Performance Characterization of 3rd generation of PCM Module in a Three-Module Phase Change Energy Storage System for Domestic Heating Applications.

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ABSTRACT

The experimental characterisation of a 3rd generation compact modular latent heat thermal energy storage system (TES) based on phase change material (PCM) was conducted to determine its thermal performance. The development of 3rd generation TES systems at the Centre for Renewable Energy Systems Technology (CREST) followed several years of research on TES systems and PCM materials at Loughborough University. These 3rd generation TES systems were created for The Advanced Distributed Storage for Grid Benefit (ADSorB) project, which "aims to disrupt the way we heat our homes by deploying and demonstrating a series of innovative, smart, and interoperable thermal energy stores". These systems are intended to be installed in test houses located at Nottingham University. The system consisted of three identical modules filled with a commercial PCM called CrodaTherm™ 53. Each of the modules in the thermal storage system had a cuboid shape and contained coiled finned heat exchangers (HX) submerged in the PCM. Each module with a heat capacity of up to 4.5 kWh equipped with Polyisocyanurate (PIR) insulation could be discharged individually or concurrently. The experimental results include measurements of charge and discharge powers, outlet temperatures and self-discharge characteristics from long-duration experiments in comparison to similar tests of 1st and 2nd gen system performance.

The system's behaviour was evaluated when all three modules were charged and discharged simultaneously, both in series and parallel arrangements with total flow rates of 1.5, 3, 4.5, and 6 L/min.

Keywords: *Phase change material, modular design, thermal energy storage, domestic heating applications.*

1. INTRODUCTION

Thermal energy storage (TES) is expected to play a pivotal role in the transition towards low and zero-carbon heating and cooling systems and the electrification of heat in buildings. TES offers a promising solution to address the inherent mismatch between energy production and demand, considering variations in temperature, time, location, and power [1,2]. Several countries have already started to implement the widespread adoption of heat pumps while others plan to create laws and regulations to force the replacement of domestic gas boilers by heat pumps, a potential challenge arises due to the lack of diversity in space heating requirements, which are strongly influenced by weather conditions.

The European heat pump market, primarily dominated by air-sourced heat pumps, is experiencing rapid growth. Expectations indicate unprecedented expansion in the coming years, rising from 14.01 billion USD in 2022 to 29.696 billion USD in 2032 [3]. This anticipated growth is substantiated by significant investments from key companies establishing new production plants in Europe. Large-scale deployment can lead to increased stress on the low-voltage network and a surge in peak winter electricity generation demands, resulting in significant tariff escalations during these periods. By employing thermal energy storage, the effective decoupling of heat generation and demand becomes achievable, resulting in reduced peak grid loads and enabling consumers to leverage periods with lower electricity tariffs. While simple sensible water-based heat storage suffices in cases where space is not a limitation, the utilization of phase change materials becomes essential to accommodate more compact storage systems in scenarios constrained by limited space. This study aims to develop a compact thermal energy storage system with a min 10 kWh storage capacity, specifically designed for charging using an air source heat pump with subsequent discharge to a low-temperature hydronic heating system for domestic hot water (DHW) and space heating.

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2. EXPERIMENTAL PROGRAM

Characterisation of 3rd gen PCM TES systems developed for ADSorB project [4] was conducted with 70°C charging and 10°C discharging temperatures for both series and parallel flow module arrangements with flow rates of 6, 4.5, 3 and 1.5 l/min flow rates.

2.1. TES systems test facility.

Performance evaluation of the 3rd gen PCM thermal energy storage systems was conducted on a designed and developed in-house experimental thermal store test facility that allows for simultaneous charging and/or discharging of up to four PCM storage modules, with precise control over heat transfer fluid volume flow rates and temperatures. Figure 1 illustrates the layout of the developed test facility.

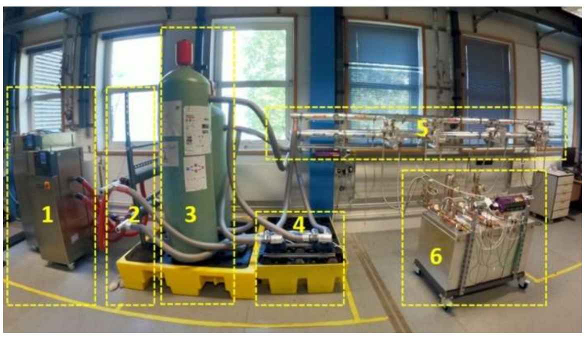

Figure 1 Photograph of PCM module test facility.

In Figure 1, the components of the test facility are two temperature-controlled Huber heat sources (1) used to charge the heat transfer fluid storage vessels (3) in the middle via tube-type heat exchangers (2), separating the primary oil-based and secondary water-based heat transfer loops. The primary water-based heating and cooling heat transfer fluid loops (5) are supplied by two pumps (4), with connections for the attachment of the 3-module TES system (6) being tested along with secondary control of heat transfer fluid flow loops located on top of each module (6). The pumping station (4) is integrated with 3-way valves, facilitating the redirection and control of fluid flow between the test loops and water storage vessels (3).

These water storage vessels function as buffer tanks, ensuring fluid temperature stabilization during the charging and discharging of the TES system.

Each of the primary fluid loops (5) is equipped with a dedicated flow meter featuring a totalizer and a set of temperature sensors at both the inlet and outlet points connected to the primary data collection system. The primary fluid loop (5) is also fitted with four 3-way flow control valves, allowing the connection of up to four TES system modules which can be tested simultaneously, with a regulated set inlet temperature.

On top of each of the PCM-based TES modules to be evaluated (6), a separate hydraulic module (secondary test loop flow control) was installed for each unit. These hydraulic modules feature dedicated flow meters, temperature sensors (on the inlet and outlet of each PCM module) connected to a secondary data acquisition system, and a set of flow control valves.

The design of the secondary test loop flow control system allows for the regulation of flow rate volume and enables clockwise and counterclockwise flow direction adjustments without the need to disconnect the stored modules being tested. The specific design facilitates the redirection and control of fluid flow through the hydraulic module, temporarily excluding the tested TES modules. This process enables the temperature of the hydraulic module to be stabilised between charge and discharge cycles before each test cycle, ensuring higher accuracy of the measured data.

2.2. PCM-based TES systems fabrication.

Figures 2 and 3 show the third generation of the three-module PCM stores. The left image in Figure 2 illustrates a single PCM module featuring a heat exchanger installed within an internal stainless-steel container (prior to hydraulic piping and instrumentation installation). The PCM store is enclosed in PIR insulation and an external aluminium container.

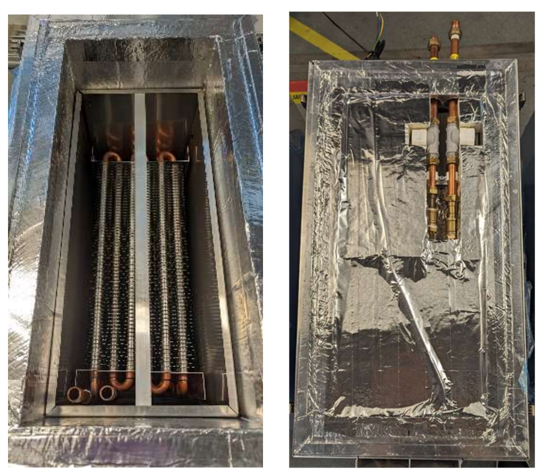

Figure 2 Photograph on left: copper/aluminium heat exchanger installed in the TES module. Photograph on the right: single module assembled with instrumentation and insulation without top cover.

The right photographs on Figure 2 shows thermal insulation and instrumentation (two flow meters and three temperature sensors) installed on a single module before closing the outer store container top cover.

Figure 3 is a photograph of the 3 fully assembled PCM modules before testing. Each module was equipped with two flowmeters to enable flow measurement for both clockwise and counterclockwise flow arrangement connections.

Figure 3 Photograph of three fully assembled PCM modules prepared for installation in test houses.

The TES modules shown in Figure 3 were equipped with secondary data acquisition systems developed by Mixergy LTD, an industrial partner in the ADSorB project which record temperature and flow rates during the operation of the PCM-based modules when installed in test houses at Nottingham University. In the process of characterization of the 3rd generation PCM modules in the laboratory, an internal data acquisition system based on a Data Taker DT-85M was utilized.

2.3. PCM properties.

The choice of PCM CrodaTherm™ 53 for the experiments was based on its thermal properties as shown in Table 1, confirmed through multiple experiments using Thermal Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC).

Table 1. CrodaTherm™ 53 thermal properties [5]

Property	Typical Value
Peak melting/solidification temperature	52°C
Latent hear, melting	226 kJ/kg
Bio-based content	100%
Density at 22 °C (solid)	904 kg/m^3
Density at 60 °C (liquid)	829 kg/m^3
Specific heat capacity (solid)	1.9 kJ(kgK)
Specific heat capacity (liquid)	2.2 kJ(kgK)
Volume expansion 22-60°C	9.1%
Thermal conductivity (solid)	0.28 W/(mK)
Thermal conductivity (liquid)	0.16 W/(mK)

Additionally, the selected PCM's properties such as low flammability, non-toxicity, and biodegradability were significant factors in the selection process. Initial TGA and DSC experimentation revealed that the majority of the melting enthalpy for CrodaTherm™ 53 occurs in the range of 51 to 54°C, with a peak at 52°C. Similarly, the majority of the crystallization enthalpy is in the range of 50 to 52°C, with the peak once again at 52°C. The measured thermal properties of CrodaTherm™ 53 especially the temperature at witch the majority of the crystallization and melting enthalpy occurs demonstrates its compatibility with a standard air source heat pump capable of delivering a temperature of 65°C for charging the TES system but also with a demand temperature of 40°C and above for DHW and various low-temperature domestic heat distribution systems.

2.4. Heat exchanger design and selection.

A significant drawback of CrodaTherm™ 53 is its relatively low thermal conductivity. To address this issue, a compact coiled finned heat exchanger was utilized (as shown in figure 4), constructed with 72 passes of compact copper tubes with an external diameter of 12.7mm and a wall thickness of 0.7mm. The aluminium fins mounted on the tubes are, 0.2mm thick, spaced 6.5mm apart. Each heat exchanger was equipped with 3mm thick end plates, resulting in a total heat exchange area of approximately 10.6 m^2. The contributions to the total area were approximately 1.3 m^2 from copper pipes, 8.8 m^2 from aluminium fins, and 0.4 m^2 from end plates.

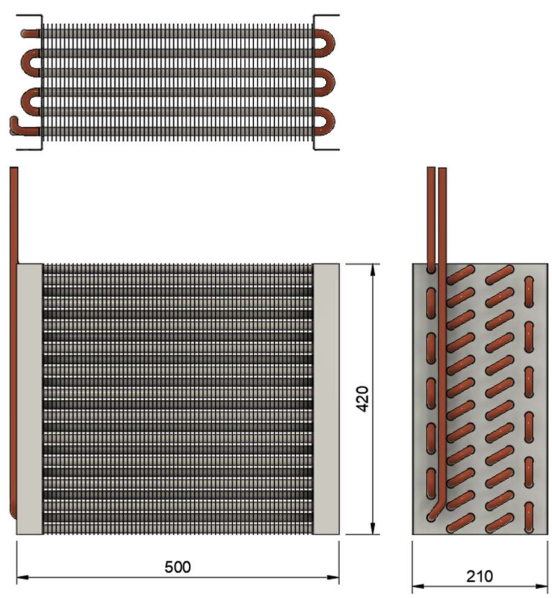

Figure 4 3d diagram of the compact coiled finned heat exchanger utilised in each PCM store module.

The HX design adopts a single-loop system with a single inlet and outlet, devoid of headers, to achieve excellent temperature at the outlet. This design aligns with the advantages of single-pass heat exchangers, offering streamlined simplicity, efficient heat transfer, and reduced pressure drop for optimal performance. The selection of the type and design of the used heat exchanger resulted from multiple tests involving different HX types and arrangements to identify the optimal solution from both a thermodynamic and economic standpoint [5, 6].

3. EXPERIMENTAL RESULTS

All experiments conducted on PCM-based modules involved charging the stores to a temperature of 70°C and discharging with a heat transfer fluid inlet temperature of 10°C for both series (S) and parallel (P) flow arrangements.

3.1. Discharging outlet temperature.

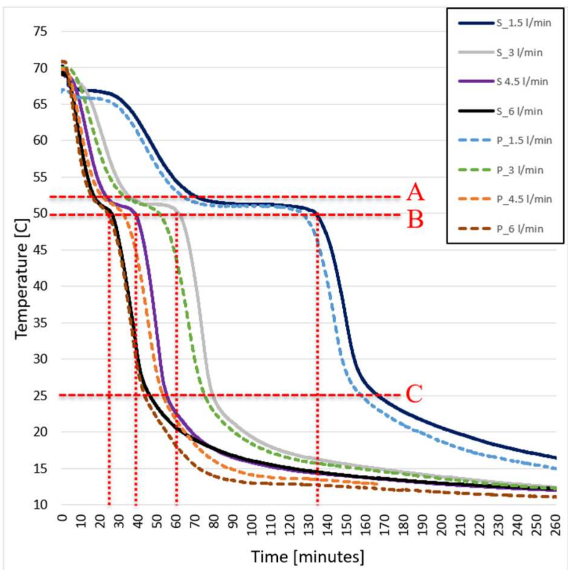

Figure 5 The measured store outlet temperature during discharging from the PCM stores for series (S) and parallel (P) flow arrangements with heat transfer fluid inlet temperature of 10°C for Gen. 3 TES system.

All experiments were conducted with flow rates of 6, 4.5, 3, and 1.5 l/min. Flow from top to bottom of the HX was used for charging, and flow from bottom to top of the HX was used for discharging in both series and parallel arrangements of the tested 3-PCM modules comprising each storage system. As shown in Figure 5, the duration of discharge decreases with higher volume flow rates. It can be seen that the temperature output is longer for modules connected in series as opposed to parallel. The rapid discharge observed above line A, indicated by decreasing outlet temperature for all flow rates, was caused by the loss of sensible heat while discharging with an inlet temperature of 10°C. Between line A and line B, corresponding to the phase change of the PCM, the rate of decrease in outlet temperature initially reduces, followed by a period of constant outlet temperature, and then it starts to decrease again. The duration of the constant outlet temperature is dependent on the heat transfer fluid volume flow rate, being longer for lower volume flow rates. The constant outlet temperature is approximately 51°C, corresponding well to the temperature of the peak crystallization enthalpy of CrodaTherm™ (52°C). Depending on the flow rate the store can deliver 27, 40, 62, and 134 minutes of outlet temperature at 50°C and above for series configurations, respectively, for flow rates of 6, 4.5, 3, and 1.5 l/min. Line C indicates full solidification of PCM and a rapid drop in outlet temperature, which decreases slowly approaching the inlet fluid temperature.

3.2. Discharging heat output.

The quantification of heat outputs shown in Figure 6 involved the measurement of heat transfer fluid inlet and outlet temperatures along with volume flow rates. Comparative analysis of both series and parallel flow configurations revealed a period of near-constant power output during the PCM phase change for the series flow arrangement.

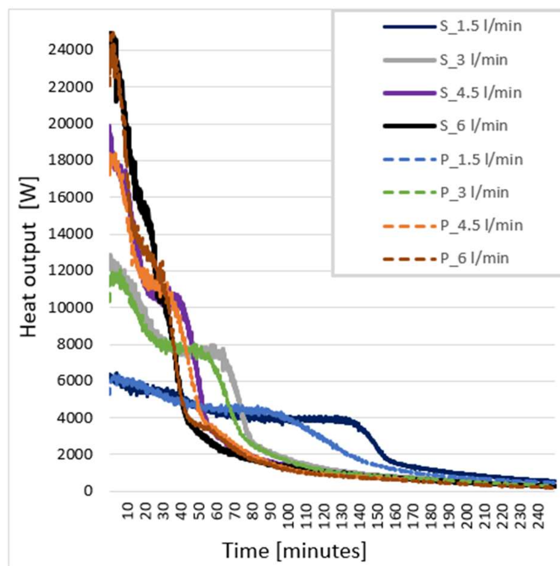

Figure 6 The calculated heat output during store discharging from the PCM stores for series (S) and parallel (P) flow arrangements with heat transfer fluid inlet temperature of 10°C. for Gen. 3 TES system.

In the initial phase of the discharge process, the power outputs display high values due to significant differences between the inlet temperature 10°C and PCM temperature of 70°C in the fully charged store. This results in power outputs of approximately 24, 18, 12, and 5.5 kW for flow rates of 6, 4.5, 3, and 1.5 l/min, respectively. As the PCM reaches its peak crystallization temperature at 52°C, the power output decreases to 15, 10, 8, and 4 kW, respectively, for the same flow rates. Slight variations in the measured flow rate introduce some noise in the heat output values shown in Figure 6. While the heat output profiles for parallel and series flow arrangements generally align, the series flow configuration maintains a consistent power output during the phase change for a slightly longer duration compared to the parallel flow arrangement.

3.3. Cumulative heat discharge.

The cumulative heat discharged from the PCM store shown in figure 7 during the phase change represented by graphs below line A, exhibits approximately constant gradients. For flow rates of 1.5 and 3 l/min, a slightly longer discharge at a constant power can be observed in the series flow configuration then the parallel flow configuration. Above line A, the temperature difference between the solid PCM and the heat transfer fluid decreases, resulting in a subsequent reduction in delivered heat.

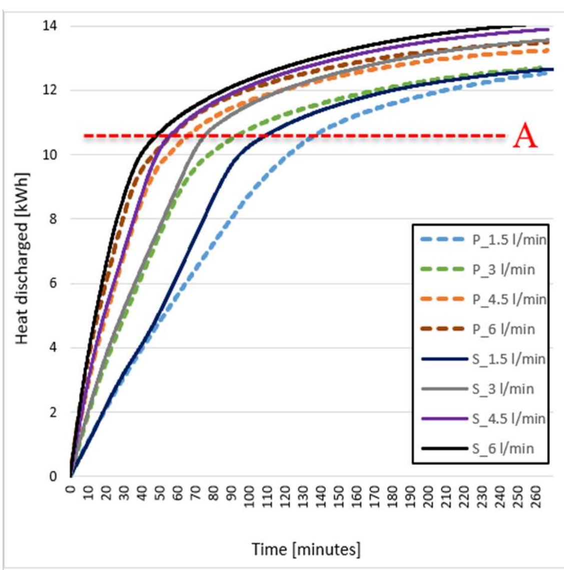

Figure 7 The calculated cumulative heat delivered from the PCM store for series (S) and parallel (P) flow arrangements with heat transfer fluid inlet temperature of 10°C. for Gen. 3 TES system.

By referring to Figures 5 and 6, it can be observed that, depending on the flow rate, for the series flow arrangement durations of 27, 40, 62, and 134 minutes with outlet temperatures at 50°C and above for flow rates of 6, 4.5, 3, and 1.5 l/min, are achieved respectively. Correspondingly, the power outputs for these configurations are 15, 10, 8, and 4 kW. This information was employed to determine the useful heat capacity of the tested third-generation PCM-based modules, as indicated in Figure 7 which shows cumulative heat delivery. The analysis established that the useful cumulative heat capacity of the 3rd generation PCM modules, delivering heat at or above the required temperature of 50 °C is approximately 10.5 kilowatt-hours.

3.4. TES systems in self-discharge tests.

Figure 8 shows the average of measured store internal temperatures during extended self-discharge experiments conducted on first, second and third-generation PCM-based TES systems. The first generation of TES systems utilized 40kg of CrodaTherm™ 53, whereas the subsequent generations employed 45kg. All generations of TES systems featured identical heat exchangers, differing solely in the internal container geometry, with the second and third generations being more optimized for PCM-based materials including additional insulation.

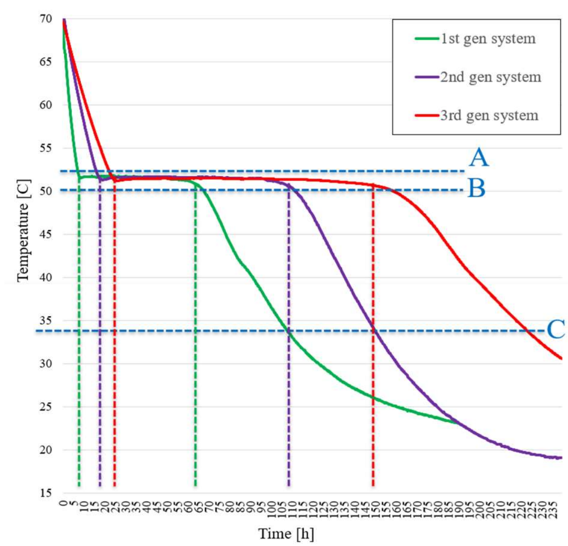

Figure 8 The experimentally measured average temperatures of the 3rd generation of the TES systems in self-discharge tests with an ambient temperature of approximately 19.5°C.

Upon analysing the experimental characteristics of the 1st and 2nd generation PCM-based TES systems, it was noted that, during the charging phase, the majority of the PCM located between the fins and in close proximity to the HX had already transitioned into to the liquid state while in the area between the HX and the internal store casing, a substantial amount of PCM persisted in a solid form. Consequently, this led to a lower heat capacity being realised in relation to the utilized volume of PCM. To address this problem and increase the efficiency of charging and discharging, the internal containers were redesigned so that the sides were much closer to the perimeter of the heat exchanger. At the same time, the thickness of thermal insulation between the inner and outer containers was significantly increased, from 40 mm (on the bottom and top) and 30 mm on the sides to 80 mm and 60 mm, respectively. This change reduces the heat loss rate and significantly extends the self-discharge period of the storage system. In all experiments, TES modules were charged to a temperature of 70°C and left in the laboratory with an ambient air temperature of approximately 19.5°C +- 0.5°C. As shown in Figure 8, the temperature inside the TES modules decreased to 52°C the crystallization temperature after 7, 17, and 24 hours for the 1st, 2nd, and 3rd generation TES systems, respectively, as represented by the graphs above line A. Temperatures inside the PCM-based modules exceeded 50°C during the self-discharging tests and remained above this threshold for 65 hours, 110 hours, and 162 hours, respectively, for modules of the 1st, 2nd, and 3rd generations, as indicated by the space between lines A and B. Temperatures in the TES modules dropped below a temperature useful for domestic low-temperature hydronic systems, represented by line C, after 120, 160, and 235 hours, respectively, for modules of the 1st, 2nd, and 3rd generations of TES systems.

CONCLUSIONS

Three generations of PCM-based modular TES systems were designed, fabricated, and characterized, showing consistent improvement performance. The 3rd generation system was characterized for both parallel and series flow through the modules and can provide in series flow 27, 40, 62, and 134 minutes of outlet temperature of 50°C and above for flow rates of 6, 4.5, 3, and 1.5 l/min, respectively. If the tested system is used for domestic hot water heating, with delivered heat above 50 °C mixed with cold water of 10 °C, it would be able to provide 240 litres of bathwater at a temperature of 45 °C. The heat delivery rate from the stores with flow rates of 1.5, 3, 5.5 and 6 l/min was greater than 4kW, 8kW, 10.5kW and 15kW for 27, 40, 62, and 134 minutes. The modular approach facilitates the addition of extra modules, thereby enhancing storage capacity. The compact design of the storage units permits the installation of separate modules in various available spaces within houses, thereby requiring more piping for connections but enabling the installation of greater storage capacity in smaller areas. The option for parallel or series operation provides flexibility, allowing either all modules or individual modules to be charged or discharged, enhancing operational versatility.

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