The Experimental Performance Characterisation of a Three Module Phase Change Energy Storage System for Domestic Heating Applications

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Abstract

The experimental thermal performance characterisation of a novel compact latent heat thermal energy storage unit comprised of three modules filled with a commercial phase change material (PCM) CrodaTherm™ 53, with a peak melting/crystallization temperature of 52 °C, was undertaken using a recently developed thermal storage module characterisation facility. For the intended space heating/hot water application a compact thermal energy storage system with at least 10kWh storage capacity was required, that could be charged using an air source heat pump and discharged to a low temperature hydronic heating system or to provide domestic hot water. Each of the three modules employed in the characterized thermal store are rectangular in cross section with a compact finned tube heat exchanger submerged into the PCM. The test facility allows the modules to be charged and discharged singly or concurrently in parallel or series with near constant heat exchange fluid inlet temperatures and volume flow rates. Experimentally measured store outlet temperatures, charge and discharge powers and cumulative heat charged and discharged to and from the store, are presented for the cases when charging and discharging the 3 modules comprising the store in both parallel and series flow modes. Fluid inlet temperatures of 70 °C were used for charging and 10 °C for discharging with four heat transfer fluid volume flow rates, 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 likely to play a significant role in the transition to low/zero carbon heating/cooling systems and in the electrification of heat in buildings because it can help to overcome the mismatch between energy production and demand. The mismatch to be addressed can be in temperature, time, location or power (Ibrahim et al. 2017, Eames et al. 2014). The large-scale application of heat pumps for domestic heat provision is planned in some countries with the intended phase out of domestic gas boilers, for example the UK plans to phase out installation of domestic gas boilers in new build dwellings by 2025 with the ambition to phase out gas boilers in all homes from 2035. Due to lack of diversity in space heating requirements which are strongly weather dependent, this is likely to lead to significantly increased loads on the low voltage electricity supply network and significant increases in peak winter electricity generating requirements. Another consequence of this is that there will probably be significant increases in electricity tariffs at these times. With an electricity generation mix that is increasingly renewables based, this will lead to greatly increased energy storage requirements. Using distributed thermal energy storage can allow heat generation and demand to be effectively decoupled, this will have the benefits of reducing peak electricity demands and grid loads and allow consumers to take advantage of any periods with low electricity tariffs to charge their thermal energy storage system. If the space required to install a thermal energy storage system is not an issue thermally stratified sensible water based heat storage can be employed, however, if space is at a premium a more compact store will be required due to space constraints and phase change material based stores may be an attractive option.

Phase change thermal energy storage systems have been proposed and trialled for both building heating and

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cooling applications. The range of phase change temperatures generally considered for building applications is 0-60 °C. Materials with phase change temperatures in this range include water/ice, a range of paraffin waxes, inorganic salt hydrates and bio based PCMs. Storage solutions developed have included micro encapsulated PCMS in for example wall boards, Tyagi et al. (2010), macro encapsulated PCMs in thermal stores with the heat transfer fluid flowing around them da Cunha and Eames (2017) and PCMs with embedded heat exchangers Fadl and Eames (2021) and Fadl et al. (2021).

An issue with PCM storage systems is that many PCMs when solid unfortunately have relatively low thermal conductivity, typically 0.2 to 0.6 $Wm^{-1}K^{-1}$, Agyenim et al. (2010). For heat storage applications when charging the store heat is transferred into the store raising the temperature of the solid PCM, causing it to melt adjacent to the heat exchange surface, when sufficient PCM melts natural convection is established enhancing heat transfer rates between the heat exchanger surfaces and solid PCM still to be melted. When discharging the store, PCM will solidify on the heat exchanger surfaces reducing the rate of heat transfer that occurs, this can lead to long discharge times and low power delivery rates. To address this important issue a number of different approaches have been proposed to increase heat transfer to and from the PCM, a review by Agyenim et al. (2010), provides an overview of some of the approaches adopted including the use of fins, embedded high thermal conductivity matrices, metal rings, carbon brushes, graphite flakes, micro and macro encapsulation. Using fins to improve heat transfer to the PCM is one of the key approaches identified with an increasing amount of research currently being performed. Amagour et al. (2021), performed a 3D CFD analysis of a compact finned tube heat exchanger to assess the effects of heat transfer fluid flow rate, heat transfer fluid inlet temperature and number of fins on charging and discharging performance. Fadl and Eames (2021) performed a detailed experimental investigation of the thermal performance of a PCM storage unit with a finned copper tube heat exchanger. Anish et al. (2021) performed simulations of an horizontal shell and tube PCM heat store with and without fins using a 2-d CFD model to assess changes in melting rates that could be achieved with different tube and fin arrangements.

2. Experimental program

2.1 PCM module and storage system design

The aim of the research undertaken was to develop a compact thermal energy storage system with at least a 10 kWh storage capacity that can be charged using an air source heat pump or electrical heating and discharged to a low temperature hydronic heating system or to provide domestic hot water.

The fabricated and characterised PCM system comprised of three identical modules. Each fabricated module shown in Fig. 1 was cuboid in shape and comprised of two containers with insulation inserted between the interior and exterior walls. To allow observation of the melting/solidification process during the charging and discharging process the containers were made so that the tops of the containers could be removed. The exterior dimensions of the inner containers made from 0.9 mm thick stainless steel 304 were 230 by 530 by 500 mm width, length, height). The interior dimensions of the outer container made from 1.2mm Aluminium were 310 by 610 by 580 mm (width, length, height). Foam board insulation of 30mm thickness was inserted at the sides and top and 40 mm at the base between the internal and external walls of the stores to reduce heat losses. A 72 pass compact copper tube and aluminium finned heat exchanger illustrated in Fig. 1 was used in each of the store modules. The exterior dimensions of the copper tubes were 12.7 mm and the aluminium fins were 0.2 mm thick, spaced 6.5 mm apart and extended continuously across the heat exchanger cross sectional area. The distance between centers of adjacent copper tubes was 35 mm. The heat transfer fluid flow arrangement through the heat exchanger leads to a vertical temperature gradient in the heat exchanger when charging and discharging. The surface area available for heat exchange per module was approximately 1.36 m^2 from the surface of the copper pipes, 8.89 m^2 from the aluminium fins, and 0.39 m^2 from the end plates providing a total heat transfer surface area of 10.64 m^2.

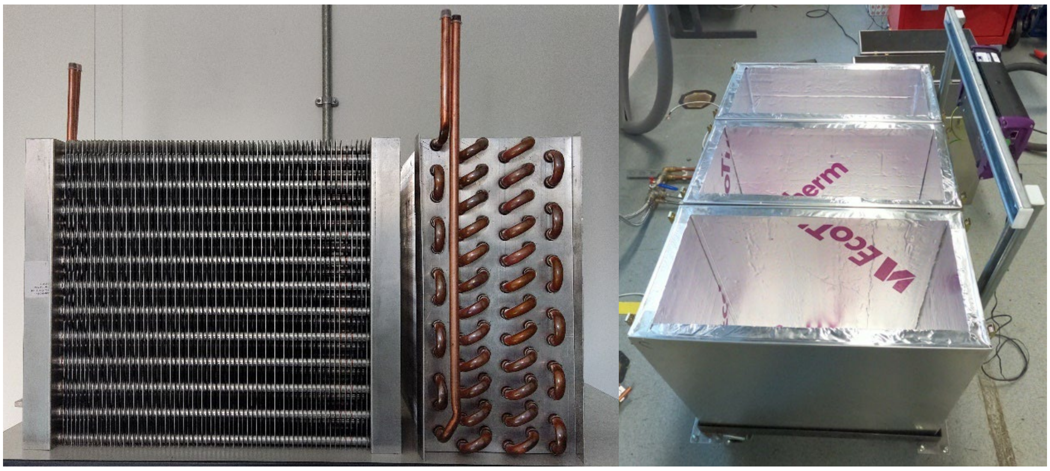

Fig. 1: Side and end view of the heat exchanger used in each of the PCM modules and the three exterior module containers with attached wall insulation.

The selection of the PCM CrodaTherm 53 that was used in these experiments was based on the delivery temperature available from a CO_2 air source heat pump, taken to be 70 °C, to charge the store, and the demand temperature, taken to be 40 to 45 °C, for low temperature hydronic heating systems, fan assisted radiators, underfloor heating or hot water for showers and baths. The key thermal properties of CrodaTherm 53 are presented in Tab. 1. From DSC and three-layer calorimetry it was found that the majority of the melting enthalpy is in the range from 51 to 54 °C with a peak at 52 °C, the majority of the crystallisation enthalpy is in the range 50 to 52 °C with the peak again at 52 °C.

Tab. 1: Thermal and physical properties of CrodaTherm™ 53 according to the manufacturer [Croda 2018].

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

The weight of the PCM used in each module was 40 kg, assuming that the store is operated between 37 and 57 °C and that the phase change occurs over a 4 °C range based on Differential Scanning Calorimetry measurements, the heat that can be stored in the PCM using the data from table 1 is approximately 10,290 kJ or 2.85kWh (latent heat of 9,040kJ between 51 °C to 54 °C and sensible heat of 990kJ between 37 °C and 51 °C and 260kJ from 54 °C to 57 °C). Based on the mass of materials used in the interior container module construction and heat exchanger, the sensible heat capacity of these components over the 20 °C temperature range is approximately 210 kJ or 0.06 kWh, the heat capacity of the water heat transfer fluid over the same temperature range is 320kJ or 0.09kWh providing a total storage capacity of approximately 3 kWh per module. For the full range of temperatures used in the experimental program, assuming the store is operated from 10 °C to 70 °C, the energy storage capacities in the range10 °C to 51 °C is 3,460kJ (0.96 kWh), from 51 °C to 54 °C is 9,080kJ (2.52kWh), and from 54 °C to 70 °C is 1,580kJ (0.44kWh) per module, or in total for each module 14,120 kJ (3.92kWh). For the full 3 module store this gives a heat storage capacity of 42,350 kJ or 11.76 kWh. From these figures it can be seen that the latent heat capacity makes up approximately 88% of the energy stored between 37 and 57 °C and for the larger temperature range, 10-70 °C, 64.3%. In addition, the mass of hot water in each module is approximately 3.7kg, the temperature of the store at the start of charging will be at 10 °C and at the end of charging 70 °C, which equates to an additional 980 kJ or 0.27 kWh increase in heat stored per module or 0.81 kWh for the 3 module store leading to a total heat storage capacity of 12.58 kWh.

2.2 PCM storage system testing

To charge and discharge PCM thermal energy storage systems a new experimental thermal store test facility was designed and developed that enables up to four PCM storage modules to be charged/discharged concurrently with well controlled heat transfer fluid volume flow rates and temperatures. The schematic in Fig. 2 shows the fluid flow circuits. A Huber Unistat 510W was used to cool the water flowing to the cooling loop storage tank and a Huber T320 was used to provide heat to the heating loop storage tank. Two and three way valves were used to select the fluid circuit flow paths and regulate the heat transfer fluid volume flows to each module. Flow meters were located on the pipe prior to the pipe connections used for attaching PCM modules for testing and in the main hot and cold fluid circulation loops.

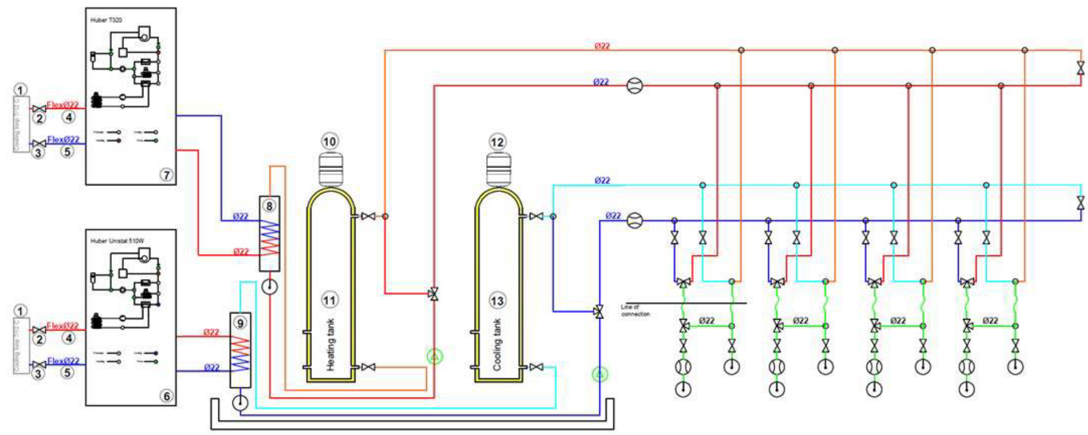

Fig. 2: A schematic diagram showing the fluid flow circuits and the key components in the developed thermal storage test loop.

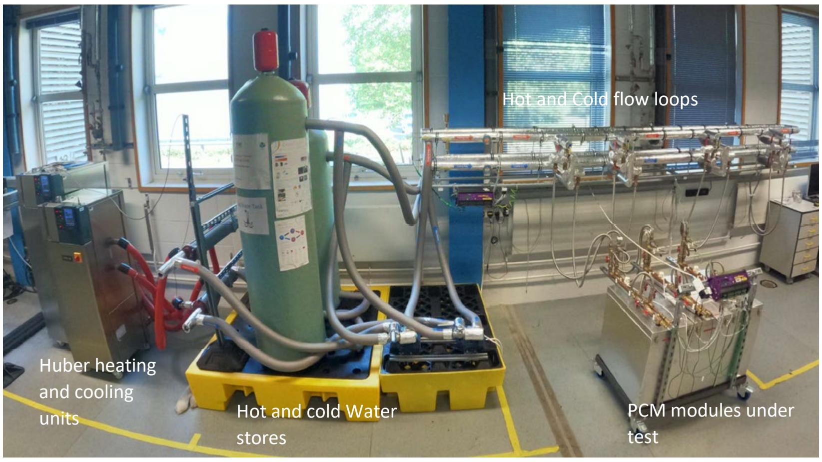

Fig. 3: An image of the developed laboratory PCM module test facility.

The developed laboratory test facility is shown in Fig. 3 with the 3 module PCM store connected prior to test.

2.3 The experimental test program

Two sets of experiments were performed, one with the PCM modules arranged in series and one with the modules arranged in parallel. The hot water charging temperature was set to 70 °C in all store charging experiments. The cold water inlet temperature for discharging was set to 10 °C in all store discharging experiments. For real charging conditions using a heat pump or electric heating constant heat input would be more realistic rather than a constant temperature input which is more likely if using a district heat supply to charge the storage system. The discharging temperature was selected to represent winter mains cold water temperatures. Fluid flow meters were used to measure flow volumes in the hot and cold flow loops and to each individual module. Temperatures were measured using T type thermocouples on the inlet and outlet pipes to each module and at a selection of locations within each PCM module monitored to enable the temperature distribution within the store to be determined. All temperature and flow measurements were taken on a 5 second basis for the full duration of each test and stored to a data logger. The heat transfer fluid flow volumes through each module used in the parallel module operation flow experiments were 0.5, 1, 1.5 and 2 l/min leading to combined flows of 1.5, 3, 4.5 and 6 l/s. For the experiments with the PCM modules arranged in series flow volumes of 1.5, 3, 4.5 and 6 l/s were used to enable direct comparison of performance characteristics. From the measurements of volume flow and inlet and outlet temperature the total heat delivered or extracted from the store and the instantaneous input/output power were determined

3. Experimental Results

3.1. PCM System Charging

With a set inlet temperature of 70 °C the measured store outlet temperatures for the four volume flow rates of 1.5, 3, 4.5 and 6 l/min for parallel and series flow operation are presented in Fig. 4.

It can be seen from Fig. 4 that for all volume flow rates the measured outlet temperatures increased more rapidly for the parallel flow arrangement than for the series flow arrangement. Higher heat transfer volume flow rates deliver greater amounts of heat and consequently lead to more rapid increases in temperatures with shorter periods of time required for each stage of charging. From Fig. 4 it can be seen that there are 4 distinct phases of charging. In the first phase of charging, (the area of the graph below line A) heat is transferred to the solid PCM from the hot inlet fluid, due to the low specific heat capacity of the solid PCM a rapid rise in PCM temperature results and the outlet fluid temperature rises rapidly. In the second phase of charging when the PCM commences melting, (the area of the graph between line A and line B) due to the high latent heat capacity the PCM temperatures increase slowly with a reduction in the rate of increase of the hot outlet fluid temperature. In the third phase after the PCM melts (the area of the graph between line B and line C) heat is transferred to the liquid PCM, due to the low specific heat capacity of the liquid PCM the PCM temperature rises rapidly and the temperature of the outlet fluid again rises rapidly. In the fourth phase (the area of the graph above line C), the store outlet temperature approaches the heat transfer fluid inlet temperature, 70 °C, the rate of temperature increase in the PCM reduces due to the decreasing temperature difference between the hot heat transfer fluid and the PCM. Increased heat losses from the store will also occur due to the greater temperature difference between the store and the ambient environment.

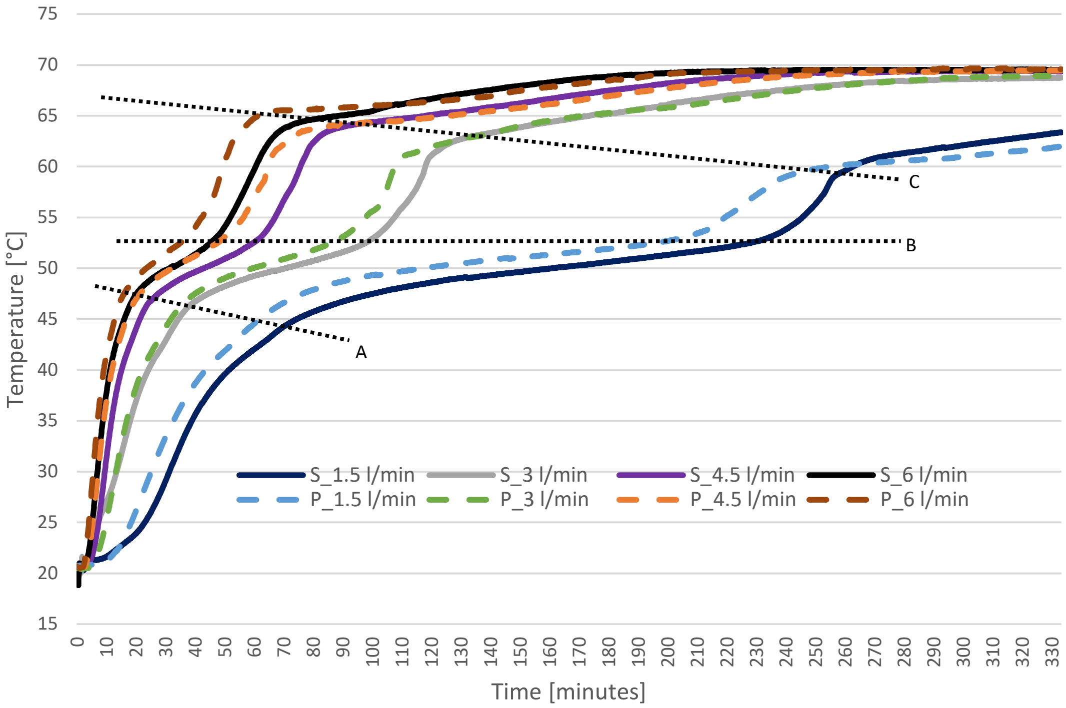

Fig. 4: The heat transfer fluid outlet temperatures from the PCM stores during charging for series (S) and parallel (P) flow arrangements with heat transfer fluid inlet temperature of 70 °C.

Using the measured inlet and outlet heat transfer fluid temperatures and the measured volume flow rates of heat transfer fluid through the PCM modules the rates of heat input to the store were calculated for both parallel and series flow arrangements for the fluid flow rates of 1.5, 3, 4.5 and 6 l/min and are presented in Fig. 6. Slight variations in the measured flow rates with time resulted in the noise that can be seen in the heat input values presented in Fig. 6. It can be seen that the heat input rates for parallel and series flow arrangements generally follow similar profiles, however the series flow arrangement maintains higher rates of heat input during phase change for slightly longer than the parallel flow arrangement. At the start of the charging process due to the large temperature difference between the hot heat transfer fluid and the store high heat input rates result, 21.5 kW for 6l/min, 15.5 kW for 4.5 l/min, 10 kW for 3 l/min and 5 kW for 1.5 l/min, a near linear relationship of peak heat input rates with flow volume. As the temperature of the PCM in the store increases the rate of heat input decreases. When PCM phase change commences the rate of decrease in heat input reduces with a period of more stable heat input. For the different flow rates 6, 4.5, 3 and 1.5 l/min the average values of heat input during phase change are 8, 6.25, 4.5 and 2kW for approximate durations of 25, 35, 70 and 170 minutes corresponding to heat inputs of 3.3kWh, 3.6kWh, 5.3 kWh and 5.7kWh clearly showing that the effects of phase change on outlet fluid temperatures are more significant for lower heat transfer fluid volume flow rates   After the phase change period the rate of heat input decreases approaching zero for all but the 1.5 l/min flow by the end of the experiment at 330 minutes.

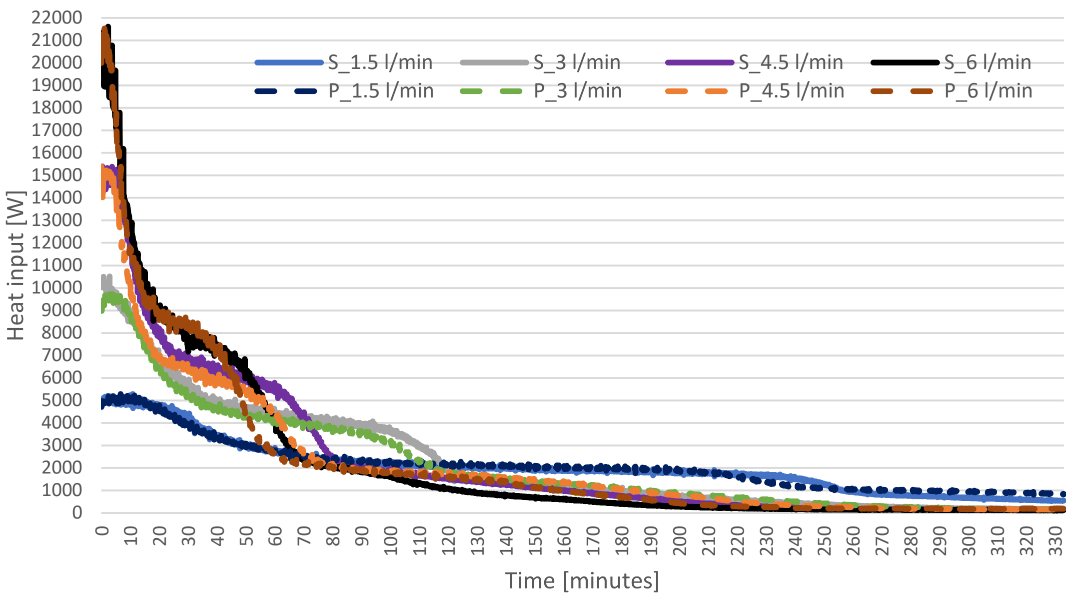

Fig. 5: The calculated rate of heat input to the 3 module PCM store for series (S) and parallel (P) flow arrangements

Using the instantaneous calculated values of heat input for each experimental test the cumulative heat input to the store during the charging period was calculated and is presented in Fig. 6. It can be seen from Fig. 6 that the series flow arrangement achieves more rapid charging for a given heat transfer fluid volume flow rate and that the rate of charging increases with increasing heat transfer fluid flow volume. For all tests the cumulative heat input to the store increases rapidly until approximately 2 kWh of heat is stored indicated by line A on Fig. 6, after this the rate of increase remains constant at a lower level until approximately 8.5kWh is stored indicated by line B, following this the rate of cumulative heat input again decreases reducing towards zero when approaching the maximum store storage capacity of 12.58 kWh.

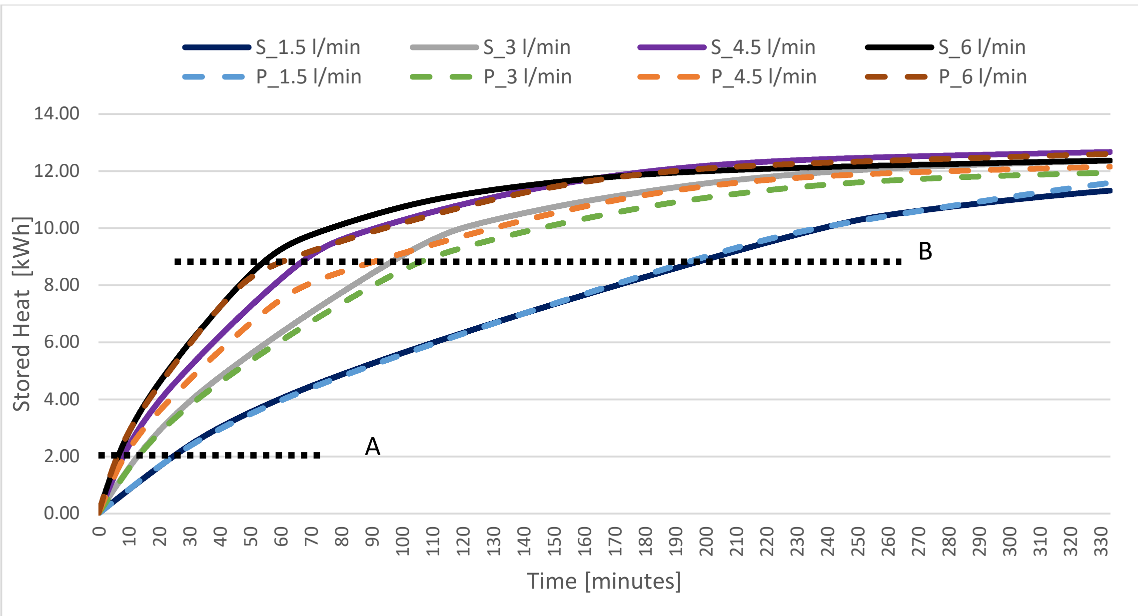

Fig. 6: The calculated cumulative heat charged to the 3 module PCM store for series (S) and parallel (P) flow arrangements

3.2. PCM System Discharging

With a set inlet temperature of 10 °C the measured outlet temperatures for the four volume flow rates 1.5, 3, 4.5 and 6 l/min for parallel and series flow operation are presented in Fig. 7. It can be seen from Fig. 7 that initially the outlet temperatures decrease rapidly at a near constant rate until phase change starts to occur indicated by line A. In the initial phase of discharging, duration decreasing with higher volume flow rate, heat is transferred from the liquid PCM to the cold inlet fluid leading to a rapid decrease in PCM temperature due to the low specific heat capacity of the liquid PCM and the outlet fluid temperature decreases rapidly to approximately 51 °C. Between line A and line B, corresponding to phase change of the PCM, the rate of decrease in outlet temperature initially reduces, followed by a period of constant outlet temperature and then starts to reduce again. The period of constant output 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 the PCM, 52 °C. For all volume flow rates the period for which a constant outlet temperature is maintained is greater for the series flow arrangement. After the PCM solidifies indicated by B on the Fig. 7 heat is transferred to the now solid PCM and the temperature of the outlet fluid again decreases rapidly to line C after which it then slowly decreases approaching the inlet fluid temperature.

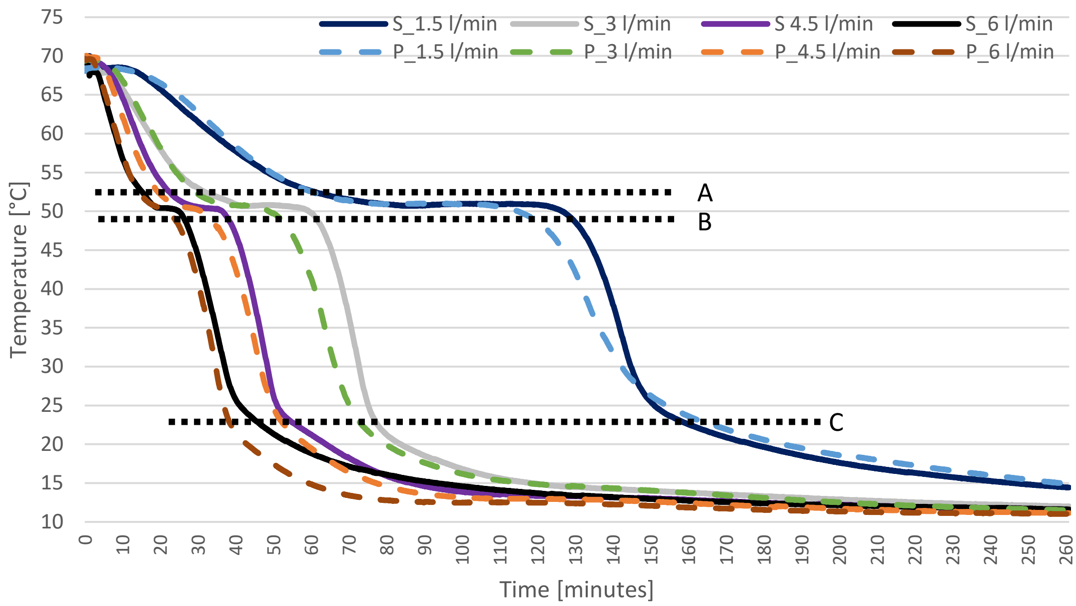

Fig. 7: The measured store outlet temperature during discharging from the PCM stores for series (S) and parallel (P) flow arrangements with heat transfer fluid inlet temperature of 10 °C.

Using the measured inlet and outlet temperatures and the measured volume flow rates of heat transfer fluid through the PCM modules the rate of heat transfer from the store was calculated for both parallel and series flow arrangements for the fluid flow rates of 1.5, 3, 4.5 and 6 l/min and is presented in Fig. 8. Slight variations in measured flow rate resulted in the noise in heat output values presented in Fig. 8. It can be seen that the heat output rates for parallel and series flow arrangements generally follow similar profiles, however the series flow arrangement maintains a constant power output during phase change for slightly longer than the parallel flow arrangement. At the start of the discharging process due to the large temperature difference between the cold heat transfer fluid and the store, high heat output rates result, over 24 kW for 6l/min, 18 kW for 4.5 l/min, 12 kW for 3 l/min and 5.5 to 6 kW for 1.5 l/min, a near linear relationship of heat output with flow volume. As the temperature of the liquid PCM in the store decreases the rate of heat output decreases. When the PCM phase change commences the rate of decrease in heat output reduces with a period of more stable heat output achieved. For the different flow rates 6, 4.5, 3 and 1.5 l/min the average values of heat output during phase change are 15, 10.5, 8 and 4kW for approximate durations of 10, 20, 40 and 80 minutes corresponding to 2.5, 3.5, 5.3 and 5.3 kWh. After the phase change period the rate of heat output decreases slowly approaching zero.

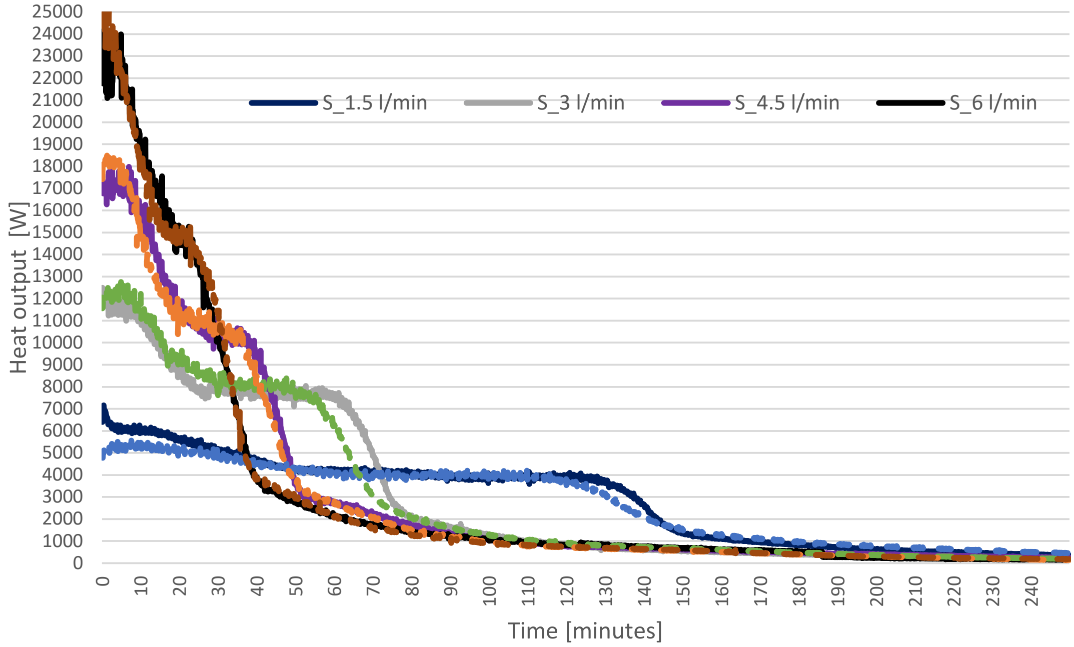

Fig. 8 The calculated heat output during store discharging from the PCM stores for series (S) and parallel (P) flow arrangements with heat transfer fluid inlet temperature of 10 °C.

Fig. 9 presents the calculated cumulative heat discharged from the PCM store. It can be seen that the heat discharged for parallel and series flow arrangements is similar for all volume flow rates. Prior to phase change commencing when sensible heat is being discharged from the liquid PCM the gradient of the lines gradually decreases corresponding to the reduction in temperature difference between the PCM and the cold heat transfer fluid. After this during phase change, below line A, the gradients of the lines are approximately constant corresponding to a steady temperature difference between the heat transfer fluid and the PCM. For the flow volumes of 1.5 and 3 l/min the slightly longer discharge at constant power can be seen for the series flow arrangement compared to the parallel flow arrangement. For the flow rates of 4.5 and 6 l/min the difference in the rate and amount of heat discharged is very small. Above line A the temperature difference between the solid PCM and the heat transfer fluid decreases with a consequent reduction in heat delivered.

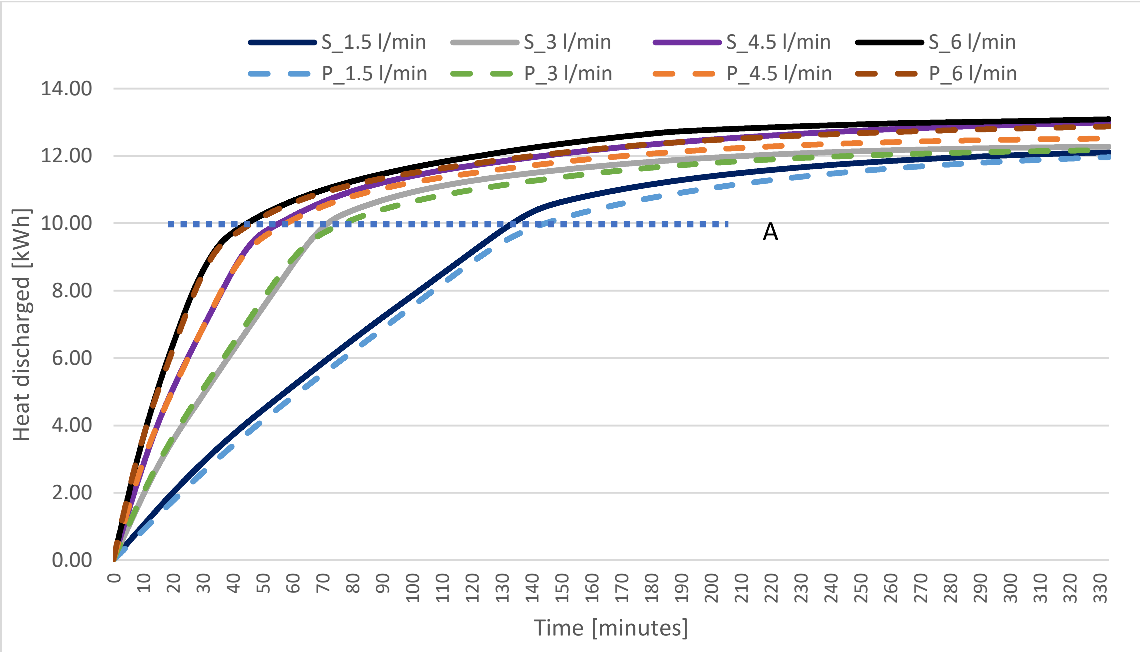

Fig. 9: The calculated cumulative heat delivered from the PCM store for series (S) and parallel (P) flow arrangements

Using figure 7 to determine the time for which outlet temperatures of over 50 °C can be delivered and figure 9 to determine the cumulative amount of heat delivered the volume of water that could be delivered at these temperatures after mixing with cold water can be determined. For example for series flow through the store with a flow of 6 l/min the duration of time for which the outlet temperature is above 50 °C is approximately 30 minutes with approximately 9.5 kWh of heat delivered, assuming that the hot water is mixed with cold water at 10 °C, 233 l can be delivered at 45 °C, sufficient to run approximately three baths.

The rate of heat output from the 3 module PCM stores achieved for flows of 1.5 l/min and 3 l/min were greater than 4 kW for 130 min and greater than 8kW for 60 min with the outlet temperatures above 51 °C. This would make the store feasible for use with a heat pump in a well insulated dwelling with a low temperature hydronic heating system, fan assisted radiators or underfloor heating. If the space heat load being met was 4kW the store if fully charged would allow the heat pump to be turned off for 2 hours at times of peak grid electrical load allowing high tariff periods to be avoided.

4. Conclusions

A 3 module PCM store was designed, fabricated and characterized for both parallel and series flow through the modules. When charged to 70 °C and discharged with heat transfer fluid flow volumes of 1.5, 3, 4.5 and 6 l/min and an inlet temperature of 10 °C heat transfer fluid outlet temperatures were maintained above 50 °C for series flow for periods of approximately 135, 65, 45 and 30min, slightly less for parallel flow. 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 similar amounts of time. For a well insulated dwelling with a space heat load of 4kW using an heat pump to provide heating the fully charged store could provide sufficient heat for 2 hours at times of peak grid electrical load allowing high tariff periods to be avoided. If used to provide domestic hot water at temperatures of 45 °C for bathing, the hot water delivered from the store at temperatures above 50 °C when mixed with cold water would be able to run three 80 l baths at just under 45 °C. The modular approach allows additional modules to be added to increase the storage capacity. The option of parallel or series operation allows all modules or individual modules to be charged/discharged providing greater flexibility in operation.

5. Acknowledgments

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