (208 V)	50	60.1
Baselined HPWH* (208 V)	50	61
Baselined HPWH (240 V)	50	69.4
Prototype Flex HPWH* (208 V)	54	79

*inlet condition warmer than standard for FHR tests.

Table 3 Comparison of storage based hot-water heater technologies to a high wattage Flex HPWH.

Hot water heater technology	Nominal Storage (Gallons)	FHR Rating
Conventional 15,000 Watt Gas	55	97
Conventional 5,500 Watt Electric	55	72
Conventional 4,900 Watt HPWH	50	66
(Estimated) 4,900 Watt Flex HPWH	54	88.3

The FHR rating of the water heater technologies in table 2 and table 3 are combined to create figure 7 in which the FHR was divided by the nominal heating power (watts) and nominal storage capacity (gallons).

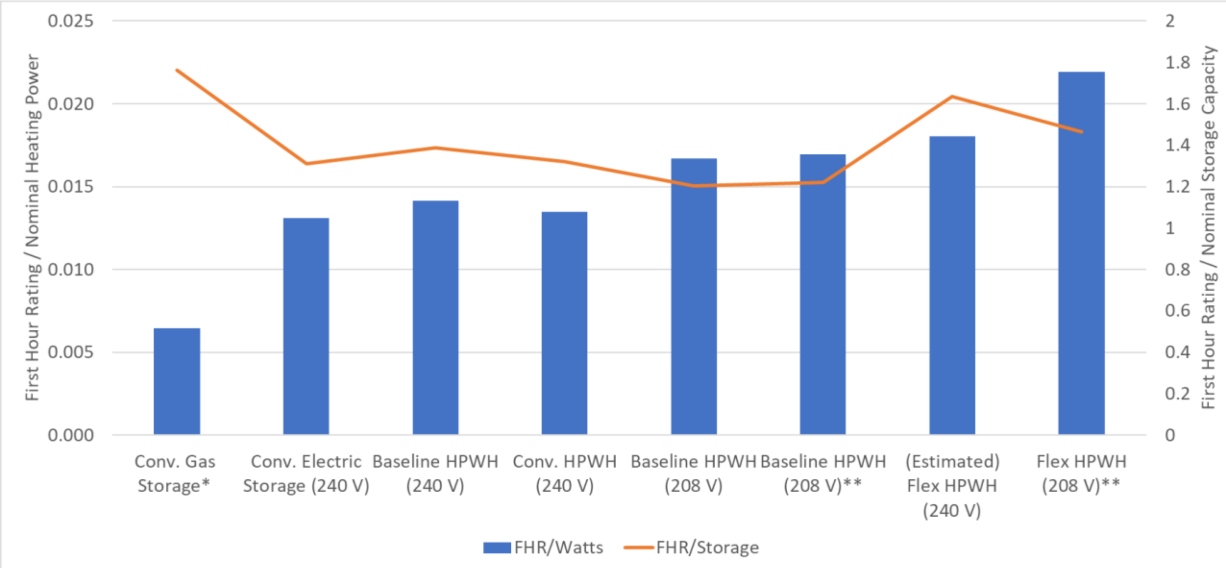

Figure 6 Comparison of first hour rating of conventional, baseline and prototype water heating.

On one side of figure 6 it can be seen a conventional gas storage water heater has a low FHR per heating power input but a very high FHR per storage capacity. This is due to heat losses in the flu and potentially an oversized burner. On the far end, the tested prototype does well on both metrics proving a balanced approach to achieving high capacity.

Furthermore, the increase in the FHR was 18 gallons in which up to 14 gallons of hot water is due to the water transferring the generated heat during phase change of the PCM. This increase in hot water volume is partly due to the potential thermal energy stored in the PCM. Here, the PCM modulates the outlet temperature of the water by first reducing the water temperature by charging the PCM and then extending the period of hot enough water during the FHR test. The delivery temperatures of the baseline compared to the prototype are shown in Figure 7.

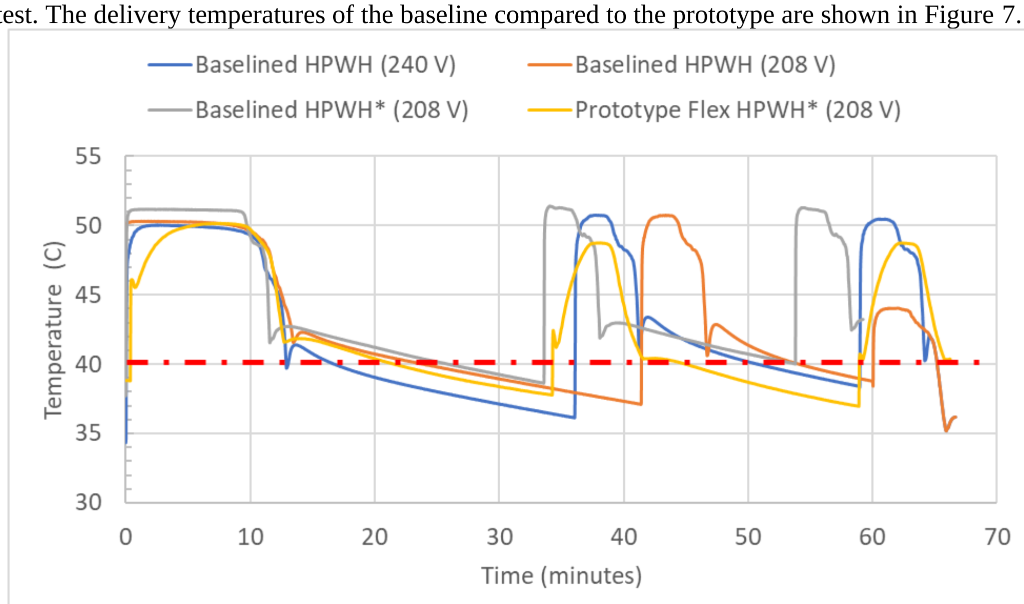

Figure 7 Delivery temperatures of the baseline test runs and the prototype with red-dashed line representing the desired cutoff temperature. The standby temperatures (e.g., negative gradient of temperature between the draws which are shown as humps in temperature) do not represent the outlet temperature.

In Figure 7, the hot-water user has longer periods of time of hot water than in the baseline conditions. The increase and decrease of the hot-water temperature in the baseline occur at a faster rate than the prototype HPWHs. A sharp increase in temperature is generally desirable, as the user will get the hottest water the fastest. An active mixing valve at the point of use can remediate this issue as the hot water is typically blended with cold water at the point of use to just above 38°C. The delivered hot water temperature in all tests was above 40°C.

3.1 PCM Utilization

As can be seen in Figure 8, the charging of the PCM takes more time due to the temperature of the water and the phase change temperature of the PCM in the tank. The solidification of the PCM, and subsequent heat release, happens faster and to a higher utilization due to the design of the D-PCM.

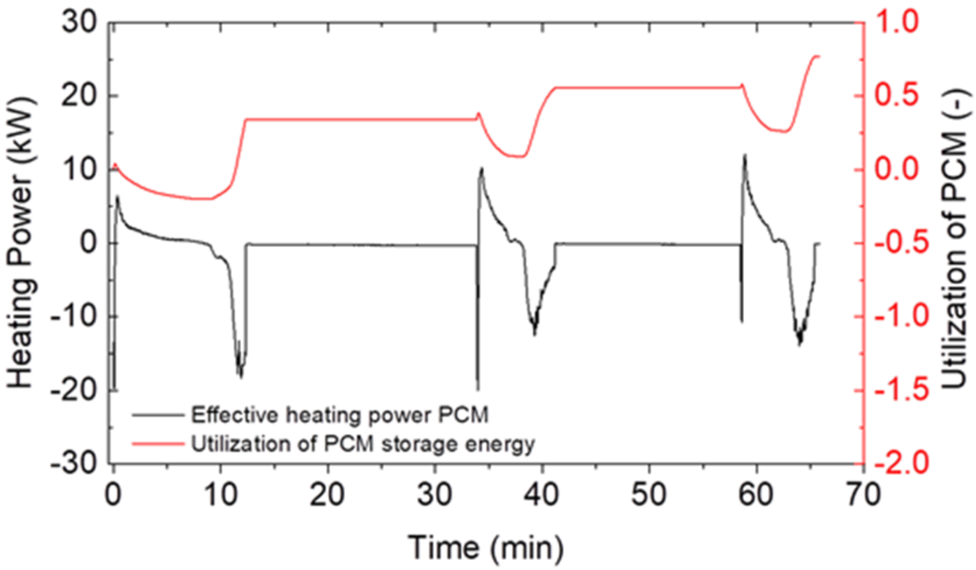

Figure 8 Heating power of the PCM capsules during the 3 draws and utilization of the PCM.

This high utilization is likely due to the PCM freezing front starting on the interior coil and moving outwards. Charging the PCM is considered a negative value on the utilization and is necessary to extend the FHR. The average charging utilization was 25% and discharge utilization was 38% over the three draws. Finally, over the three draws in the FHR test, 77% of the energy stored in the PCM was utilized. Maximizing the discharge of the PCM will further improve the performance of 79 gallons of hot water delivered by increasing the heat.

3.2 Ongoing and Future Work

The balance between improved heat transfer via. internal and external coils and constructability of the capsule is a question that needs solution in the commercialization stage of the invented capsule. The heat transfer implications are also being studied in a Beta capsule design and experimental test bed created to better quantify the behavior of the capsule in thermally stratified hot water.

4. CONCLUSIONS

The design of the encapsulated PCM is critical to the heating power realized. To replace typical storage tank electrical heating elements or gas burners the heating power needs to be on the order of 1,000’s of watts. This first prototype is estimated to provide an average 500 watts of heating during the standard First Hour Rating test.
The novel PCM capsules significantly increased the FHR by charging and discharging PCM during each draw of the FHR without decreasing the temperature of the water below what users require. The FHR was increased by 18 gallons by adding 3.3 kg of PCM inside an external 6-gallon tank. The average charging utilization was 25% and discharge utilization was 38% over the three draws. Over the full FHR test, 77% of the energy stored in the PCM was utilized. These results suggest that there is still room for improvement of the utilization by tuning a combination

of the following: the PCM phase change temperature, the hot-water setpoint temperature, the heat transfer design of the encapsulation, and the amount of PCM placed inside the tank.

Future investigations are needed to bring the conceptual design to reality. The conditions that will balance these forces and allow for neutral buoyancy below the desired outlet temperature will be critical to the development of this design. The impact of the PCM on stratification will also be quantified in future studies.

Acknowledgments

We would like to thank A. O. Smith for providing the hot-water tank used in the development of this prototype. Also, for assistance in prototype construction and experimentation Brian Goins and Jeff Chambers.

This work was sponsored by the U.S. Department of Energy's Building Technologies Office under Contract No. DEAC05-00OR22725 with UT-Battelle, LLC. The authors would also like to acknowledge Mr. Antonio Bouza, Technology Manager – HVAC&R, Water Heating, and Appliance, U.S. Department of Energy Building Technologies Office.

References

ASTM International. 2011. "ASTM E1269-11, Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry."

Energy, Department of. 2017. *Code of Federal Regulations: Title 10 → Chapter II → Subchapter D → Part 430 → Subpart B → Appendix Title 10: Energy PART 430-ENERGY CONSERVATION PROGRAM FOR CONSUMER PRODUCTS Subpart B-Test Procedures APPENDIX E TO SUBPART B OF PART 430-UNIFORM TEST METH*.

Field, John, and Andrew Bissell. 2020. "ENERGY STORAGE SYSTEMS." 78.

Kenisarin, Murat M., Khamid Mahkamov, Sol Carolina Costa, and Irina Makhkamova. 2020. "Melting and Solidificaiton of PCMs inside a Spherical Capsule: A Critical Review." *Journal of Energy Storage* 27(101082):1–38.

Mallya, Nithin, and Sophia Haussener. 2021. "Buoyancy-Driven Melting and Solidification Heat Transfer Analysis in Encapsulated Phase Change Materials." *International Journal of Heat and Mass Transfer* 164:120525. doi: 10.1016/j.ijheatmasstransfer.2020.120525.

Suresh, C., and R. P. Saini. 2020. "Experimental Study on Combined Sensible-Latent Heat Storage System for Different Volume Fractions of PCM." *Solar Energy* 212:282–96. doi: 10.1016/j.solener.2020.11.013.

TA Instruments. 2021. "TRIOS Software."

Trant, Troy E., and Qian Zhang. 2019. "APPARATUS AND METHODS FOR HEATING WATER WITH REFRIGERANT AND PHASE CHANGE MATERIAL." 43.