

RESEARCH ARTICLE

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Smoothing cooling demand of buildings with PCM thermal batteries

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Received: 6 March 2023 / Received in final form: 19 February 2024 / Accepted: 22 February 2024

Abstract. Escalating energy tariffs and peak cooling demands due to climate change along with expanding use of variable renewable energy supply are presenting new challenges and opportunities for air conditioning system operation and control. This research presents the outcome of an investigation into the use of a thermal battery using salt-hydrate phase change material (PCM) in commercial buildings. A 1.2 m³ modular thermal battery using 15 °C melting temperature salt-hydrate PCM has been designed and fabricated. Its cooling performance and feasibility of integration into a chilled water-cooling system of commercial buildings has been comprehensively investigated. This storage unit can accommodate approximately 52 kWh of energy, featuring a rapid heat discharge rate of 32.58 kW during the initial 30 min to effectively address sudden cooling demands. The overall heat discharge rate closely aligns with simulation results, reaching approximately 96% accuracy. This has been achieved through optimisation of the heat exchanger design through mathematical simulation, detailed testing to match various operational scenarios and evaluation of economic and peak load shifting benefits. The results demonstrate the environmental and economic effectiveness of the PCM thermal battery as an independent component in building cooling systems. It provides a timely response to peak cooling demand and improves thermal comfort of the buildings.

Keywords: Phase change material / thermal battery / peak demand shifting / thermal comfort / commercial building

1 Introduction

Due to the increased frequency and severity of extreme weather events, there has been a significant increase in the amount of energy required to provide indoor thermal comfort, along with an escalation of peak demand [1]. This has caused considerable concern both in Australia and around the world. In the Australian context, extreme heat causes the majority of problems – primarily cooling issues during summer [2]. According to the Australian government, approximately 10% of Australian's greenhouse gas emissions can be attributed to non-residential and commercial buildings, including shops, restaurants, offices, industrial buildings, schools and hospitals [3].

In an effort to reduce the energy consumption and peak demand of buildings, the Australian government has introduced various energy policies such as the solar feed-in scheme [4] and Australian Building Greenhouse Rating [5]. Furthermore, the SA government “has had a commitment that all newly constructed office buildings with an

area greater than 2,000 m² to be used by the Government must be built to at least a five-star rating under the Australian Green Building Council's ‘Green Star Office Design’ and ‘Green Star Office As Built’ rating systems since 2004” [6]. In the meantime, the electricity grid in many areas is experiencing a glut of renewable supply during sunshine hours due to the rapid expansion of rooftop solar installation. This has led retailers to introduce “time-of-use” (TOU) electricity tariffs, which are pricing schemes where the cost of electricity varies according to the time of day, typically with higher rates during peak demand periods and lower rates during off-peak times.

In response to these changes, various technologies have been trialled to increase energy efficiency and reduce costs in commercial buildings, such as utilising various renewable energy sources, electrical battery system, thermal storage system using ice, and conventional air-based HVAC systems coupled with a chilled beam cooling using water chiller.

However, there are still various issues with the application of those technologies including: (i) renewable energy sources are unreliable and intermittent; (ii) the

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intermittency has led to fluctuations in the cost of energy depending on TOU in and will continue to do so with increasing renewable supply; (iii) solving the intermittency and unreliability problems with fossil fuels is polluting, expensive and creates greenhouse gases; (iv) the unreliability problem has created a large demand for storage for commercial buildings as well as data centres and; (v) electrical battery storage can be used but are still expensive. Moreover, commercial buildings have experienced an increase in ventilation needs in the post-Covid era, which often necessitates air conditioning peak capacity beyond the capabilities of existing systems.

For more than three decades, the use of phase change materials (PCMs) has gained considerable attention as a promising solution for smoothing energy supply-demand variations. PCMs are materials that change state, from solid to liquid and back by storing and releasing latent heat (LH) energy in the process. A PCM thermal battery uses the LH during the phase change process [7]. The LH has much higher energy storage capacity than the sensible heat used for thermal storage appliance such as hot/chilled water tank. A PCM thermal battery for heating and cooling (H&C) of commercial buildings is inherently & uniquely efficient as conversion losses (from electricity to heat and back) are almost eliminated and air conditioning equipment can be operated using low-cost renewable electricity at maximum efficiency. Research on PCMs in building applications has demonstrated the value of PCMs in improving the thermal performance of buildings by moderating indoor temperature fluctuation and shifting peak load during extremely hot and cold periods [8,9]. LH thermal batteries using PCM is a renewable energy source implemented in space H&C applications due to their high-energy storage density [10].

In an effort to reduce the energy consumption and peak demand of buildings, Isothermix teamed up with University of South Australia (UniSA) in 2019 to develop a PCM thermal energy storage (PCM-TES) system based on over 20 years of UniSA's research into LH thermal storage using PCM. Through the Australia Industry Entrepreneurs' Programme in 2021, the first functional prototype of PCM thermal battery (ChillBankTM15) using a newly formulated PCM (ISO⁺15) and an optimised thermal battery using a shell and tube heat exchanger (HEX) was developed by Isothermix as shown in Figure 1. The ChillBankTM15 is designed to rapidly deliver chilled water for air conditioning during peak demand periods. The PCM used in the battery can be frozen using off peak or renewable electricity, or even with 'free cooling' (without using a cooling system) on cool nights. It is an environmentally friendly and off-the-shelf component which can readily be integrated into existing and new chilled water air conditioning systems.

2 Methodology

A 1.2 m³ PCM thermal battery containing a PCM with a melting point of 15 °C was built and a test setup was constructed as shown in Figure 2. This study demonstrates

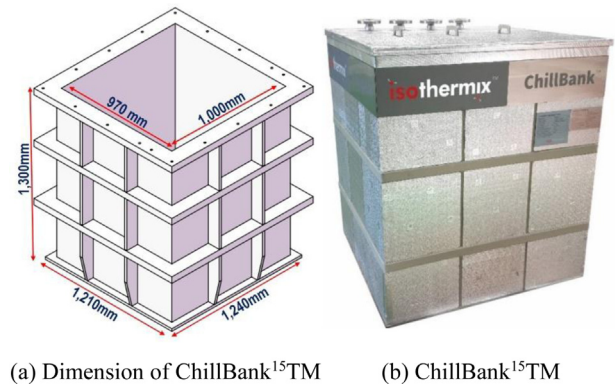


Fig. 1. PCM thermal battery and experimental setup.

the cooling performance of the prototype of ChillBankTM 15 in terms of heat transfer rate, storage capacity and long-term stability through more than 200 charging and discharging experiment.

2.1 PCM thermal battery (ChillBankTM 15) description

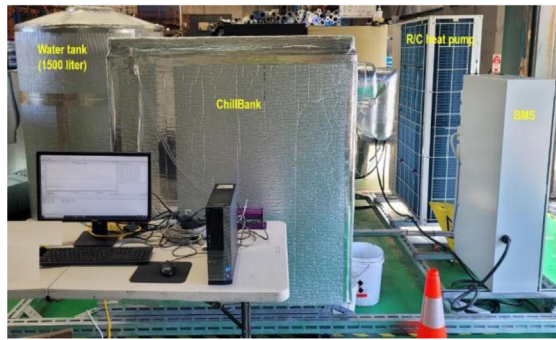
The ChillBankTM 15 is composed of (i) a PCM with melting temperature (or phase change temperature, PCT) 15 °C, (ii) a tank for containing the PCM, and (iii) a heat exchanger (HEX) immersed in the PCM-tank for transferring heat between the PCM and the working fluid.

2.1.1 PCM and its development

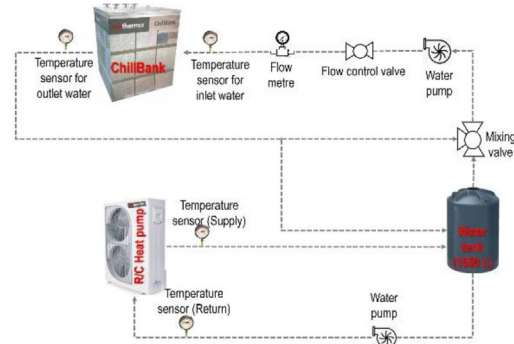
The PCM used for ChillBankTM15 is formulated using a eutectic salt-hydrate material and has been validated by UniSA. Various compositions of two chemicals with water have been tested to find the appropriate ratio, PCT, specific heat capacity and LH by using differential scanning calorimetry (DSC) technique. The eutectic PCM with PCT 14–15 °C and LH 140 kJ/kg was successfully synthesized. The two problems of sub-cooling and phase separation were resolved by adding 2 wt% agents. The long-term stability has been confirmed by more than 200 repeated heating and cooling cycle tests.

2.1.2 Heat exchanger design and optimisation

The correct HEX design of a PCM-TES system is somewhat more challenging than conventional HEX. More specifically, the geometry and thermal parameters of the containers for a given volumetric density of PCM directly affect the heat transfer characteristics and performance of PCM-TES [11,12]. In order to achieve satisfactory heat transfer rate between PCM and heat transfer fluid (HTF), various HEX designs have been studied, in which the PCMs are stored in mainly rectangular and cylindrical containers. The most commonly studied designs are flat plates, shell-tube, finned tubes and cylindrical tank with spherically encapsulated PCM [11,12].

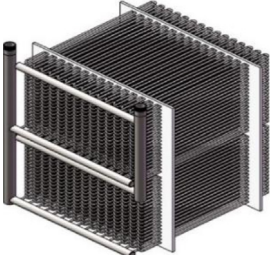


(a) Experimental setup



(b) Computer-based control system and sensor location

Fig. 2. Experimental setup and diagram of computer-based control system.**Table 1.** Viable heat exchanger designs in the market.

(a) Shell and Tube	(b) Pillow flat plate [13]	(c) Gasket plate [14]
Average heat transfer rate ¹⁾ for the first one hour: 30~34 kW HEX material: Stainless steel / Titanium / HDPE Surface area is smaller than flat plate design and required more than 1800 tubes. Difficulty in finding U-bend for plastic HEX Price range for 1m ³ Stainless steel: ≈ US\$ 4,000 Titanium: ≈ US\$ 5,000	Average heat transfer rate for the first one hour: 40~42 kW HEX material: Stainless steel Easy to fabricate and customise the size of water channel and gaps between plates. Difficulty in flow control Price range for 1m ³ : > US\$ 8,000	Average heat transfer rate for the first one hour: 40~42 kW HEX material: Stainless steel (Rubber gasket required) Largest heat transfer area, unit size can be minimised Expensive, risk of leakage and corrosion Price range for 1m ³ > US\$ 10,000
		

Note 1). The average heat transfer rate was predicted by TRNSYS simulation based on the product specification.

Various HEX designs currently available in the market were considered. In addition, the design details and customisability were discussed with the manufactures. As listed in Table 1, three types of HEXs are available in practice. Their detail information with a comparison is provided in Table 1. The simulation study used the PCM thermal battery component for TRNSYS (TRaNsient SYStem simulation program) developed and verified by the UniSA [15,16] to evaluate the performance of the PCM thermal battery based on the specifications obtained from the manufacturers. The TRNSYS software is a widely recognized and used tool for modelling and simulating energy systems, and its use in this study provides a reliable and accurate representation of the PCM thermal battery's performance.

The shell and tube design is a popular option for HEXs as it offers versatility in terms of tubing material and size. It has the advantage of being the most cost-effective option among the designs in Table 1. However, it presents a challenge in terms of tube bending, especially when using polymer material, to achieve desired lengths required for thermal batteries.

Another design option is the pillow flat plate design [13] which is a modified version of the flat plate design and is used to address the issues with water flow control in the conventional flat plate design. The products on the market are made of steel, and dimples are used on the plate to regulate water flow. This design has the advantage of being customizable to the user's requirements and allowing for parallel addition of plates as required. Additionally, it

provides improved heat exchange performance due to its higher surface area compared to the shell and tube design. However, it has the disadvantage of being much more expensive to manufacture than the shell and tube design. The gasket plate design [14] is another option, which has the advantage of being able to reduce the size of the HEX, but it is the most expensive to manufacture among the three designs and requires the use of rubber gaskets, which can lead to PCM leakage and corrosion over time.

Based on current market research, considering cost and practical application, the shell and tube design was deemed the most practical and suitable design. To determine the optimal shell and tube design, parametric investigations were conducted by using a numerical model developed and validated by the co-authors [7,16]. It is a two-dimensional conduction heat transfer model in the PCM annular domain coupled with a one-dimensional convective heat transfer model in the heat transfer fluid domain. The effect of natural convection in the liquid PCM is included in the heat conduction equation by using an effective thermal conductivity. The model has been implemented in a self-written FORTRAN code and incorporated as a component into the TRNSYS software. In addition, the cooling capacity required in real market applications and the performance of the thermal battery were evaluated through a case analysis of the target cooling system to which the product would be applied.

2.1.3 PCM storage tank

Figure 1 depicts the PCM thermal battery, and storage container that is constructed from polypropylene and has interior dimensions of $970 \times 1,000 \times 1,300$ mm ($L \times W \times H$) with a 30 mm wall thickness. The custom-made polypropylene tank is filled with PCM which has a storage capacity of 53.5 kWh. The battery storage density is about eight times higher than a water storage of the same volume, with maximum water storage capacity of 6.56 kWh within the application temperature difference of 7 K. The storage tank insulation helps to maintain the temperature of the PCM and reduce heat loss to the environment. The use of extruded polystyrene foam as insulation material is effective as it has low thermal conductivity. The removable feature of the insulation boards allows for easy maintenance and inspection of the storage tank, if necessary.

2.2 Experimental setup

For performance testing of the prototype, the test equipment and a computer-based control system (Building Management System, BMS) were prepared. The test equipment consisted of a reverse cycle (R/C) heat pump, a water tank, a mixing valve, a water pump, and a ChillBankTM 15. Additionally, two resistance temperature detectors (RTDs) are placed to monitor the inlet and outlet water temperatures of the HEX and a variable speed flow meter is also installed to regulate the flow rate of the HTF to ensure the optimal heat exchange performance. The R/C heat pump, with a capacity of 32 kW, supplied HTF in the form of warm water (up to 40 °C) and chilled water (5 °C).

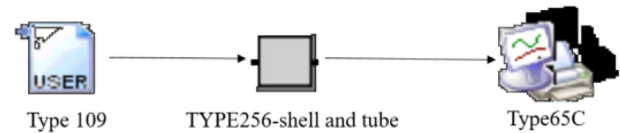


Fig. 3. TRNSYS model for parametric study.

The 1500-liter water tank stored water returned from the ChillBankTM 15 and the R/C heat pump. The mixing valve was used to control the T_{IN} to the ChillBankTM 15. The monitoring system allows the user to remotely control the heating and cooling of water, T_{IN} and flow rate with an interface for real-time monitoring of heat transfer rates in kilowatts and accumulated energy in kilowatt-hours. The collected data was periodically (every 30 s) transmitted to a cloud server and can be downloaded for analysis at any time. Six RTDs were also installed inside the ChillBankTM 15 to monitor the PCM temperature (T_{PCM}), and the data was stored separately on a desktop PC. Note that the accuracy of RTDs is less than 0.1 °C, and the flow meter accuracy is less than 2% of the measured value.

The ChillBankTM 15 is connected to a reverse cycle (R/C) heat pump to charge with a water at 7–10 °C and discharge with a water temperature of 22–23 °C, assuming the inlet water is coming from the return line of the water chilling system of the building. The latter provides comfort cooling by distributing chilled water with variable volume flow between 0.67 l/s to 1.34 l/s. During discharging, the thermal battery is designed to cool down the return water. The test setup was designed to study the performance of the ChillBankTM 15 in various field and weather conditions, and accurately measures and controls the heat transfer processes taking place in the HEX as shown in Figure 2.

2.3 Data analysis method

Due to the nature of PCM thermal batteries, which usually show a gradual decrease in heat transfer rate, this test focuses on their cooling performance at various time frames to simulate the response to sudden changes in peak load due to increased occupancy and extreme weather condition. For charging performance, the relationship of charging hours to T_{IN} and water flow rate was analysed. In particular, the focus of the discharging analysis was on determining how long the ChillBankTM 15 can maintain the outlet water temperature (T_{OUT}) as low as possible until the latent heat of the PCM has been exhausted at varying conditions.

For comparing the results of experiment to those from simulation, the simple TRNSYS model (Fig. 3) was designed. This model was also used for a parametric investigation to determine the optimal dimensions of the HEX. For this model, the authors utilized TRNSYS software components (Type 109, Type 65C) and the PCM-TES ('Shell and tube' type) component developed by UniSA [7,14] to create the model. The PCM-TES ('Shell and tube' type) component is using a simplified two-dimensional numerical model to estimate the heat transfer rate under ideal conditions but it has a limitation in accurately capturing the non-linear nature of heat transfer between the HTF and

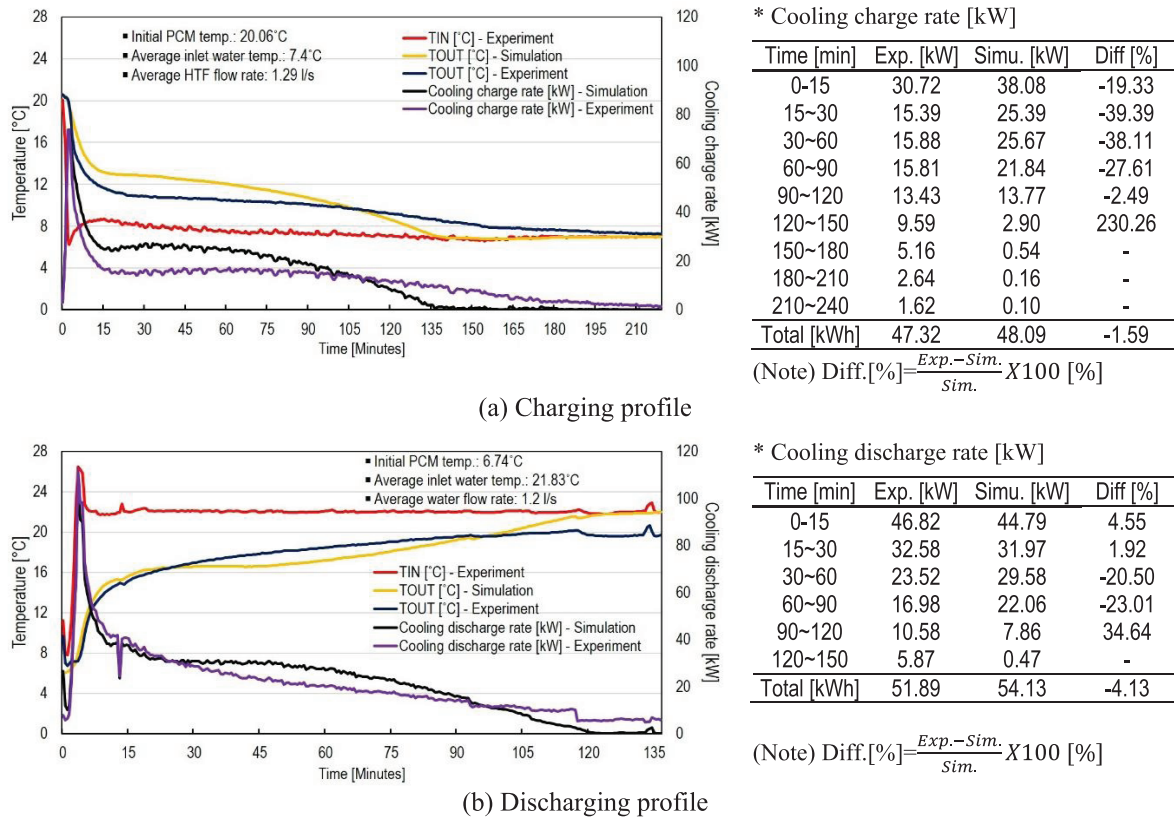


Fig. 4. Comparison of charging and discharging profiles (simulation vs. experiment).

PCM. The Type 109 component reads data from a data file and provides the T_{IN} (7–26 °C) and flow rate (0.5–1.341/s) to the PCM-TES component as time-varying forcing functions. The PCM-TES component models the thermal behaviour of the shell and tube HEX filled with the PCM and calculates the heat transfer rate between the HTF and the surrounding PCM, taking into account the phase change of the PCM and the heat transfer through the exchanger walls. The Type 65C component is an online plotter used to display selected system variables during the simulation. The varying parameters such as initial T_{PCM} , inlet water temperature (T_{IN}) and volumetric water flow rate (Q) obtained every 30 s from the experiment were applied to the simulation for this comparison analysis.

3 Results and discussion

A comparison is initially carried out between the results of the TRNSYS simulation and the experiment to assess the validity of the optimum configuration of the HEX determined through simulation in predicting the results of the ChillBankTM15 prototype. The charging and discharging profiles of the prototype with its cooling performance in various filed situation are also presented. The long-term stability of the ChillBankTM15 is demonstrated in the final section through a series of over 200 charging and discharging experiments.

3.1 Charging and discharging performance (Simulation vs. experiment)

Figure 4 a typical charging and discharging profile and compares the performance of the ChillBankTM15 using results from the TRNSYS simulation and experiment. The initial T_{PCM} , T_{IN} and volumetric water flow rate (Q) obtained every 30 s from the experiment are compared to the simulation.

In experiment, the initial T_{PCM} was recorded at 20.6 °C when the charging process started. The average T_{IN} throughout the charging process was 7.4 °C, and the average water flow rate (Q) was 1.29 l/s. As seen in the experimental results in Figure 4a, the first 15 min is a period when the sensible heat of the PCM is mainly contributing to the charging process. The cooling charge rate decreases quickly along with the T_{PCM} that reaches around 15 °C after 15 min. This indicates that the heat from the inlet water is absorbed by the PCM and stored as sensible heat. After 15 min, the cooling charge rate becomes steady at around 20 kW, meaning the PCM has started its phase change from liquid to solid and additional heat is stored as latent heat. The latent heat storage continues for 2.5 h, after which the phase change of the PCM seems to be complete. The experimental results show that the charging process takes approximately 3.5 h and the total energy stored in the PCM is approximately 43.05 kWh. However, the simulation with the optimum parameters predicts

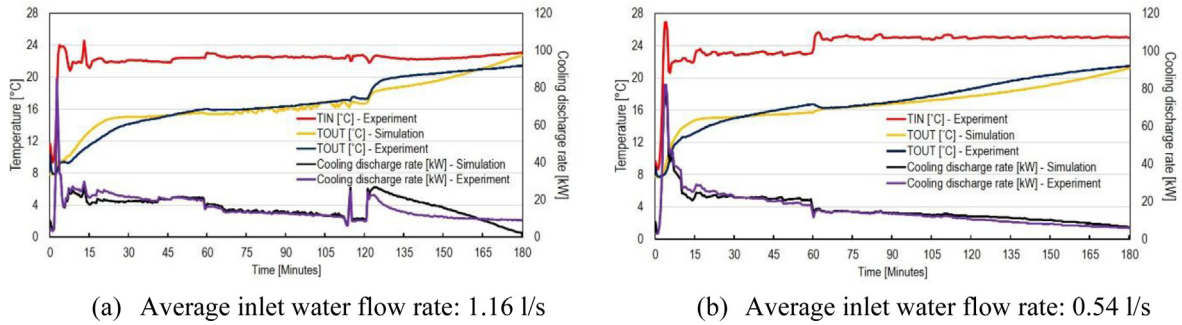


Fig. 5. Discharging profiles depending on inlet water flow rate (simulation vs. experiment).

improved heat transfer efficiency and a shorter charging time, as depicted in Figure 4a. The experimental results show a 25–30% lower heat transfer performance during phase change period of the PCM and longer charging time, taking over an hour to charge the PCM compared to the simulation results.

Figure 4b compares the results of a simulation and an experiment of a discharging process. Likewise in the charging process, the PCM melting temperature and initial temperatures obtained in the experiment were applied to the simulation. The results of the simulation and experiment were similar during the first 30 min of the discharging process, however, the difference in the cooling discharge rate increased until one hour after that and then gradually decreased. Particularly, during the phase change of the PCM (30–90 min), the simulation predicts a heat transfer rate 20–25% higher than the experimental results. The experimental results also show an actual capacity of 51.89 kWh during the 2.5-hour discharge, which was 96% of the simulated capacity of 54.13 kWh for a 2-hour discharge.

In the subsequent comparison test, it was found that the simulation more accurately predicts the results of the experiment at lower water flow rates. As seen in Figure 5, when flow rates of 1.0 l/s and 0.54 l/s were applied, the results from the experiment and simulation became closer in terms of heat transfer rate and discharging time.

The differences between simulation and experiment at high flow rates can be attributed to several factors, including: (i) Overestimation of the natural convection effect in liquid PCM. The two-dimensional conduction model utilized an empirical correlation to account for the natural convection in the liquid PCM, which was determined from a previous experiment. However, this correlation may not be applicable in the current experimental conditions with high water flow rates. (ii) Uneven arrangement of tubes. It was observed that the tubes were not evenly arranged by the manufacturer, resulting in unequal tube spacing and uneven flow distribution. (iii) Unequal temperature distribution of the PCM at different heights. During the discharging process, it was found that the temperature of the PCM at different heights was not uniform (with higher temperatures closer to the top of the tank due to natural convection). However, in the simulation, a uniform temperature was assumed as the initial condition. (iv) An open system with partial filling of

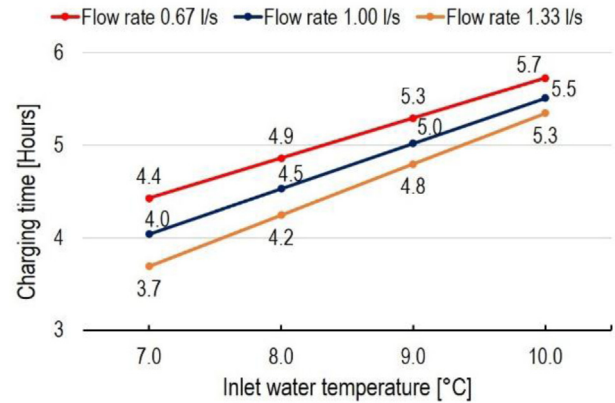


Fig. 6. Charging profiles.

the tubes by the flowing water. (v) Differences could also be due to errors in the thermo-physical properties used for the simulation, such as thermal conductivity and viscosity.

3.2 Parametric study of charging profiles

The charging profile of a PCM thermal battery is a crucial aspect, as it should be charged during off-peak hours when energy prices are low or there is an abundance of renewable energy, to maximize economic and environmental benefits. The charging process is impacted by several factors, but the main parameters are the T_{IN} and flow rate, as demonstrated in Figure 6. The experiment demonstrates that these two variables have a direct linear relationship with the charging time, with the T_{IN} having a positive effect and the flow rate having a negative effect. As the PCT of the PCM is around 15 °C, it is recommended that the T_{IN} for charging the PCM is at least 10 °C to achieve a cooling of 5 °C, ensuring that the PCM will freeze within the desired time frame. Consequently, the optimal flow rate and T_{IN} can be determined based on the specific conditions of the site and cooling system.

Additionally, based on the BOM weather data of Adelaide and Melbourne in 2013, there were 24 and 56 days, respectively, where the wet bulb temperature was less than 12 °C (Delta T : 3 °C) during the summer nights. During these periods, ChillBankTM15 can take advantage of free cooling without the need for the air conditioning

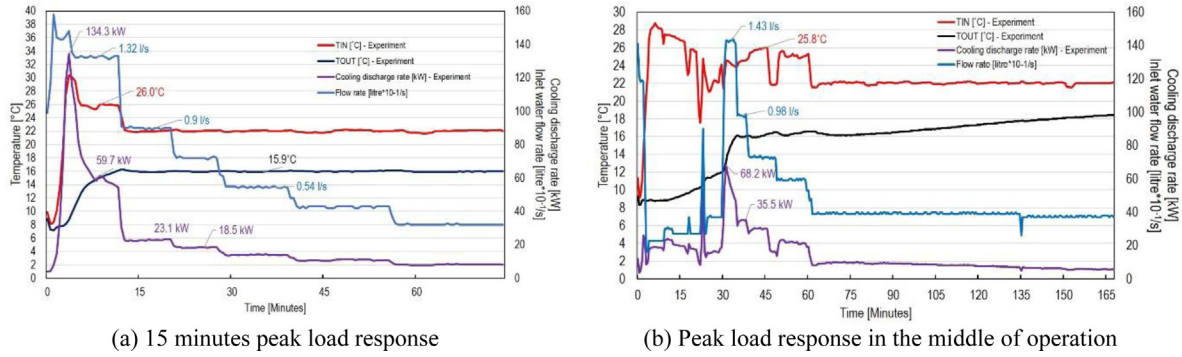


Fig. 7. ChillBank™ 15 corresponding various field situation. (a) 15 minutes peak load response. (b) Peak load response in the middle of operation.

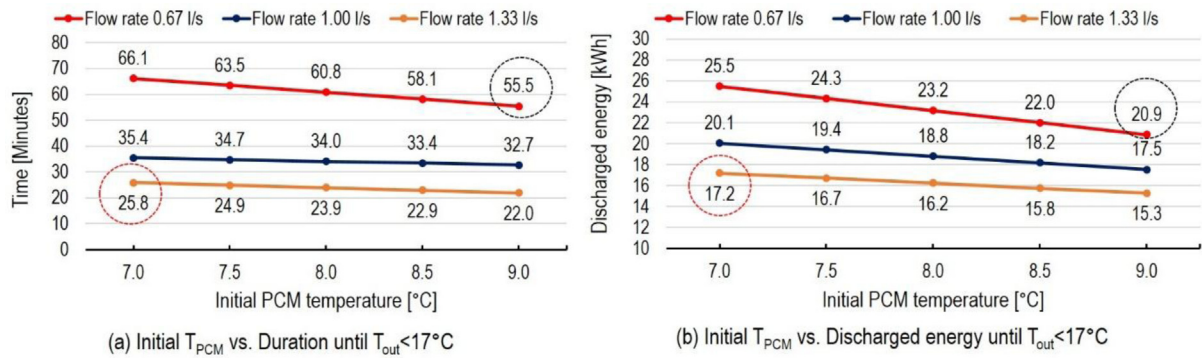


Fig. 8. Discharging performance of ChillBank™ 15 until $T_{out} < 17^\circ\text{C}$.

system. Commercial buildings typically use air-conditioning systems for over 300 days a year, and if the PCM can be frozen using an air-conditioning system at night, or through free cooling, and if the stored cool energy in the PCM can then be used during peak demand periods, it can shift the peak load from the day to night and flatten the cooling load over the hours. This, in turn, can result in reduced overall energy consumption for building cooling.

3.3 Simulation of cooling performance of ChillBank™15 in various field situations

In Section 3.1, the experiment carried out with a constant flow rate demonstrated excellent cooling capability, with 46.82 kW and 32.58 kW recorded during the first 15 min and 30 min, respectively. Although the cooling rate decreased, it remained above 10.58 kW for 2 h, and then gradually declining to zero over the next 3 h.

As a crucial aspect of evaluating the performance of the ChillBank™15, two tests were performed to determine if the ChillBank™15 can handle specific field scenarios with sudden peak loads, such as a lecture theatre and an unexpected peak load increase. Figure 7a evaluates the ChillBank™15's ability to respond to a 15-minute peak load. This test is designed to address a sudden and short cooling load during extreme weather conditions or those typically encountered in a lecture theatre, especially at the

start of a lecture. The scenario assumes that the return water temperature from the building is higher than 26°C . To handle the sudden increase in demand, the water flow rate was set to over 1.3 l/s. During the first 15 min, the average discharge rate of the ChillBank™15 was recorded as 53.1 kW, and the T_{OUT} from the ChillBank™15 was maintained below 16°C for the period. The sensible heat of the PCM also contributes to meet the initial cooling load. After 15 min, to maintain the lowest possible T_{OUT} , the water flow rate was gradually reduced. This allowed the T_{OUT} to be maintained below 17°C for a duration of 3 h.

The cooling test depicted in Figure 7(b) aims to address cooling demands in typical retail buildings and offices on extremely hot days. In this scenario, it is assumed that a 15 min sudden peak load increase occurs halfway through the ChillBank™15's operation, i.e., after 30 min. In this test, after 30 min, the T_{IN} begins to increase, reaching 26°C . To respond to this cooling load, the water flow rate was increased to 1.43 l/s. During the peak load, its average cooling rate was recorded as 38.78 kW and the T_{OUT} was kept below 16°C . It is important to note that at the beginning of the test, the T_{IN} was not regulated. To mitigate this, the water flow rate was adjusted, allowing approximately 10 kWh of stored energy to be released before the peak load increase occurred. As shown in Figure 7, the ChillBank™15 demonstrates outstanding cooling performance with a fast discharge rate and the ability to handle various field scenarios.

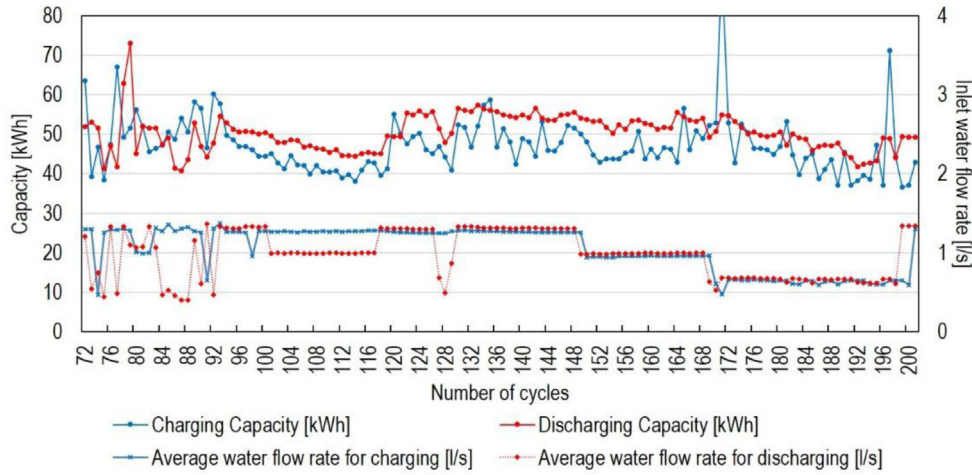


Fig. 9. Storage capacity during 200 charging and discharging cycles.

It is also noteworthy that maintaining the lowest possible T_{OUT} at a constant flow rate is another crucial aspect of the ChillBankTM15's performance. The experiment reported in Figure 8 aimed to examine the ChillBankTM15's ability to regulate the T_{OUT} and release stored energy. The results indicated that the flow rate and initial T_{PCM} play a significant role in determining the quantity and duration of energy discharged until the T_{OUT} reaches 17°C. In mild weather conditions, the ChillBankTM15 can maintain the T_{OUT} below 17°C for 55.5 min and release 20.9 kWh stored energy at a flow rate of 0.67 l/s by charging the PCM with 9°C chilled water. In extreme weather conditions, the ChillBankTM15 can maintain the T_{OUT} below 17°C for 25.8 min (17.2 kWh) at a flow rate of 1.33 l/s by charging the PCM with 7°C chilled water. Overall, the results demonstrate the ChillBankTM15's ability to regulate the T_{OUT} and release stored energy effectively in various weather conditions.

3.4 Long term performance

Due to the long-term usage requirement of the ChillBankTM15, evaluating its performance during continuous charging and discharging is crucial. The consistency of performance is directly tied to the thermal stability of the PCM and ultimately impacts the product's quality. Figure 9 displays the results of the final 131 cycles of the charge and discharge capacities of 201 cycle testing. For the first 71 cycles, various tests were carried out to assess the product's performance, which included various interventions such as installing cameras to monitor changes in the PCM. The graph demonstrates a steady trend in the charging and discharging capacity, with a slight reduction in capacity towards the end of the cycles, attributed to the low flow rate. When the flow rate is low (e.g., 0.5 l/s), the charge and discharge capacities tend to be lower, which makes it challenging to accurately determine the conclusion of the process. The data presented in this analysis is based on tests that were terminated when the heat transfer

rate reached 1.5 kW. The elevated charging capacity observed at the 172nd and 196th cycles is a result of the high initial temperature of the PCM. In previous discharging procedures, the PCM was heated to 40°C and 30°C to assess its stability.

4 Conclusions

The study comprehensively evaluates the cooling performance of the Isothermix's first thermal battery prototype, which was designed utilizing an optimal configuration of a shell and tube HEX and a new thermally stable PCM. ChillBankTM15 exhibits excellent cooling capabilities, with flexible timely charging and rapid discharge to handle peak loads effectively, taking into account various site and weather conditions. The results of the experiments confirmed that ChillBankTM15 is a highly effective cooling solution for conventional chilled water cooling systems in buildings by effectively cooling the return warm water. Furthermore, the simple installation and maintenance processes of ChillBankTM15 can make it a highly desirable and economical option to enhance cooling system size and performance.

The comparison between the results of the TRNSYS simulation and the experiment showed good agreement, particularly at lower water flow rates. However, some difference was observed at high flow rates, which can be attributed to factors such as overestimation of natural convection in liquid PCM and uneven arrangement of tubes in the HEX. Nevertheless, the results of this study highlight the potential of TRNSYS as a valuable tool for designing and optimizing PCM-TES systems, providing insights into the performance of the ChillBankTM15. The long-term stability of ChillBankTM15 was also demonstrated through a series of over 200 charging and discharging experiments, further confirming its potential for practical applications.

In conclusion, the prototype provides an efficient cooling solution with the ability to effectively regulate temperature and handle peak loads. The design, incorpo-

rating both a shell and tube HEX and a thermally stable PCM, is highly effective in achieving optimal cooling performance. The modular design, along with its ease of installation and maintenance, renders it a highly promising complementary component to conventional cooling systems. The findings of this study contribute to the advancement of thermal battery technology and provide valuable insights for future developments in this field.

Funding

This research received in-kind support from Isothermix.

Conflict of interest

The authors declare no competing financial interests. Seung Ho Lee and Ming Liu are employed by Isothermix, which provided in-kind support for the research reported in this publication. Wasim Saman is an emeritus professor at the University of South Australia and contributed voluntarily to this publication. Michel Bostrom, CEO of Isothermix, provided funding for this publication.

Author contribution statement

Seung Ho Lee performed the experiments, conducted the simulation study, and analyzed the data. Ming Liu reviewed the results and provided comments on the experiments and simulation study based on her expertise. Wasim Saman and Michel Bostrom reviewed the final output, provided advice, and contributed to writing corrections.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Cite this article as: Seung Ho Lee, Ming Liu, Wasim Saman, Michel Bostrom, Smoothing cooling demand of buildings with PCM thermal batteries, *Renew. Energy Environ. Sustain.* **9**, 6 (2024)