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Enhanced latent thermal energy battery with additive manufacturing

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Abstract. The low thermal conductivity of Phase Change Materials (PCMs), such as paraffin waxes, hinders efficient latent heat storage, especially for rapid charging and discharging cycles. To address this issue, this study explores experimentally and numerically the use of metal additive manufacturing to create a latent heat storage system operating at medium temperatures (around 90°C). A 3D Cartesian metal lattice is manufactured through laser powder bed fusion to optimize heat conduction within the PCM. Experimental tests show impressive specific power densities (approximately 714 ± 17 W kg^{-1} during charging and 1310 ± 48 W kg^{-1} during discharging). Moreover, the device exhibits stability over multiple cycles. Finally, the validated finite-element model has the potential to provides a basis for general design guidelines to boost the system's performance further. Potential applications of this technology are highlighted in the automotive industry, where such systems could efficiently manage thermal energy, for instance, by capturing excess heat from an engine's cooling radiator to expedite the warm-up process during a cold start, which is a critical phase for reducing pollutant emissions.

1. Introduction

Thermal energy storage (TES) is crucial for enhancing sustainability in various sectors, such as solar [1–5] and automotive [6, 7] industries, enabling efficient utilization of intermittent heat sources. Latent TES, based on phase change materials (PCMs), offers higher energy density and precise heat release control compared to sensible TES [8, 9]. Paraffin waxes are commonly used PCMs for medium temperatures, but their low thermal conductivity limits specific power, leading to longer charge and discharge times. Previous approaches have introduced highly conductive fillers like graphite nanoparticles [10–16] or foams [2, 17, 18] to enhance thermal conductivity. However, achieving uniform filler dispersion remains challenging. In contrast, the inclusion of 2D metal grids in paraffin matrices has shown promise for heat transfer improvement. Metal additive manufacturing offers the potential to take this concept further by producing complex 3D structures with high porosity and surface-to-volume ratio [19–24].

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This article utilizes metal additive manufacturing to create a 3D Cartesian metal lattice for improving latent heat storage performance with paraffin waxes at around 80 °C fusion temperatures. The study includes numerical simulations and experimental tests to assess energy storage and release, charge and discharge times, and power density. Notably, specific powers of approximately 714 ± 17 W kg^{-1} and 1310 ± 48 W kg^{-1} are achieved during charging and discharging, respectively, with stable device performance over multiple cycles [25]. The intended application is in the automotive sector to recover and reuse waste heat from engine cooling systems for reducing cold-start emissions.

2. Materials and Methods

In this study, an innovative TES system was investigated with the goal of achieving rapid thermal charge and discharge cycles. The system employed a three-dimensional metal structure fabricated through laser powder bed fusion (L-PBF) [26–28], which was subsequently infiltrated with paraffin wax. This unique design aimed to leverage the high thermal conductivity of the metal lattice to homogenize the temperature of the PCM matrix and reduce its melting and solidification times. Additionally, the metal lattice served as a heat exchanger between a heat-transfer fluid (HTF) and the TES system.

The designed metal structure, represented in Fig. 1, had a cubic shape (80 mm × 80 mm × 80 mm) with an internal Cartesian lattice consisting of identical hollow cubic elements (6 mm side). The HTF flowed through both an inner duct and external fins on the device's surface, facilitating heat transfer. The 3D Cartesian lattice was fabricated using an aluminum alloy powder bed, AlSi10Mg, via L-PBF, a technique that utilizes a laser beam to melt metal powders layer by layer. The resulting device had a mass of approximately 630 g and a porosity of 71%. A test bench was employed to evaluate the TES system's performance, comprising a 20 L water tank, an electric heater, a volumetric pump, three thermocouples, and a data acquisition (DAQ) system. During testing, the water in the tank was heated by the electric heater, and a three-way valve directed the hot water toward the TES prototype and back to the tank. Thermocouples were used to measure water temperatures at the inlet and outlet of the prototype, as well as ambient temperature. Paraffin wax with a melting temperature of about 70°C was chosen as the PCM, and the HTF flow rate was set at 3.3 L/min, typical for automotive TES systems.

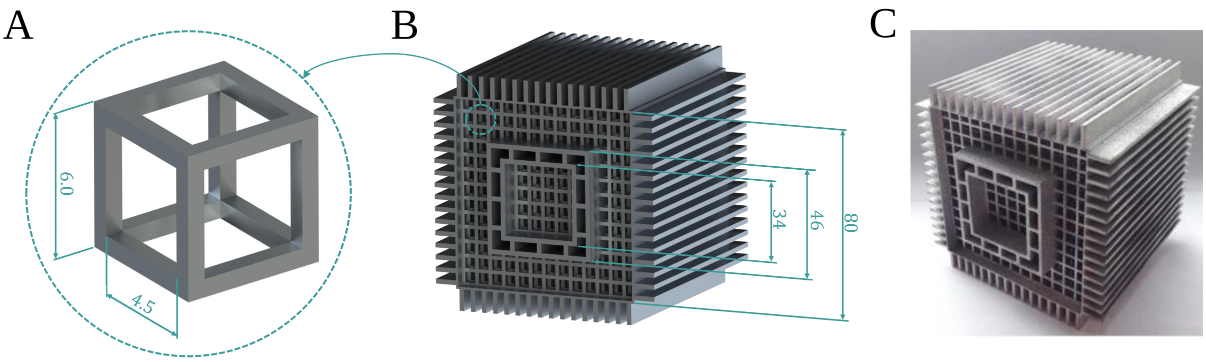

Figure 1. Design of the heat storage prototype. (A) Single hollow cubic element used to create the ordered Cartesian lattice. **(B)** 3D CAD model of the device realized. A STL file of the device can be downloaded from the Supplementary Material. All the quotes are expressed in mm. **(C)** Picture of the realized prototype. Picture taken from Ref [25], under licence CC BY 4.0.

A finite elements model implemented using COMSOL Multiphysics was used to simulate the device's behavior. The model considered energy conservation within the PCM and fluid flow within the HTF channels [25]. The fusion and solidification of paraffin wax were modeled using the apparent specific heat capacity method, which models the latent heat as a temperature-dependent function presenting peaks at the characteristic temperatures of phase change, to be added to the specific heat capacity. Material properties such as density, thermal conductivity, and specific heat capacity were provided for aluminum, wood, and mineral wool. Extensive details are reported in Ref. [25].

3. Results

The charge and discharge processes of the device manufactured were tested both experimentally and numerically. In particular, the experimental results were used to validate the FEM model developed in COMSOL Multiphysics (see Fig. 2). The system demonstrated an impressive energy storage capacity, capable of storing approximately 125 kJ of thermal energy. One of the most remarkable features of the TES prototype was its charging and discharging time. In detail, the characteristic time required to store or release 90% of the available latent heat (i.e., t_{90}) was equal to 176 ± 4 seconds (see Fig. 2a) and 88 ± 3 seconds (see Fig. 2b) for the charging and discharging phases, respectively. This rapid charging/discharging time is particularly crucial for applications where quick response times are required, such as renewable energy integration and automotive systems. The specific power density during both charging and discharging processes was also notable, with values ranging from approximately 714 W/kg to 1310 W/kg during charging. This indicates the TES system's capability to absorb and release energy quickly and efficiently [25].

Moreover, numerical simulations provided a detailed understanding of the PCM's melting process within the TES system. These simulations revealed that the PCM near the HTF channels melted rapidly, around 50 seconds into the process (see Fig. 2c). Subsequently, it took an additional 40 seconds for the PCM surrounding the metal lattice to be completely melted. The remainder of the process relied on thermal diffusion within the PCM. The incorporation of the 3D-printed metal lattice within the TES system significantly enhanced heat transfer efficiency. The lattice structure, with its high thermal conductivity, effectively homogenized the temperature distribution within the PCM, reducing both the melting and solidification times.

Finally, the TES prototype experimentally demonstrated stability and repeatability over multiple cycles, affirming its reliability for long-term use [25]. This stability is a crucial characteristic for applications that require consistent thermal energy management.

4. Discussion and Conclusions

This study demonstrated the promising potential of additive manufacturing, specifically laser powder bed fusion, for creating innovative latent thermal energy storage systems. The rapid charge and discharge capabilities, along with high power density, make such systems suitable for various applications, including automotive and renewable energy. The integration of phase change materials, such as paraffin wax, into the design allowed for substantial energy storage through latent heat. Moving forward, future research could focus on optimizing the 3D-printed lattice structure, potentially altering the size and geometry of elementary cells to enhance performance further. Additionally, investigating the scalability of this technology for larger or industrial-scale applications would be of great interest, paving the way for broader adoption of this innovative TES system. In summary, this research highlights the significant advancements achievable in thermal energy storage through additive manufacturing techniques, offering solutions for efficient and rapid thermal energy management in various domains.

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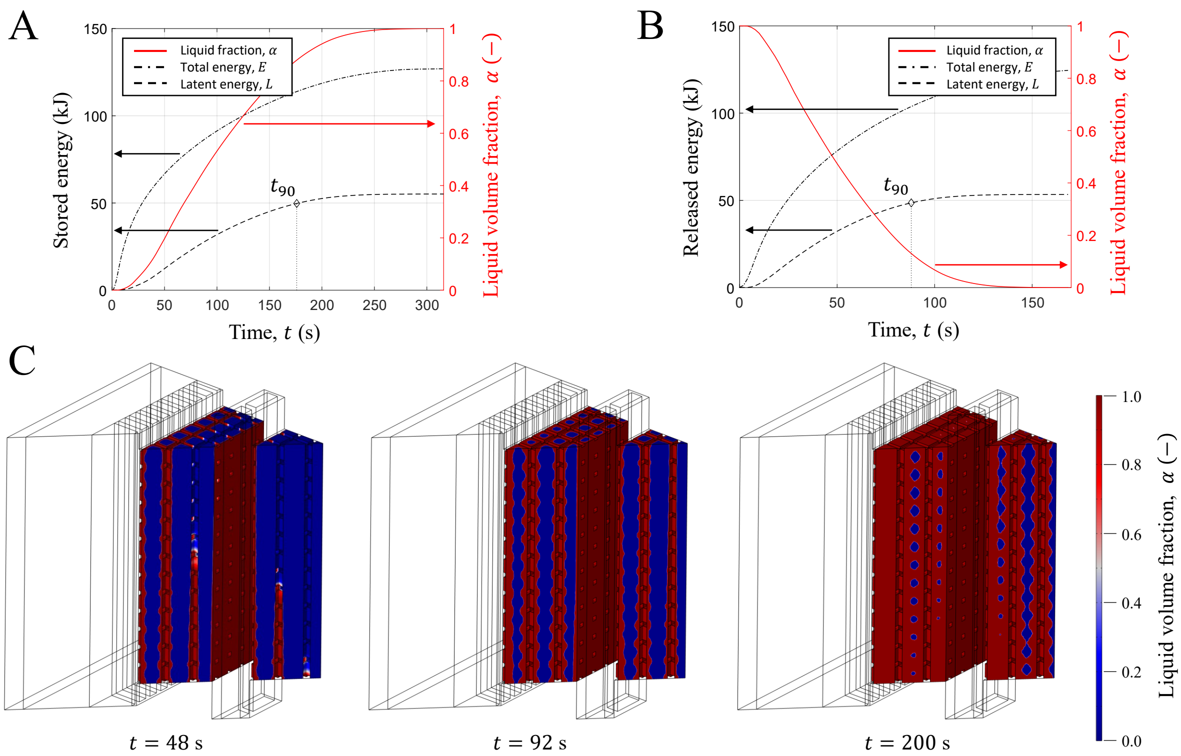

Figure 2. Thermal energy storage performance of the device: numerical results. Analysis of the percentage of the melted volume of PCM (α, red data) and thermal energy stored **(A)** or released **(B)** during the charging and discharging phases. Simulation results show that the tested conditions lead to faster solidification rather than melting. **(C)** Liquid volume fraction α of the PCM during the simulated charging process at different time frames. Picture taken from Ref [25], under licence CC BY 4.0.

and Thermal Energy Storage Enhancement by Foams and Nanoparticles (2017F7KZWS).

4.2. Declarations
This proceeding is a summary of the results published in *Journal of Energy Storage* (see Ref. [25]: doi.org/10.1016/j.est.2023.107350).

References

[1] Xu J, Wang R and Li Y 2014 *Solar Energy* **103** 610–638
[2] Liu G, Du Z, Xiao T, Guo J, Lu L, Yang X and Hooman K 2022 *International Journal of Thermal Sciences* **182** 107809
[3] Liu G, Xiao T, Guo J, Wei P, Yang X and Hooman K 2022 *Applied Thermal Engineering* **212** 118564
[4] Bologna A, Fasano M, Bergamasco L, Morciano M, Bersani F, Asinari P, Meucci L and Chiavazzo E 2020 *Applied Sciences* **10** 4771
[5] Giagnorio M, Morciano M, Zhang W, Hélix-Nielsen C, Fasano M and Tiraferri A 2022 *Desalination* **543** 116083
[6] Narayanan S, Li X, Yang S, Kim H, Umans A, McKay I S and Wang E N 2015 *Applied Energy* **149** 104–116
[7] Narayanan S, Kim H, Umans A, Yang S, Li X, Schiffres S N, Rao S R, McKay I S, Perez C A R, Hidrovo C H *et al.* 2017 *Applied Energy* **189** 31–43
[8] Sharma A, Tyagi V V, Chen C and Buddhi D 2009 *Renewable and Sustainable energy reviews* **13** 318–345
[9] Han G G, Li H and Grossman J C 2017 *Nature Communications* **8** 1446
[10] Wang J, Xie H and Xin Z 2009 *Thermochimica Acta* **488** 39–42
[11] Kim S and Drzal L T 2009 *Solar Energy Materials and Solar Cells* **93** 136–142
[12] Sari A and Karaipekli A 2007 *Applied Thermal Engineering* **27** 1271–1277
[13] Lin C and Rao Z 2017 *Applied Thermal Engineering* **110** 1411–1419
[14] Fasano M, Bigdeli M B, Sereshk M R V, Chiavazzo E and Asinari P 2015 *Renewable and Sustainable Energy Reviews* **41** 1028–1036
[15] Li M 2013 *Applied energy* **106** 25–30
[16] Ribezzo A, Bergamasco L, Morciano M, Fasano M, Mongibello L and Chiavazzo E 2023 *Applied Thermal Engineering* **231** 120907
[17] Abujas C R, Jové A, Prieto C, Gallas M and Cabeza L F 2016 *Renewable energy* **97** 434–443
[18] Zhang P, Meng Z, Zhu H, Wang Y and Peng S 2017 *Applied Energy* **185** 1971–1983
[19] du Plessis A, Razavi S M J, Benedetti M, Murchio S, Leary M, Watson M, Bhate D and Berto F 2021 *Progress in Materials Science* 100918
[20] Righetti G, Savio G, Meneghello R, Doretti L and Mancin S 2020 *International Journal of Thermal Sciences* **153** 106376
[21] Mancin S, Diani A, Doretti L, Hooman K and Rossetto L 2015 *International Journal of Thermal Sciences* **90** 79–89
[22] Hu X and Gong X 2020 *Applied Thermal Engineering* **175** 115337
[23] Diani A, Nonino C and Rossetto L 2022 *Applied Thermal Engineering* **215** 118969
[24] Chiavazzo E, Ventola L, Calignano F, Manfredi D and Asinari P 2014 *Experimental Thermal and Fluid Science* **55** 42–53
[25] Morciano M, Alberghini M, Fasano M, Almiento M, Calignano F, Manfredi D, Asinari P and Chiavazzo E 2023 *Journal of Energy Storage* **65** 107350
[26] Calignano F, Cattano G and Manfredi D 2018 *Journal of Materials Processing Technology* **255** 773–783
[27] Ventola L, Robotti F, Dialameh M, Calignano F, Manfredi D, Chiavazzo E and Asinari P 2014 *International Journal of Heat and Mass Transfer* **75** 58–74
[28] Fasano M, Ventola L, Calignano F, Manfredi D, Ambrosio E P, Chiavazzo E and Asinari P 2016 *International Communications in Heat and Mass Transfer* **74** 36–39