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Efficient storage and recovery of waste heat by phase change material embedded within additively manufactured grid heat exchangers



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ABSTRACT

The low thermal conductivity of organic phase change materials (PCMs) hinders their usage for energy storage purposes. We demonstrate a compact PCM-based thermal battery that employs three-dimensional (3D) printed metal surfaces for a robust thermal energy storage and recovery. The thermal battery could be utilized to store excess heat from various sources. The concept includes organic paraffin and fatty acid PCMs embedded within aluminum silicon alloy grid heat exchangers (GHE) produced via additive manufacturing. The heat exchangers consist of two parts: (i) a planar part with embedded water channels and (ii) a surface extrusion grid outside the planar part embedded in the PCM storage system. Three different grid designs are investigated and compared with a simple planar heat exchanger (PHE) without grid extension. The charging and discharging processes of the thermal battery were analyzed experimentally. The laboratory scale experiments reveal that the 3D printed grid surfaces of GHE significantly reduce the charging and discharging time from more than 240 min to less than 20 min. In contrast to PHE, the GHE may increase thermal power by a factor of ~ 20 from 35 W to 670 W. Furthermore, the grid structure positively restrains the natural convection flow of the PCM melt, increasing conduction in the highly conductive grid structure and resulting in high charging-discharging power of the thermal battery. The swift charging and discharging with high power and energy density make the compact grid thermal battery a promising solution for thermal energy management.

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1. Introduction

The use of renewable energy and waste heat grows in importance due to the increasing energy demand and climate goals on the decarbonization of energy sector with around three quarters of greenhouse gas emissions worldwide [1]. The implementation of such sustainable energy resources, due to their intermittent nature, i.e. time and location discrepancies in their availability and demand, relies on energy storage technologies [2–4].

Thermal energy storage (TES) captures and recovers energy by changing the internal energy of thermal materials [5,6]. Sensible TES, based on water, rock, or concrete as the storage media, is widely used owing to its simplicity and affordability [7,8]. However, it suffers from the low energy density and required large volume of the storage media. Recently, there has been a growing interest in latent TES based on phase change materials (PCMs). PCMs

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store and release energy through latent heat of phase transition, providing larger energy density, considerable volumetric reduction, reduced operational temperature range and higher storage efficiency compared to those of sensible TES [9–11]. PCMs are categorized as organic, inorganic and eutectic. Organic PCMs are further divided into paraffins and non-paraffins such as fatty acids [12–14]. The desired features of organic PCMs for TES include appropriate fusion temperature range, large latent heat, chemical stability, small volume change during fusion, availability, non-corrosiveness and cost-effectiveness [15,16].

Low thermal conductivity (TC), however, is a major drawback of organic PCMs, significantly hindering their application for TES [12,17]. The low TC restricts the heat transfer rate within the PCM and thus reduces the charging and discharging power (W) of the TES system. Paraffin shows TC values around 0.22 W/(mK), which is typical for organic PCMs [12]. Several methods have been applied to enhance the heat transfer within such TES systems, for example, by incorporating high TC material-based fins, finned tubes with different configurations, rings and bubble agitation, as well as carbon additives mixed with the PCM [12,18]. Inserting highly

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conductive wire nets with periodic structures can also improve the heat transfer in PCM mediums. Such configurations can be optimized by maximizing combined convection and conduction heat transfer rates. In this type of structures, the cell size plays a significant role, smaller cell sizes result in higher heat transfer rate [19]. The addition of carbon fibres to paraffin PCM was found to improve the TC and crystallization time of the PCM, yet obstructed and reduced the effect of natural convection in the system [20]. The melting time, however, was not reduced and for lower carbon concentration it was even longer which was due to the suppressed convection in the liquid phase.

Among different TC enhancement techniques, the use of fins, extended metal surfaces, appears to be the most practical and easy to implement [18,21,22]. The most commonly studied design for the fins includes shell and tube heat exchangers [23-25]. However, the experimental study of PCM-based horizontal shell-in-tube TES systems revealed that the melting behavior of paraffin drastically varies within the storage unit, where the PCM melt ascends from lower part towards the upper part by the natural convection [26]. The numerical analysis of a PCM-based passive cooling system using enclosures with five different geometries also confirmed a strong vertical stratification within the enclosure, with the bottom of the enclosure being the coldest and locating the last melted fraction of the PCM [27]. These issues cause an undesirable temperature variation within the system and a prolonged charging time, which consequently reduce the storage efficiency of tube-shell fin designs.

PCM-based TES systems with enhanced TC can be effectively utilized as heat-sink for the thermal management of electronics [28-30]. For example, the electronic devices related to the 5G technology are very powerful that can generate a considerable amount of waste heat [31]. An efficient thermal management of such electronic systems is indispensable since the accumulation of excessive heat during operation can harm the device and possibly the users. Herein, we propose a PCM-based thermal battery that provide fast dissipation of the generated heat from such powerful electronic devices and store it for further use, for example, in space heating and hot water production. The thermal battery consists of a grid type metal alloy heat exchanger filled with organic PCM, which can be connected to the heat generating device through a heat carrying fluid loop. The alloy grid makes the fast conduction as the primary mode of heat transfer and boosts the efficiency of the thermal battery by overcoming the poor thermal conductivity of the PCM. Furthermore, the grid structure positively restrain the natural convection flow of the PCM melt within the storage unit resulting in a more uniform temperature stabilization throughout the system. Novel grid geometries are fabricated with the aid of additive manufacturing (3D printing), which is recently attracting growing interest for the development of new powerful heat exchanger designs [30,32]. To the best of our knowledge, there are limited studies exploiting the relatively new fabrication method of additive manufacturing for creating new effective designs for thermal energy storage systems, particularly not yet explored for the proposed application as heat-sink and waste heat management of powerful electronic devices e.g. 5G radios.

Herein, we aimed (i) to develop an experimental PCM based thermal energy storage (TES) offering fast charging and discharging, and (ii) to explore the sensitivity of the developed TES on the geometrical design. As such, a lab-scale PCM-based TES system was explored for heat storage and recovery including a mediumtemperature heating source simulating the role of the heat generating electronics, which is a common procedure in laboratorybased thermal system-level studies. Three different compact geometries for the grid heat exchangers (GHEs) were designed and fabricated via additive manufacturing to study the effect of extended surfaces on the phase change behavior of the PCM storage. They were also compared with a reference planar heat exchanger (PHE) with no grid extension where the slow convection was the dominant heat transfer mode. Paraffin and myristic acid (a plant-based fatty acid) were selected as the target organic PCMs providing a melting temperature relevant to the cooling requirement of such heat generating electronics. We studied paraffin as a commonly used PCM in thermal system-level studies to be able to compare our results with the literature. However, myristic acid has been rarely studied in system-level studies. The thermophysical properties of the PCMs were determined by differential scanning calorimetry (DSC). Laboratory scale system experiments were performed to systematically examine the charging and discharging processes of the thermal battery. The recovered heat provided temperature range (40–65 °C) suitable for domestic heating and hot water production.

2. Materials and methods

2.1. Phase change materials

Two organic PCMs, namely paraffin (VWR Chemicals, technical grade) and myristic acid (Merck), were selected as the thermal materials. They were characterized by differential scanning calorimetry (DSC) on a Netzsch DSC204F1 Phoenix DSC instrument to measure the specific heat capacity, melting temperature range and latent heat of fusion. The PCM samples (10-20 mg) were exposed to a dynamic DSC heating-cooling program to record the heat flow rate in the sample as a function of temperature, which is the DSC curve. The latent heat of fusion was determined as the area under the endothermic peak on heating and the fusion temperature was assigned to the peak temperature. The DSC program included four consecutive cycles under 5 K/min heating-cooling rate within 10 to 70 °C. Sapphire correction Cp method was used to measure the specific heat capacity (Cp) by the DSC. The thermal conductivity was measured on a C-Therm thermal conductivity analyzer (C-Therm TCi).

2.2. Design of heat exchanger

Due to the low thermal conductivity of the selected organic PCMs, heat transfer enhancement is vital especially for improving the charging and discharging power and response time of the TES system. Herein, we designed four different types of heat exchangers for our thermal battery. All heat exchangers were additively manufactured from aluminum silicon alloy (AlSi10Mg) using a SLM 500 Machine (SLM Solutions) by FIT Prototyping GmbH (Lupburg, Germany). A planar single plate heat exchanger (Fig. 1), with no extended surfaces was fabricated as reference (referred here as type A). For the grid heat exchangers (types B, C, D), a 3D printed grid net (Fig. 2) was built around the planar part as a solid wireframe. The comprehensive design of the planar heat exchanger is reported in our previous work [33]. Briefly, it encompassed twenty coolant channels that were separated by 1.6 mm thick walls. Ten middle channels directed the heat transfer fluid (HTF) directly from inlet (inner tube) to the opposite end of the heat exchanger, where the HTF turns and returns along ten outer coolant channels towards the outlet (outer tube).

Three different grid geometries were designed as types B, C, and D, illustrated in Fig. 2. The heat exchanger type B composed of rectangular grids with 1.5 mm thickness. Type C composed of orthogonal grids to the planar part with 1.5 mm thickness and parallel grids to the planar part with 0.75 mm thickness. The type D included 0.75 mm parallel grids to the planar part, while its orthogonal grids to the planar part were tapering, i.e. they were 2 mm thick at the base and narrowed towards the tip to 0.75 mm. Dimensions of the heat exchangers including the grid spacing are



Fig. 1. Heat exchanger type A: the reference planar heat exchanger with no external grid.



(a)







Fig. 2. Grid heat exchangers: a) Type B and b) Type B grid design with uniform fin thickness (1.5 mm); c) Type C and d) Type C grid design with thinner thickness (0.75 mm) for the fins parallel to the planar part; e) Type D and f) type D grid design with tapering thickness ($2 \rightarrow 0.75$ mm) for the fins orthogonal to the planar part. See the dimensions of the grids in Table 1. I: orthogonal grid, II: parallel grid, III: grid spacing.

Table 1

Dimensional parameters of the heat exchangers. See in Fig. 2: (I) orthogonal grid, (II) parallel grid, (III) grid spacing.

Heat exchanger type	Orthogonal grid thickness	Parallel grid thickness	Grid spacing	Mass
	(mm)	(mm)	(mm)	(g)
Α	-	-	-	398
В	1.5	1.5	3.5 × 3.5	2020
С	1.5	0.75	3.5 × 4.25	1393
D	$2.0 \rightarrow 0.75$	0.75	$3.0\times3.0\rightarrow4.25\times4.25$	1364





Fig. 3. a) Laboratory setup and b) PID controller setup used in the experiments. The Roman numbers on both images are related to **i**: Pressure release valve, **ii**: boiler, **iii**: pump, **iv**: rotameter, **v**: thermocouples, **vi**: data logger, **vii**: thermal battery, **viii**: cooling tank, **ix**: 3-way valve.

compiled in Table 1. The volume of the heat exchanger was decreased around 30% by reducing the grid thickness, which enables more PCM to be inserted in the system.

2.3. Thermal energy storage setup

A laboratory TES system was constructed as illustrated in Fig. 3. The system consisted of (i) pressure release valve, (ii) heat source

to provide hot water HTF, (iii) pump, (iv) rotameter, (v) K-type thermocouples, (vi) data logger and (vii) the PCM thermal battery. An Ariston BLU EVO R 10/3 EU boiler with 1200 W heating coil capacity and 10 litres buffer tank was used as the heat source. The water temperature inside the boiler was controlled by a thermostat. The thermostat worked on-off bases, which was set to keep the water temperature in the tank between 68 $^\circ$ C and 75 $^\circ$ C. The hot water was circulating in a closed loop, flowing from the boiler through the thermal battery and then back to the boiler. The cold water source in the discharging loop was the tap water. The TES container was a transparent rectangular plexiglass box with a storage volume of 2.507 dm^3 . The inner dimensions of the container were as 21.5 cm height, 10.6 cm width and 11 cm length. Due to the volume change during the phase change process, the upper part of the container was kept open to avoid a pressure difference caused by the expansion and contraction of the PCM. The walls of the container were insulated with a 10 mm thick polyurethane foam in order to reduce heat losses to the environment. The heat exchanger was placed in the container which was then filled with the PCM. Of note that as the top part of the container was not fully insulated, there was some heat loss that can be calculated by an energy balance equation.

The temperature distribution within the PCM storage was recorded by K-type thermocouples (calibrated with 2.2 °C accuracy). Seven thermocouples were used in total. Two thermocouples were installed at the inlet (TC1) and outlet (TC2) of the TES container to measure the temperature of the inflow and outflow water. The rest of the thermocouples were set to measure the temperature of the PCM. With the type A heat exchanger, three thermocouples were distributed in the vertical middle of the TES (TC4), while two were located in the top (TC5) and bottom (TC3) of the TES far away from the heat exchanger (at 4.5 cm distance from the planar part). With the grid type heat exchanger, the thermocouples were distributed close to the planar part with the channels (at 1 cm distance), two further away (at 4.5 cm distance), and one in the middle of these (at 2.5 cm distance).

To explore the repeatability of the storage performance, four consecutive charging-discharging cycles were carried out on all the heat exchangers. Experiments were conducted under operational parameters including 1.5 kg/min mass flow and 68–74 °C temperature range of the HTF. The volumetric flow of water was measured with a rotameter having accuracy of 1%. Due to the different metal volume of the heat exchangers, the volume of the inserted PCM was different for each heat exchanger type. Table 2 shows the volume and mass of the PCM according to the employed heat exchanger. The end of charging and discharging processes were set at the end of phase change reactions when all thermocouples indicated temperatures higher than 60 °C.

The energy charge-discharge power (P) is a function of HTF flow rate and temperature, as following Eq. (1) shows:

$$\mathbf{P} = \dot{m}c_p\Delta T \tag{1}$$

where \dot{m} [kg/s] presents the mass flow of water, c_p [kJ/kg] is the specific heat capacity of the water, and ΔT is the difference be-

Table 2

Volume, mass and ratio of PCM in the system, and the energy storage capacity and energy density determined for paraffin using Eq. (2).

Volume (ml)	Mass (g)	ratio (%)	Storage capacity (kJ)	Energy density (kJ/dm ³)
2306	1800	82	545	-
1800	1405	41	426	170
2016	1574	53	477	190
2035	1588	53	481	192
	Volume (ml) 2306 1800 2016 2035	Volume (ml) Mass (g) 2306 1800 1800 1405 2016 1574 2035 1588	Volume (ml) Mass (g) ratio (%) 2306 1800 82 1800 1405 41 2016 1574 53 2035 1588 53	Volume (ml) Mass (g) ratio (%) Storage capacity (kJ) 2306 1800 82 545 1800 1405 41 426 2016 1574 53 477 2035 1588 53 481

Table 3

Thermophysical properties of the used PCMs.

Thermophysical properties	paraffin	Myristic acid
Density solid/liquid (kg/m3)	900/770	990/862
Melting temperature (°C)	56	62
Thermal conductivity (W/m °C) solid/liquid	0.35/0.17	0.47/0.16
Latent heat of fusion (kJ/kg)	210	213
Specific heat capacity (kJ/kg °C) solid/liquid	1.90/2.40	1.70/2.26
Volume expansion (%)	8-10	15–17

tween the inflow and outflow water temperature. The thermal energy storage capacity (Q) by the PCM depends on the latent heat of fusion (ΔH), the specific heat capacity (c_p) and mass (m) of the PCM, as follows:

$$Q = m \times (c_{p_s}(T_{p_1} - T_1) + \Delta H + c_{p_l}(T_2 - T_{p_2}))$$
(2)

where T_{p_1} and T_{p_2} are the temperatures where the phase change begins and ends, T_1 and T_2 are the initial and final temperatures, m is the PCM mass, c_{p_s} and c_{p_l} are the specific heat capacities of solid and liquid PCM, respectively. Accordingly, Table 2 reports the calculated energy storage capacities for paraffin using the c_p values of solid and liquid states and latent heat of fusion in Table 3. Additive manufacturing enabled the adjustment of the grid design for maximizing the ratio of inserted PCM and consequently the energy storage capacity.

3. Results and discussion

3.1. Material thermophysical properties

The phase change properties of the PCMs are shown in Table 3. The DSC and Cp curves of the PCMs are illustrated in Fig. 4. The melting reaction occurs between 56 and 62 °C. The Cp values ranged from 1.7 kJ/kg°C for the solid to 2.40 kJ/kg°C for the liquid state. The thermal conductivity values were very low as 0.35/0.17 W/m^2K and 0.47/0.16 W/m^2K (solid/liquid) for paraffin and myristic acid, respectively. Low thermal conductivity is expected for such organic PCMs, which also motivates the heat transfer enhancement objective of the present study.

3.2. Storage charging process

During the charging process, the PCM melts while the thermal energy is stored as latent heat. Due to the rapid conduction of the alloy, the phase change begins at the surfaces of the heat exchanger. The melting front propagates until the phase change is complete. Figure 5 shows the melting of the paraffin wax with type A (PHE) and type D (GHE). In the type A heat exchanger, the presence of natural convection is clearly visible due to the tilted orientation of the melting front (i). The vertical temperature variance and the circulation of the liquid PCM due to natural convection transfers most of the heat to the top part of the heat exchanger, slowing down the melting process of the PCM fraction in the lowest part of the storage tank. As the fraction of the melt increases, the conical shape flattens towards the lowest part of the storage tank (ii). After 240 min, there is still some fraction of the solid PCM left in the bottom corners (iii). Similar effect of natural convection during charging process has been previously reported within PCM-based horizontal shell-in-tube TES units [26,34]. The natural convection flow of liquid PCM originates from the synergic effect of buoyancy caused by the density difference as well as the pressure gradient caused by the volume change of the solid and liquid states [34].

The melting process of the PCM within the GHE in Fig. 5 is dominated by conduction along the grid. The melting front initiates uniformly along the surfaces of the plate part instead of forming a clear conical shape (iv). Natural convection still exists in the system, yet, its effect is less noticeable (v). Consistently, such reduced convection effects have been previously observed for melting of paraffin within other fin designs and copper foam [30,34,35]. The charging time with the GHE (less than 20 min) was significantly faster compared to the PHE (over 240 min). Such a significant improvement is due to two main reasons. First, the grid spans the entire TES, enabling rapid heat conduction towards the outer parts. Second, the increased surface area with the aluminum silicon alloy grid increases the rate of heat transfer. Therefore, the grid balances the heat distribution in the system.

The charging power and the measured temperatures with each heat exchanger type can be seen in Fig. 6. The power peak at the beginning of charging process can be explained by the large temperature difference between the HTF and the PCM. With the PHE, the power decreases rapidly after the first peak and fluctuates consistently with the inlet temperature variations. The fluctuations result from the boiler thermostat which controls the water temperature. Considering the prolonged time and relatively poor charging power, see Fig. 6a, the PHE provides very low efficiency for the energy storage when employing low thermal conductivity organic PCMs. The poor thermal conductivity causes strong thermal resistance against heat transfer, leading to a large temperature variance along the horizontal direction in the PHE. In the vertical direction, as seen in Fig. 6b at around 35 min, the temperature of PCM located in the upper part of the storage tank begins to rise quickly (i), indicating the PCM fraction has melted and the thermal energy is shifting to the sensible heat of the liquid PCM. Between 50-60 min, the temperature in the top part of the storage approaches the inlet HTF temperature and starts fluctuating along the inlet water (ii). After the PCM fraction in the bottom part of the TES melts, the temperature starts to fluctuate in the bottom part as well (iii). The temperature levels in the top part of the storage are noted to grow significantly higher than the melting temperature of the PCM. This suggests that due to the natural convection, the charged heat is being transferred to the melted PCM in the upper part of the storage, retarding the phase change in the bottom part and a temperature stratification within the PHE. As the result, a clear temperature stabilization by the latent heat storage during melting was not observed for the PHE. Similar effect of natural convection was previously reported for the melting process in tube-in-shell heat exchangers, where accumulation of heat in the liquid PCM at the top part caused a slowing effect on melting at the bottom part [26,27,34].



Fig. 4. The DSC curves of (a) myristic acid and (b) paraffin under 5 K/min heating-cooling rate, and (c) the specific heat capacity curves.



Fig. 5. Melting of paraffin wax using the type A (top row) and type D (bottom row) heat exchangers versus charging time (min).

Figure 6d shows the measured temperatures during the charging process with the GHEs. A great improvement in both the charging time and power was observed for the GHEs compared to that of the PHE. The charging power generated by all three grid types followed a similar trend. The charging time with the grid type B was the fastest which is due to the highest alloy content of the grid, enabling a more effective heat transfer. Due to the fluctuation of the inlet temperature, there was a local minimum (vi) in the charging power at around 7.5 min as seen in Fig. 6c. A similar trend for the power distribution (1220-300 W) generated during the charging phase was also observed for a copper tube finned exchanger containing PCM and graphite powder mixture [36]. Contrary to the PHE, a synchronous temperature rise of the PCM within the grid is observed. Most of the PCM at the middle part of the GHE, where the HTF circulates, melted within the first 5 to 10 min, as also illustrated in Fig. 5. The point where the temper-



Fig. 6. The charging power and temperature levels versus time of experiment for all heat exchanger types. a) Charging power with the PHE, b) temperature levels during the charging process with the PHE, c) charging power with the GHEs, d) temperature levels during the charging process with the GHEs.

ature of the PCM stabilizes in Fig. 6d is the time where the massive phase change begins (iv). During the massive phase change, the temperature of the PCM remains close to its melting temperature since the charged heat is being stored as the latent heat. Majority of the phase change occurs approximately within 5 to 15 min after the start of the experiment. After melting, the energy is stored only as sensible heat and the temperature of the PCM starts to rise rapidly (v). The temperature stabilization through the endothermic melting reaction is quite distinct for the grid owing to the higher effective thermal conductivity and restricted flow of liquid PCM by the grid structure. For example, the type D GHE with 53% paraffin content provided a total charging time of less than 20 min, energy capacity of 481 kJ, and average power of 604 W. Previously, a total melting time of more than 3 h was reported for a copper tube heat exchanger, while a steel tube exchanger with aluminum fins required about 2 h of melting time for an equivalent 48% PCM mass content [36]. The effect of HTF on charging process is provided in Appendix A.

3.3. Storage discharging process

During the discharging process the liquid PCM solidifies while the latent heat is released and transferred to the HTF. The solidification begins at the surface of the plate part of the heat exchanger and proceeds from there towards the edges of the storage tank. Due to the formation of a solid PCM layer on the heat exchanger surfaces, the effect of natural convection decreases during the discharging. This is because the temperature of the solid-fluid interface decreases as the thickness of the solid PCM increases as explained by the Fourier's law ($q'' = -k\nabla T$). Furthermore, natural convection dominates initially the heat transfer, yet when the solid layer continues to progress on the surface, conduction becomes the prevalent heat transfer mode [26]. Thus, the natural convection assisted circulation of the liquid PCM is reduced by the increasing thickness of solidified PCM on the HE surface.

The discharging power and measured temperatures with each heat exchanger type can be seen in Fig. 7. Similarly, the power peak at the start of discharging stems from the high initial temperature difference between the PCM and HTF. However, as noted in Fig. 7a, the peak power in the discharging power with the PHE is low compared to the charging process and other heat exhcanger types. Based on the temperature levels in Fig. 7b, with the PHE the bottom part of the storage tank solidifies prior to the top part, which happens due to the effect of natural convection. The solidification of the PCM begins at around 10 min in the bottom part and at 50 min in the top part (i). The massive phase solidification ends in less than 120 min (ii), which is faster than the massive phase change during charging process (melting). The faster discharge is due to two reasons. Firstly, the temperature difference between the coolant HTF and the liquid PCM is much higher in the discharging process, providing better conductive heat transfer and higher cooling rate. Secondly, since the effect of natural convection is smaller, less thermal energy is consumed for the sensible heat of the circulating liquid PCM. This observation is consistent with previously reported findings with the tube-in-shell design, where solidification time was found to be shorter than melting time [26].

A shorter discharging time is observed for the grid type heat exchanges as well. Since the effect of natural convection is not significant, the faster discharging originates from the higher temperature difference between the HTF and the melting temperature of the PCM. The massive phase change begins at approximately 3 min with all three grid types (iii). The type B heat exchanger is noted to offer the highest discharging power, while not much difference is observed in the performance of the type C and type D heat exchangers. The massive solidification with the type B heat exchanger ends at approximately 9 min, while with the type C and type D it was completed at around 11 min (iv). This suggests that



Fig. 7. Discharging phase for the grid type heat exchangers versus process time. (a) Variance in the power level. (b) Temperature variance. Solid line: PCM temperature, dashed line: Inlet water temperature, i&iii: massive phase change begins, ii&iv: massive phase change ends.

 Table 4

 Average thermal power of different heat exchangers during the massive phase change and its duration.

Heat exchanger type	Charging		Discharging	
	Power [W]	Duration [min]	Power [W]	Duration [min]
A	80	220	35	90
В	450	9.67	670	6
С	430	11	545	7.85
D	405	10	604	7.33

the higher alloy content employed in the type B heat exchanger facilitates the heat transfer within the PCM more effectively, yet the total efficiencies of the studied grid heat exhangers were not significantly different.

The average thermal power of A-D type heat exchangers during the phase change are listed in Table 4. The average values are calculated only over the massive phase change when the heat is stored or released as latent heat of the PCM within the TES. Table 4 also includes the duration of the phase change, as indicated in Figs. 6 and 7. It is observed that the average discharging power with the grid type heat exchangers is higher than the charging power, while the duration of the massive phase change was shorter for discharging (solidification time) compared with that of charging (melting time). In the case of type A heat exchanger, it is noted that even though the discharging power is lower than the charging power, the discharging time is still shorter than charging time. Thus, the effect of natural convection in PHE shifts the heat storage to the sensible heat of the liquid PCM in the top part of the storage tank while decreasing the fraction of latent heat of the melting in the bottom. These results indicate that the enhancement of heat transfer by the 3D printed alloy grid skeleton accelerates the phase transition rate of the PCM leading to an improved efficiency of energy storage and release. Similar improved rates of solidification and melting by thermal conductivity enhancement were also reported previously by the insertion of paraffin wax into hexagonal boron nitride porous scaffolds with continuous thermal conductive paths [37]. The effect of HTF on discharging process is provided in Appendix A.

3.4. Repeatability of storage performance

The cycle-to-cycle variation (CCV) of the charging process for type A and type B heat exchangers, and of the discharging process for type B is shown in Fig. 8. The temperature levels between different charging and discharging cycles with the grid type heat exchangers reveal no significant variation. The effective performance of our grid design is attributed to high conduction and the low convection thermal resistance, which can compete with the performance of previously reported PCM-based composite heat sinks such as paraffin within copper foam [34], carbon fiber brush [20], external and internal finned triplex tube [38], printed external and internal fined tube [30], and copper tube heat exchanger and steel tube exchanger with aluminum fins [36]. The highest variation is observed for the PHE (type A), suggesting that its storage performance is not as predictable as that of the grid type heat exchangers. This is a major disadvantage with the type A heat exchanger. The CCV for designs C-D was noted to be on a low level, and hence, the results are not shown here to avoid repetition. For the dis-



Fig. 8. Repeatability of the charging process of the TES with a) type A PHE and b) type B GHE, c) repeatability of the discharging process with type B GHE. i: inlet water, ii: TC1&2, iii: TC4&5, iv: top TC, v: bottom TC.



Fig. 9. The a) charging and b) discharging temperature levels with myristic acid. c) The melting process of myristic acid versus process time.

charging with the PHE (type A), the CCV was observed to be rather high. Based on the experiments, it is obvious that the designs B-D outperform the design A in terms of predictability. The long thermal cycles of the PHE due to the high thermal resistance against heat transfer implies that the design is not practical for most of the potential applications.

The experiments were repeated with non-paraffin PCM from fatty acids category. The charging and discharging temperatures along with the visual melting process using myristic acid with the type D heat exchanger can be seen in Fig. 9. Similar trends in process time and temperature were observed for the fatty acid compared with those of paraffin. The massive phase change during charging occurred between 4 min and 20 min, with the average charging power of 435 W. During the discharging process, the massive phase change took place between 2 min and 8 min, which in comparison is much faster than the charging process. The average power during the massive phase change was 895 W, which is more than double compared with the charging power as the result of higher cooling rate. Similar to melting of paraffin in Fig. 5, myristic acid started to melt from planar part of the heat exchanger and progressed along the grid until fully melted within 20 min (Fig. 9c). Such promising results point to the sustainable solution of bio-based TES. Unlike paraffinic PCMs, which have been extensively explored for different TES systems, plant-based fatty acids have remained underused in system level applications despite showing several advantages of high latent heat storage, natural origin and cost-effectiveness.

3.5. Storage applications

The grid-PCM thermal battery provides several advantages, e.g. compact storage design, high energy-density storage, high powerdensity supply, and rapid charging-discharging process for various applications. For example, it can be exploited for producing hot water temperature about 50 $^\circ$ C, which is consistent with the melting temperature of the selected PCMs, using inlet cold water temperature (10-20 °C). It can also be employed for space heating to maintain a comfortable indoor room temperature e.g. above 16–20 °C [39]. It can be installed as intermediate storage unit for heat pumps in heating systems providing a stable storage temperature thanks to the almost constant charging temperature (melting) of the PCM [40], which was demonstrated with our results. The storage system could also act as a suitable heat-sink and thermal buffer for powerful electronics and battery systems. Such PCMbased storage systems could be integrated in urban environment or domestic applications for waste heat recovery. Importantly, the selection of the PCM will depend on the application of interest. A suitable PCM provides a phase change (melting and solidification) within the charging-discharging temperature range of the target application [41].

4. Conclusions

Heat transfer enhancement is vital when organic PCMs are used for thermal energy storage and waste heat recovery purposes. Here, we employed 3D printed metal alloy surfaces to enhance the heat transfer within a PCM-based thermal battery that can be used for waste heat recovery from various heat generating sources such as powerful 5G electronics. In this concept, the thermal battery cools the 5G device by capturing the generated waste heat, whilst the stored heat can be applied for further use in e.g. space heating or hot water production. As such, three different geometries of the grid heat exchangers (GHEs) were produced via additive manufacturing and explored to optimize the heat transfer and PCM content of the thermal battery. Their performance was also compared to a reference planar heat exchanger (PHE) with no extended surfaces. A lab-scale TES system was built to test the thermal battery for medium-level heat storage and recovery using paraffin and fatty acid PCMs. The results demonstrated that the charging and discharging processes by the PHE produced very low thermal power and poor temperature stabilization. On the other hand, the weak heat transfer caused by the low thermal conductivity of organic PCMs was effectively overcome by the extended surfaces of our 3D printed GHEs, which resulted in reduced charging time by 92% and increased recovered thermal power by a factor of nineteen. Significantly higher charging and discharging rates were achieved by the 3D printed GHEs owing to the dominant heat transfer mode of the highly conductive alloy surfaces when compared to that of the PHE operating mainly based on a poor convection heat transfer mode. The most effective grid design provided charging-discharging time less than 10 min (duration of phase change), energy capacity of 426 kJ, and average power of 670 W through the phase transition of the PCM. Additive manufacturing enabled new promising designs to minimize the metal content of the 3D printed GHEs by reducing the thickness of the fins without a significant impact on the charging power of the thermal battery.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

CRediT authorship contribution statement

Maryam Roza Yazdani: Conceptualization, Investigation, Methodology, Formal analysis, Visualization, Supervision, Writing – original draft. Alpo Laitinen: Conceptualization, Formal analysis, Visualization, Writing – original draft. Valtteri Helaakoski: Methodology. Lorant Katona Farnas: Investigation, Methodology. Kirsi Kukko: Methodology. Kari Saari: Investigation, Methodology. Ville Vuorinen: Conceptualization, Supervision, Resources, Writing – review & editing, Funding acquisition.

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Appendix A. Effect of HTF Mass Flow Rate

A set of experiments was also conducted to assess the effect of HTF mass flow rate (1.5 and 2.5 kg/min) on the charging and discharging time, which are shown in Fig. A1. It can be seen that with the higher mass flow rate of the HTF, the main phase change completes in a slightly shorter time, which is due to a higher heat transfer rate.



Fig. A1. The effect of HTF mass flow rate on a) charging and b) discharging processes; temperature levels versus process time using paraffin.

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