

Article

Enhancing Solar Thermal Energy Storage via Torsionally Modified TPMS Structures Embedded in Sodium Acetate Trihydrate

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Abstract

This study focuses on the numerical analysis of the impact of geometric modifications of sheet-gyroid structures on heat transfer in thermal energy storage systems utilizing sodium acetate trihydrate as a phase change material. The aim was to enhance the thermal conductivity of SAT, which is inherently low in the solid phase, by embedding a thermally conductive metallic structure made of aluminum alloy 6061. The simulations compared four gyroid configurations with different degrees of torsional deformation (0° , 90° , 180° , and 360°) alongside a reference model without any structure. Using numerical analysis, the study evaluated the time required to heat the entire volume of SAT above its phase transition temperature (58°C) as well as the spatial distribution of the temperature field. The results demonstrate that all gyroid configurations significantly reduced the charging time compared with the reference case, with the highest efficiency achieved by the 360° twisted structure. Temperature maps revealed a more uniform thermal distribution within the phase change material and a higher heat flux into the volume. These findings highlight the strong potential of TPMS-based structures for improving the performance of latent heat thermal energy storage systems.

Keywords: TPMS; sheet-gyroid; sodium acetate trihydrate; numerical analysis



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1. Introduction

The rapid advancement of additive manufacturing technologies over the past decade has opened new dimensions in the design and fabrication of engineering components with complex internal geometries. Thanks to additive techniques such as selective laser melting (SLM) [1], Stereolithography (SLA) [2], and metal powder sintering [3], it is now possible to produce three-dimensional structures that were previously unfeasible using conventional manufacturing processes [4–7]. These technologies enable the precise formation of internal cavities, channels, and surfaces with extremely high geometric complexity while maintaining the mechanical integrity and functional performance of the final product. Among the geometries that particularly benefit from the capabilities of additive manufacturing are the so-called Triply Periodic Minimal Surfaces (TPMSs). These mathematically defined surfaces possess zero mean curvature and exhibit spatial periodicity in all three orthogonal directions [8]. One of the most well-known TPMS geometries is the gyroid [9], originally discovered as a solution to a variational problem of surface area minimization under specific boundary conditions. The gyroid structure is characterized by a high surface-to-volume ratio [10], a three-dimensionally interconnected channel network [11], and intrinsic

symmetry, which is advantageous for both heat transfer and laminar flow. From a practical standpoint, gyroid structures are increasingly being employed in thermal processes as thermally conductive fillers [12], heat exchange surfaces [13], and passive mixing elements [14]. The application of TPMS structures as heat exchangers or thermal flow distributors is particularly attractive in systems where enhanced heat transfer is required.

An example of such an application is the use of phase change materials, which serve as heat storage media in low-temperature thermal energy storage systems [15]. Among the various materials classified as phase change material (PCM), sodium acetate trihydrate (SAT) stands out as a particularly attractive candidate due to its combination of favorable properties—it is non-toxic, cost-effective, chemically stable, and exhibits a relatively high latent heat capacity [16]. At a temperature of approximately 58 °C [17], SAT undergoes a phase transition from solid to liquid, during which it absorbs or releases a significant amount of thermal energy with only a minimal change in temperature. This phenomenon is advantageous for the design of compact thermal storage units, which can serve either as a heat source during discharging or as a thermal buffer to stabilize the temperature during transient demand conditions.

However, a fundamental limitation in the application of SAT and similar PCMs lies in their inherently low thermal conductivity, particularly in the solid phase. Reported thermal conductivity values for solid SAT typically range from 0.4 to 0.7 W·m^{−1}·K^{−1} [18], which results in slow charging and discharging rates within thermal accumulators. Heat is transferred into the PCM volume primarily by conduction through its boundary, leading to temperature gradients and thermally “dead” zones that diminish the overall efficiency and performance of the storage unit. This issue has been addressed in the literature through several enhancement strategies, including the addition of metal foams, graphite, and nanoparticles and the implementation of thermally conductive inserts.

Sodium acetate trihydrate (SAT) was selected for this study due to its combination of desirable thermal and practical properties. It possesses a melting temperature of approximately 58 °C, which aligns well with the operational range of solar thermal systems and low-grade waste heat applications. SAT also provides a high latent heat of fusion (~264 kJ/kg), minimal supercooling, and relatively low thermal expansion during phase transition, reducing mechanical stress on storage containers. Its non-toxic nature, chemical stability over multiple thermal cycles, and low material cost further enhance its suitability for scalable thermal energy storage systems. Compared with other hydrated salts or paraffinic PCMs, SAT offers a strong balance between thermal performance and operational safety, making it a robust candidate for experimental and industrial deployment.

Garay Ramirez et al. [19] focused their research on improving the thermophysical properties of SAT by incorporating a mixture of carboxymethyl cellulose, silica gel, and silver nanoparticles. Their primary objective was to enhance the latent heat capacity. Wang et al. [20] conducted experiments aimed at evaluating the thermal and technical performance of PCM by using a composite based on expanded graphite. This material contributed to an increase in the amount of stored heat and accelerated both the charging and discharging processes. Myat et al. [21] investigated the effects of adding polyethylene glycol to PCM, reporting that the modified thermal conductivity of the mixture resulted in an approximately 25% reduction in the time required for charging and discharging the storage unit. Liu et al. [22] aimed to improve PCM performance by embedding a porous structure that acted as a conductive framework, thereby achieving more efficient thermal charging and discharging times. Hassan et al. [23] proposed a solution for passive cooling of electronic components using PCM enhanced with nanoparticles and copper foam with extremely high porosity (97%). Falcone et al. [24] highlighted a substantial improvement in the thermal conductivity of paraffin-based PCM after the inclusion of copper

foam—specifically, an increase from 0.2 to 7 W · m^{−1} · K^{−1}. Al-Najjar et al. [25] introduced a thermal storage concept incorporating a metallic foam layer with various configurations, which allowed for control over the duration of the charging phase. Chen et al. [26] analyzed the impact of arc-shaped fins in a shell-and-tube heat exchanger, where their presence improved the temperature distribution and accelerated the melting of the PCM. Zhao et al. [27] designed a thermal storage unit combining SAT with copper metal foam, and their experimental results demonstrated a significant influence of the specific spatial configuration on the thermal behavior of the system.

One of the most effective and simultaneously technologically feasible solutions is the embedding of a thermally conductive metallic structure with a high surface area into the PCM volume. Such a structure acts as an element that conducts heat throughout the entire material. A geometrically ideal candidate for this role is the sheet-gyroid—a type of gyroid that forms a continuous wall rather than discrete voids or lattice networks. Compared with the skeletal-gyroid, the sheet-gyroid contains a greater volume of solid material and a continuous surface network, enabling more efficient thermal contact with the surrounding PCM. Moreover, its periodic structure can be further geometrically modified to increase the total heat exchange surface area. From a manufacturing perspective, the use of aluminum alloy 6061 is highly relevant, as it is widely adopted in industry for its favorable balance between thermal conductivity, mechanical strength, and corrosion resistance. Modern additive manufacturing (AM) techniques—particularly selective laser melting (SLM)—enable the precise fabrication of intricate TPMS structures such as the sheet-gyroid from aluminum alloys, which are otherwise difficult to produce by conventional methods. This technological feasibility supports the potential integration of such structures in commercial thermal storage units. Moreover, sodium acetate trihydrate (SAT) is already utilized in practical applications such as portable hand warmers and domestic thermal buffers, owing to its low cost, non-toxicity, and latent heat capacity. The combination of AM-produced aluminum structures and SAT thus represents a promising direction for scalable latent heat thermal energy storage systems that align with current industry standards.

The present study focuses on a numerical analysis of the effect of implementing a sheet-gyroid structure into the volume of a thermal energy storage medium, with the aim of improving the charging efficiency of the system by enhancing its effective thermal conductivity. Moreover, due to the favorable phase change temperature of SAT and the potential for high thermal storage density, the proposed system is particularly well-suited for applications in solar thermal energy storage. The improved heat transfer dynamics facilitated by torsionally modified TPMS structures can significantly enhance the efficiency and responsiveness of compact latent heat storage units integrated into solar energy systems, including solar water heaters, thermal cookers, and buffer tanks for domestic heating. The study considers a specific geometric modification of the sheet-gyroid structure in the form of a full-body twist about its central axis by 90°, 180°, and 360°. This alteration changes the internal trajectory of heat propagation within the structure as well as the total heat transfer surface area, both of which may significantly affect the overall energy transfer rate. The motivation for this modification stems from previous research on gyroid structures [28–30], which demonstrated that geometric adjustments such as the so-called twisted gyroid can improve the thermophysical performance of heat exchange components. The current work builds on these findings and extends them by conducting a systematic comparison of different levels of torsion in the context of PCM storage unit charging.

2. Materials and Methods

As part of the present study, four variants of thermal energy storage structures were developed, each differing in the geometry of the embedded sheet-gyroid body. All variants were designed as three-dimensional models using the CAD software Solidworks 2024. The base of each structure consisted of a periodic gyroid geometry, represented analytically as a triply periodic minimal surface defined by Equation (1) [31].

$$\sin x \cos y + \sin y \cos z + \sin z \cos x = 0, \quad (1)$$

Using this equation, a base unit of the structure with dimensions of $10 \times 10 \times 10$ mm was generated. This unit was then regularly arranged and concatenated into a prismatic volume measuring $30 \times 30 \times 50$ mm. To create a solid body with a defined wall thickness, the resulting surface was transformed by applying a material thickness of 0.5 mm. For the purposes of subsequent numerical analysis, this volume was modified into a cylindrical shape with a base diameter of 20 mm. In addition to the baseline, unaltered sheet-gyroid geometry, three modified structures were also created. These were geometrically transformed by applying torsional deformation to the entire gyroid volume about its vertical axis by 90° , 180° , and 360° , respectively, resulting in variants with altered internal topology. In order to investigate the influence of torsional deformation on heat transfer performance, four gyroid configurations were created by applying a progressive twist to the base structure around its vertical axis. The twist angles selected— 0° , 90° , 180° , and 360° —correspond to the cumulative angular displacement of the top face relative to the bottom face of the structure. These values were chosen to represent a systematic increase in torsional distortion, with 0° serving as the undeformed baseline and 360° representing the upper bound of feasible geometric complexity within the given design volume. The deformation was applied using the Twist feature in SolidWorks, which continuously rotates horizontal cross-sections along the structure's height. This approach allowed us to observe the thermal effects of increasing surface curvature and internal flow redirection while ensuring that the deformed structures remained suitable for potential fabrication using additive manufacturing techniques.

These modifications were introduced with the aim of influencing the heat transfer pathways within the solid body as well as potentially altering the temperature distribution during the heating phases. Figure 1 presents the 3D models of the applied gyroid structures in both front and side views. Each model used in the numerical analysis consisted of two primary components: a solid, thermally conductive body represented by a sheet-gyroid structure and a surrounding volume into which this body was embedded—the phase change material sodium acetate trihydrate. The model was designed to represent a compact form of an elementary thermal storage unit with well-defined dimensions, carefully chosen to balance simulation accuracy and computational efficiency.

The SAT volume was shaped as a cylinder with a diameter of 22 mm and a height of 52 mm, with its outer walls offset by 1 mm from the outermost points of the sheet-gyroid structure. This offset eliminated direct contact between the storage medium and the external environment, thus simulating conditions closer to thermal insulation in a closed system. For reference purposes, a comparison model without the sheet-gyroid structure—referred to as the “blank” model—was also created. In this case, a solid cylinder with the same volume as the sheet-gyroid structure was centrally placed within the SAT volume. By keeping the cylinder height fixed at 50 mm, the diameter was calculated to yield a total volume of 2397 mm^3 , ensuring volumetric consistency across all configurations for meaningful comparison of heat transfer effects.

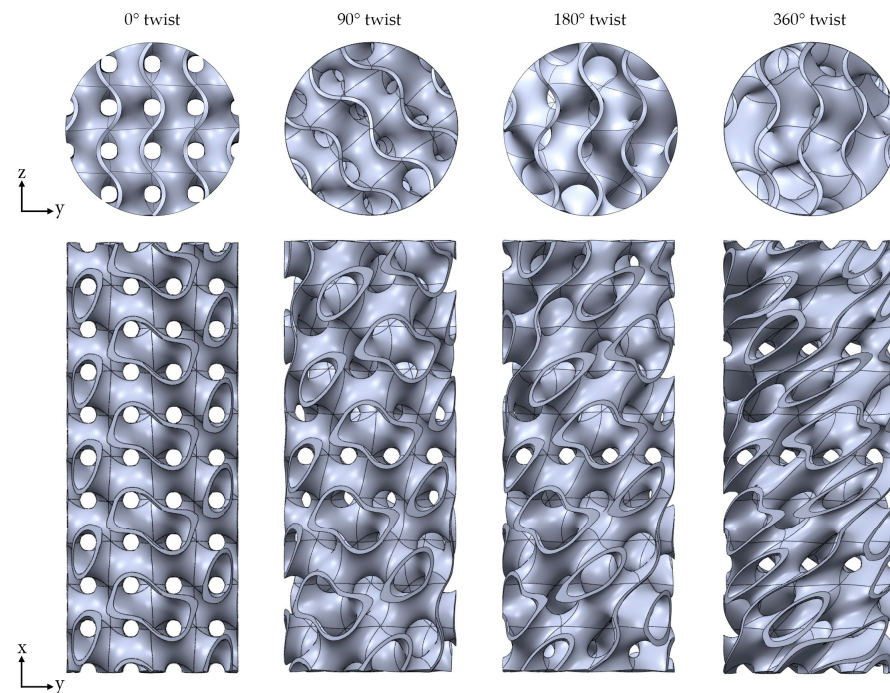


Figure 1. Front and side views of the four gyroid structures with 0°, 90°, 180°, and 360° torsional rotation about the vertical axis.

Table 1 summarizes the final values of volume and external surface area for the individual sheet-gyroid configurations, as well as the respective SAT volumes. For the sheet-gyroid, the listed values correspond to the volume and external surface area, which serves as the active heat transfer interface to the PCM. For the SAT, only the total volume of the storage medium is provided. The analysis of the tabulated data reveals that the volumes of the solid structures remain nearly identical across all configurations, with differences on the order of tenths of a cubic millimeter. In contrast, the external surface area of the sheet-gyroid structures—which serves as the heat transfer interface—increases noticeably with higher degrees of torsional deformation. The baseline (non-twisted) configuration exhibits a surface area of approximately 10,038 mm², while the 360° twisted structure reaches nearly 10,975 mm², corresponding to an increase of roughly 9%. On the other hand, the reference “blank” model without any embedded structure has a significantly smaller heat transfer surface (only 1326 mm²), clearly illustrating the contrast between the plain configuration and the sheet-gyroid-filled models.

Table 1. Summary of the external surface area of the sheet-gyroid structure (i.e., the heat exchange surface) and the volumes of the sheet-gyroid structure and the SAT body for a cylindrical model with a diameter of 22 mm and a height of 52 mm denoted as a blank.

	Volume (mm ³)	Surface Area (mm ²)
Sheet-gyroid		
0° twist	2396.52	10,038.39
90° twist	2396.73	10,100.31
180° twist	2397.02	10,282.63
360° twist	2397.60	10,975.28
blank	2397.36	1326.31
SAT body		
0° twist	15,718.11	-
90° twist	15,717.37	-
180° twist	15,717.19	-
360° twist	15,719.42	-
blank	15,717.30	-

For the purposes of numerical simulation, the sheet-gyroid structure was modeled using aluminum alloy 6061, while the thermal storage medium was represented by sodium acetate trihydrate ($\text{CH}_3\text{COONa} \cdot 3\text{H}_2\text{O}$). The fundamental thermophysical properties of both materials were adopted from the literature. For aluminum 6061, the following constant values were used: a thermal conductivity of $167 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, a specific heat capacity of $900 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and a density of $2700 \text{ kg} \cdot \text{m}^{-3}$. The thermophysical parameters of SAT were determined based on available correlations that express the temperature dependence of the relevant properties over the simulated operating range, which in this case involved a charging process beginning at 20°C and concluding at 58°C . The temperature-dependent specific heat capacity, thermal conductivity, and density of SAT were defined according to Equations (2)–(4), based on established sources [32,33]:

$$\rho_s = 8.07 \cdot 10^2 + 4.77T - 8.84 \cdot 10^{-3}T^2, \quad (2)$$

$$c_s = 1.43 + 2.03 \cdot 10^{-3}T, \quad (3)$$

$$k_s = 2.79 - 1.31 \cdot 10^{-2}T + 1.88 \cdot 10^{-5}T^2, \quad (4)$$

where ρ_s is the density of SAT in the solid phase ($\text{kg} \cdot \text{m}^{-3}$), T is the system temperature ($^\circ\text{K}$), c_s is the specific heat capacity of solid SAT ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), and k_s is the thermal conductivity of solid SAT ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$). For the reference temperature of 20°C , the following values were used: a thermal conductivity of $0.576 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, a specific heat capacity of $2015 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and a density of $1450 \text{ kg} \cdot \text{m}^{-3}$. The melting point of SAT was set at 58°C , which represents a critical threshold temperature in terms of energy storage via latent heat.

All simulations were conducted as transient heat conduction problems without considering phase change or convection, meaning that only conductive heat transfer in the solid PCM was analyzed. The initial temperature of the entire system was uniformly set to 20°C . A constant heat flux of $1000 \text{ W} \cdot \text{m}^{-2}$ was applied to the external surface of the sheet-gyroid structure, or to the cylindrical surface in the reference case with a solid cylinder, in order to evaluate the effectiveness of heat transfer from the metallic structure into the SAT volume. Outer walls were defined as thermally insulated (adiabatic), thereby eliminating parasitic heat losses to the surroundings and focusing the simulation exclusively on the efficiency of heat conduction through the structure and its distribution within the SAT volume. A representation of the boundary conditions used in the numerical analysis is shown in Figure 2.

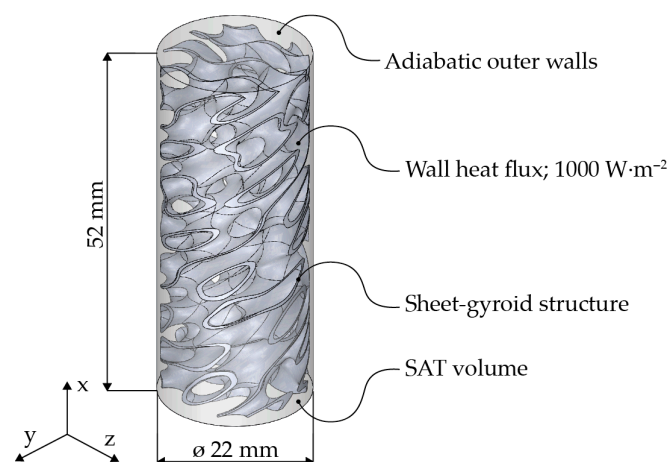


Figure 2. Boundary conditions of the numerical analysis and dimensions of the model.

The numerical analysis was conducted using SolidWorks Flow Simulation software, version 2024. Given the absence of a flowing medium, only the module enabling heat transfer analysis between two solid bodies was activated. During the simulation, no user-defined functions or external codes were employed to modify the computational algorithms. The simulation time domain was defined based on the time required for the minimum temperature of the SAT to reach 58 °C, representing the point at which the entire assessed volume of SAT exceeded its melting temperature. Once this temperature was reached, the calculation was terminated. Data logging was configured at intervals of 0.5 s. The numerical computations were performed using an implicit solver based on the finite volume method (FVM), with a convergence criterion set to 10^{-6} for all governing equations. The governing equation describing the phenomenon of anisotropic heat conduction in solid materials is expressed in Equation (5):

$$\frac{\partial \rho e}{\partial t} = \frac{\partial}{\partial x_i} \left(\lambda_i \frac{\partial T}{\partial x_i} \right) + Q_H, \quad (5)$$

where ρ is density, e is specific internal energy ($e = C \cdot T$), C is specific heat, T is temperature, Q_H is specific heat release (or absorption) per unit volume, and λ_i are the eigenvalues of the thermal conductivity tensor. It is supposed that the heat conductivity tensor is diagonal in the considered coordinate system. For an isotropic medium, $\lambda_1 = \lambda_2 = \lambda_3 = \lambda$.

For the purposes of numerical simulation, the thermal storage unit model was transformed into a computational mesh, with meshing performed exclusively for regions representing solid bodies—namely, the aluminum sheet-gyroid structure and the volume of the phase change material (SAT) in its solid state. SolidWorks Flow Simulation utilizes a computational mesh based on a Cartesian coordinate system. With this meshing approach, it is not necessary to conform the mesh to the geometry itself; instead, the geometry is “immersed” into a regular grid of cuboidal cells. This allows for efficient meshing of highly complex and organic shapes, such as TPMS structures. Individual mesh cells may intersect multiple material regions, and when they cross the interface between two bodies, the software automatically applies appropriate boundary conditions through the immersed boundary method. This approach is particularly suitable for modeling heat conduction in solid bodies with intricate geometry and in the absence of fluid flow. Since the computational domain was limited exclusively to solid phases, the mesh density requirements were reduced, thereby shortening the overall computational time without compromising result accuracy. However, the effort to minimize computational time can, in some cases, result in reduced simulation accuracy due to an overly coarse mesh resolution. Such simplifications may lead to deviations in output values, not due to the physical characteristics of the model, but as a consequence of an inadequate spatial resolution. To avoid such inaccuracies, it is advisable to perform a mesh independence study, which helps verify whether changes in mesh density significantly affect the simulation results.

For the given geometric configurations, different levels of mesh refinement and optimization methods were sequentially applied, and, for each, the time required for the entire volume of SAT to reach a minimum temperature of 58 °C was evaluated. The results of this comparison are shown in Figure 3, where a clear stabilization of the evaluated variable can be observed with sufficiently refined mesh density, confirming that the simulation outcomes are not dependent on further mesh refinement.

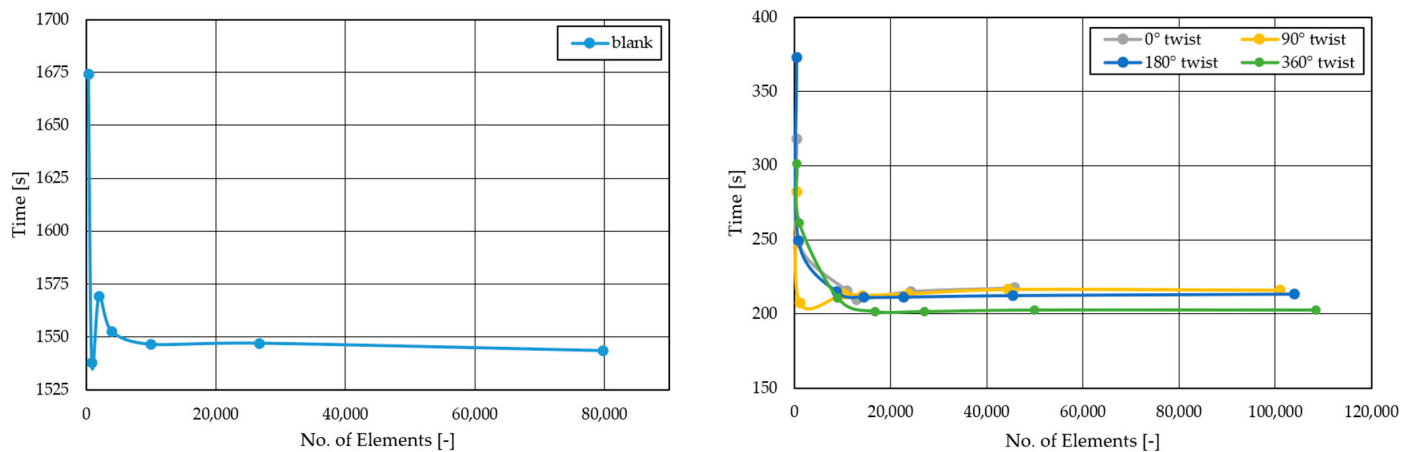


Figure 3. Results of the grid independence study for the reference case without the sheet-gyroid structure (left) and for the modeled cases with sheet-gyroid structures twisted by 0° , 90° , 180° , and 360° (right).

3. Results and Discussion

One of the main objectives of the numerical analysis was to quantitatively assess the influence of the geometric configuration of the sheet-gyroid structure on the dynamics of heat transfer within the solid phase of the SAT storage medium. Due to the specific thermal behavior of the material, the minimum temperature within the entire SAT volume was selected as the key reference variable. Particular attention was given to the time required to reach 58°C , which corresponds to the onset of the phase transition from solid to liquid. The simulations were initiated with a uniform system temperature of 20°C , and a constant heat flux was applied to the external surface of the sheet-gyroid structure (or to the cylindrical shell in the reference case). Throughout the calculation, the time-dependent values of the minimum temperature within the SAT volume were continuously monitored, enabling detailed tracking of the thermal response up to the point at which all regions of the PCM exceeded the phase transition threshold.

For the purposes of interpretation and visualization, the simulation results were processed at two levels of detail. The first graph (Figure 4) presents the complete thermal response over the time interval from 0 to 1600 s and includes all five evaluated configurations—namely, the four versions with the sheet-gyroid structure (rotated by 0° , 90° , 180° , and 360°) as well as the reference model without any structure (denoted as “blank”). The graph clearly demonstrates that embedding a thermally conductive metallic structure within the PCM volume has a significant positive impact on heating efficiency. While the structured cases reached the critical temperature within approximately the first 220 s, the reference model without the structure required around 1543 s to do so. This contrast highlights the effectiveness of using a metallic gyroid matrix in overcoming the limitations imposed by the low thermal conductivity of SAT in its solid state.

Since the differences among the individual versions of the gyroid structure manifested within a narrow time interval, a second visualization was created to better capture these subtle distinctions. The second graph (Figure 5) displays only the cases with sheet-gyroid structures and is zoomed in on the time interval from 180 to 220 s. This magnified time scale allows for precise differentiation of the times required to reach the 58°C temperature in the whole SAT volume, depending on the specific geometric modification of the structure.

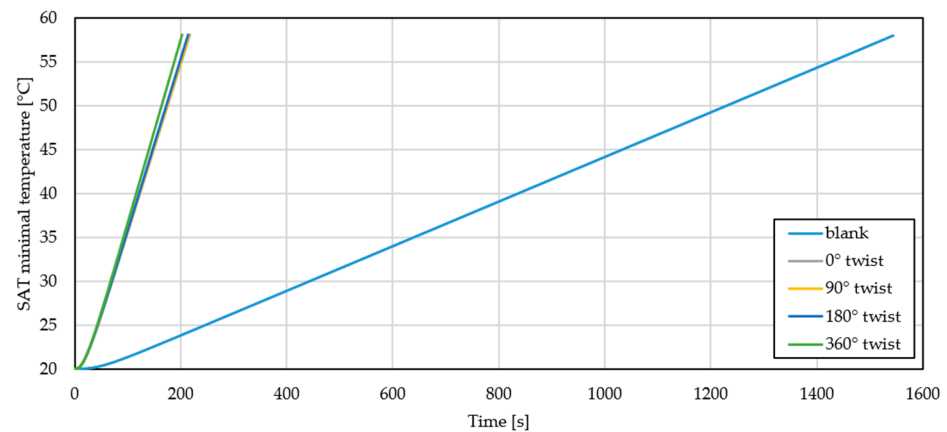


Figure 4. Time evolution of the minimum temperature in the SAT volume until reaching the phase change threshold of 58 °C.

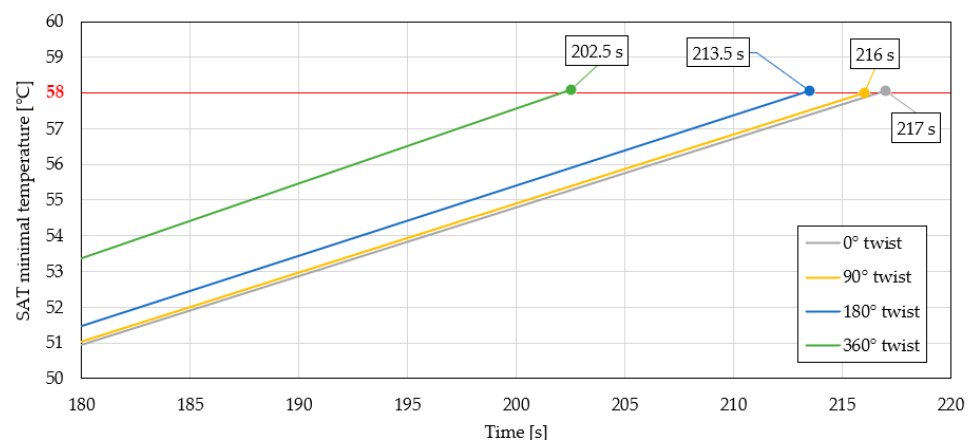


Figure 5. Time evolution of the minimum temperature in the SAT volume until reaching 58 °C for the four selected sheet-gyroid configurations, shown over the interval from 180 to 220 s.

The recorded trend indicates that torsional deformation of the gyroid structure has a positive effect on heat transfer efficiency. The reduction in the required heating time is attributed both to the increase in the active heat exchange surface area and to the altered internal heat flow paths resulting from the geometric reconfiguration of the structure. These results confirm that the geometric optimization of TPMS structures is not merely a structural design experiment but has a tangible impact on system performance, particularly in applications where the storage material has inherently low thermal conductivity.

In addition to the time required to reach the phase change temperature, the analysis also monitored the maximum temperature within the SAT volume at the moment when its minimum temperature reached 58 °C. This parameter provides supplementary insight into the uniformity of the temperature field within the PCM and indicates how effectively the supplied heat is distributed throughout the domain. Ideally, the difference between the minimum and maximum temperature should be as small as possible, as this signifies homogeneous heat transfer and minimizes the risk of local overheating or thermal gradients, factors that can negatively affect the mechanical stability and long-term cyclic durability of the PCM.

The results shown in Figure 6 demonstrate that, at the point when the minimum temperature reached 58 °C, the maximum temperature in the SAT volume varied depending on the structure's geometry. The highest temperature was observed in the 360° twisted structure (63.72 °C), followed by 180° (63.17 °C), 90° (62.94 °C), and the lowest in the base 0° configuration (62.88 °C). The difference between minimum and maximum temperatures

thus ranged from 4.88 °C to 5.72 °C. Although these differences are relatively small, the trend suggests that a higher degree of torsion leads to faster heat transfer, but also to slightly higher local overheating. These findings highlight the importance of optimizing the design not only for heating rate but also for temperature uniformity throughout the PCM volume in order to minimize thermal stress and ensure phase change stability during cyclic operation. The spatial location of the temperature maximum can be observed in Figures 7 and 8. It consistently appears in the upper portions of the SAT domain, particularly near the outer boundary where the gyroid surface exhibits higher curvature and longer contact length. These regions are subjected to more intense localized heat transfer due to the proximity to the exposed structure and the tortuous geometry that enhances conductive paths. This thermal behavior explains why configurations with higher torsional deformation, such as the 360° twist, exhibit both faster heating and slightly elevated temperature gradients.

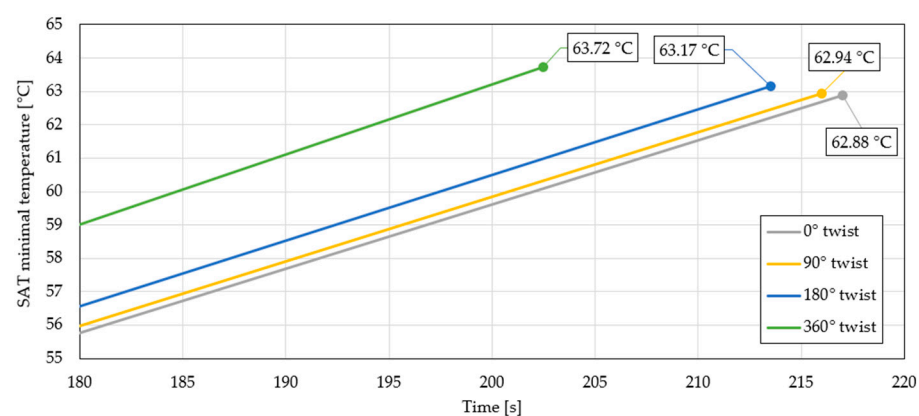


Figure 6. The maximum temperature in the SAT volume at the moment when the entire volume reaches the melting point.

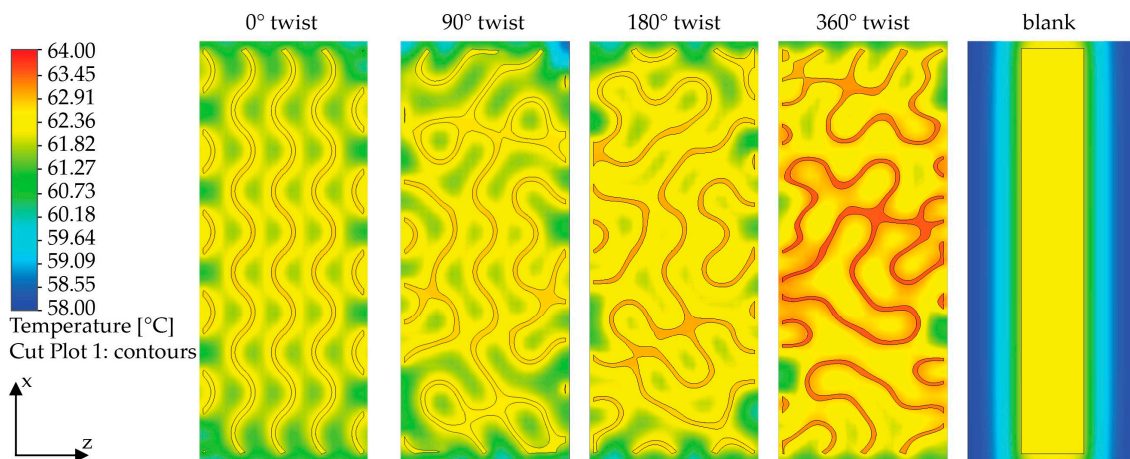


Figure 7. Temperature field distribution on the XZ plane at the center of the model.

As part of the numerical analysis, the heat transfer from the sheet-gyroid structure to the SAT volume was also evaluated quantitatively. Specifically, the heat flux was assessed across the surface of the sheet-gyroid structure that was in direct contact with the SAT. The integral heat transfer was calculated based on local temperature gradients and material properties, yielding the effective thermal power transferred into the adjacent volume. The obtained values served as an important supplementary parameter to the time-based heating analysis and enabled a comparison of thermal transfer efficiency among different geometric configurations. The results show that the 360° twisted structure delivered the

highest thermal power into the SAT—up to 9.596 W—followed by the 180° (8.995 W), 90° (8.849 W), and 0° (8.799 W) configurations. The reference “blank” model, which lacked an internal structure, transferred only 1.168 W—approximately eight times lower than the most efficient structure. These results confirm that increasing the active heat exchange area and altering the internal geometry of the structure have a direct impact on the intensity of energy transfer and that torsional modification of the sheet-gyroid can be an effective tool for optimizing thermal energy storage units.

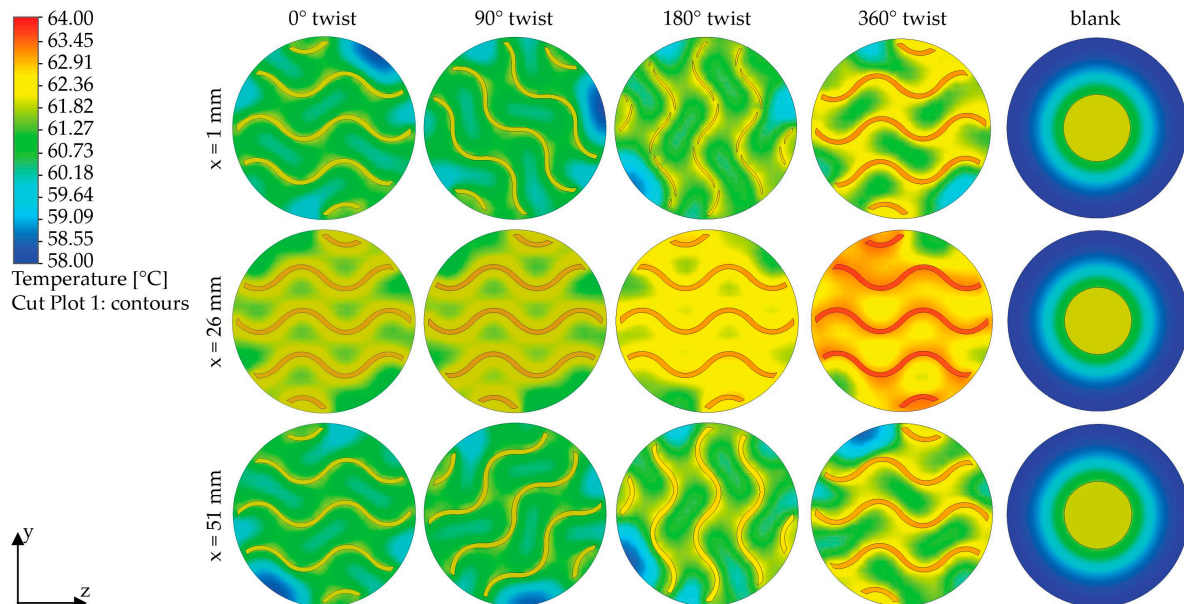


Figure 8. Temperature field distribution in transverse cross-sections of the model (YZ plane) at heights of 1 mm, 26 mm, and 51 mm from the model boundary.

To further investigate heat transfer within the PCM volume and compare the effectiveness of the different geometric configurations, detailed visualizations of the temperature field were generated from cross-sections of the models. These images provide spatial insight into the heat distribution during the charging phase. The first image (Figure 7) displays the temperature distribution on the XZ plane for all five analyzed cases—four with the sheet-gyroid structure and one reference “blank” model without structure. The XZ plane passes through the center of the SAT volume and captures the temperature field at the moment when the minimum temperature in the PCM reaches 58 °C. From the comparison of temperature fields, it is evident that greater torsional deformation of the structure results in more irregular and multi-directional contact areas between the structure and the PCM. This leads to more intensive and deeper heat penetration, visualized as broader regions of elevated temperature—particularly in the 360° configuration, where dominant zones exceeding 63 °C are clearly visible. Conversely, in the reference model without structure, the heat transfer geometry is simple and localized around the cylindrical heating core, with the temperature decreasing toward the outer boundaries. This configuration shows the lowest heat transfer efficiency and the greatest temperature non-uniformity.

The second image (Figure 8) illustrates cross-sections on the YZ plane at three vertical levels: 1 mm, 26 mm, and 51 mm from the base of the model. These cross-sections provide a representative view of the heat distribution along the vertical axis of the PCM. At each height level, it is evident that configurations with higher torsional rotation ensure a more uniform temperature distribution across the width of the PCM.

Particularly in the 360° configuration, the structure intersects all levels in a multi-dimensional fashion and spans a larger volume, enabling faster and more homogeneous

heat penetration into deeper PCM layers. In the 0° and 90° configurations, the structure appears more linear and aligned, resulting in lower heat transfer intensity in the Z-direction. Notably, in the reference case without structure, the isothermal zones are strictly concentric, once again confirming the slow and inefficient heat transfer toward the PCM core. These visualizations clearly demonstrate that not only the presence of a metallic structure but also its geometric modification significantly influence the spatial temperature distribution. The 360° twisted configuration proves to be the most effective, as it utilizes the model volume most efficiently for uniform heat transfer. These insights have direct implications for optimizing the design of phase change thermal energy storage systems, particularly with regard to the strategic geometry of embedded metallic inserts.

An additional important layer of comparison among the evaluated configurations is provided by the visualization of surface temperature on the sheet-gyroid structures, as shown in Figure 9. This visualization offers a three-dimensional overview of the temperature distribution directly on the surface of the metallic structure, which plays a crucial role in transferring heat to the storage medium SAT. Based on previous results, it has already been demonstrated that the degree of torsional deformation of the structure significantly influences the intensity and spatial extent of heat transfer. The surface temperature visualization clearly confirms these findings and provides further insight into the underlying mechanisms.

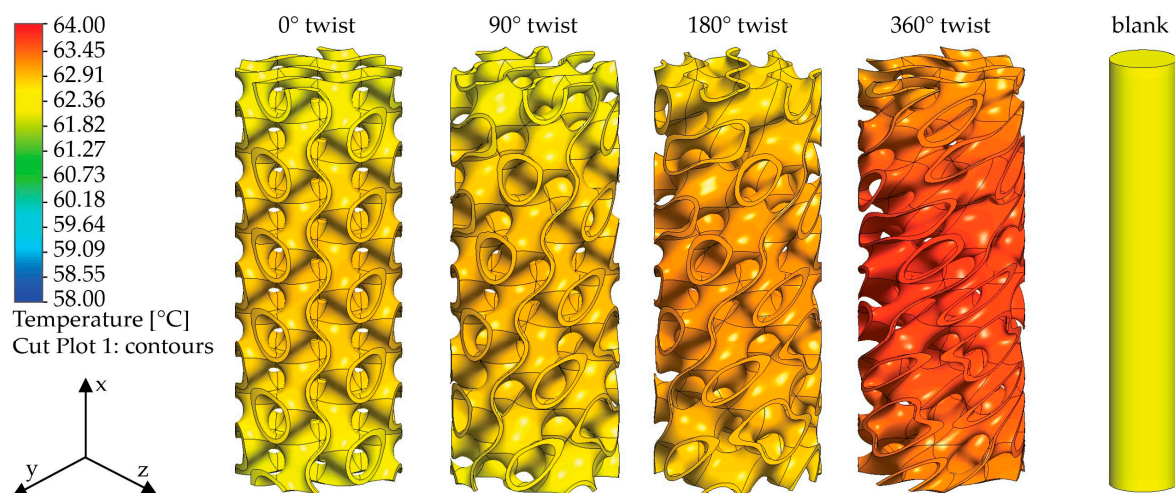


Figure 9. Temperature distribution on the outer surface of the heat exchange structure.

The 360° twisted configuration exhibits the highest surface temperature values—large areas of the structure reach up to 64°C , the maximum temperature observed in the entire simulation. This phenomenon is associated with the effective “unfolding” of the heat exchange surface, which in this configuration is more geometrically curved, thereby increasing the contact area between the aluminum and the PCM while simultaneously shortening the thermal pathways required for heat to penetrate into the deeper layers of SAT. This effect has previously been supported by the recorded maximum heat transfer rate (9.596 W) and the shortest time to heat the entire SAT volume to 58°C .

A gradual decrease in surface temperature intensity, visible as less intense coloration, is observed for configurations with lower degrees of twist (180° , 90° , and 0°), which correlates directly with their lower recorded heat transfer rates and maximum temperatures in the PCM. Although the 180° and 90° configurations still exhibit slightly elevated surface temperatures compared with the base version (0°), the extent of their hottest surface zones (depicted in red to dark orange tones) is significantly smaller than in the 360° case. The base version without torsional deformation (0°) shows a uniformly distributed surface

temperature with a significantly lower maximum and lower heat transfer dynamics, which is reflected in the longest heating time among all structured variants.

The reference case without any structure (“blank”) appears as a uniformly yellow cylinder, indicating a stabilized and limited surface temperature resulting from poor heat transfer efficiency. This visualization aligns with the previously presented graphs, where the blank case was characterized by the lowest heat flux (1.168 W) and the fastest transition into thermal stagnation, caused by the insufficient dispersion of the input energy throughout the PCM volume.

In summary, the surface temperature visualization provides compelling evidence that the intensity and uniformity of structure heating are critical factors in the overall efficiency of heat storage in PCM. The 360° torsional configuration, in particular, demonstrates that proper geometric design of the structure not only increases the heat exchange surface area but also ensures higher local temperatures, thus promoting efficient and dynamic heat transfer into the thermal storage medium.

Based on the presented results, it can be concluded that the integration of a metallic sheet-gyroid structure into the volume of the thermal storage medium SAT significantly improves the dynamics of heat transfer. In all cases involving the structure, a reduction of more than 85% in the time required to reach the phase change temperature (58 °C) was observed compared with the reference model without the structure. The most effective configuration was the one with a 360° torsional twist, which achieved the target temperature in just 202.5 s. This variant also exhibited the highest heat flux and most intense surface heating of the structure, confirming the high efficiency of thermal energy transfer into the PCM volume. Graphical outputs further revealed that geometric modification of the structure affects not only the heating rate but also the temperature distribution within the PCM. Torsionally modified configurations ensured a more uniform distribution and more extensive coverage of the active volume. These findings clearly confirm the importance of the spatial arrangement of TPMS structures in optimizing the performance of phase change thermal energy storage systems.

Despite the significant improvements in heat transfer rate and temperature uniformity achieved by embedding sheet-gyroid structures in the SAT volume, certain limitations must be considered for their practical implementation in real-world storage systems. First, the geometric complexity of TPMS structures requires advanced manufacturing techniques, which can be technologically and economically demanding—especially for large-scale applications. The material and time-intensive production of components using metals like aluminum 6061 presents a barrier, particularly if the structures are intended to be integrated into compact modular units for commercial or residential use.

Another important consideration is the interaction between the metallic structure and the PCM. As an organic substance, SAT may undergo volumetric changes during repeated melting and solidification cycles, potentially causing mechanical stress at the interface with the structure and leading to material failure. In addition, fouling or chemical degradation within the narrow channels of the structure may reduce the effective heat exchange area over time and compromise the system’s long-term stability. Air entrapment or improper PCM distribution during manufacturing and filling processes may also pose challenges, particularly in structures with very fine internal channels.

From a practical standpoint, successful implementation of sheet-gyroid structures requires optimization not only of their shape and placement but also of the enclosure design, PCM filling strategy, material compatibility, and thermal cycling performance. These aspects should be the subject of further experimental research focused on validating the mechanical, chemical, and thermal stability under long-term operating conditions, as well as evaluating the real-world feasibility of large-scale manufacturing and deployment.

While the present study focuses exclusively on torsional deformation of the sheet-gyroid structure, it is acknowledged that other forms of geometric modification—such as bending, expansion, or spatially localized distortion—could also affect the thermal conductivity and flow characteristics of the system. These deformation modes remain outside the scope of the current analysis but will be considered in future work to build a more comprehensive understanding of geometric influences on TPMS-based thermal storage systems.

4. Conclusions

The presented numerical study focused on evaluating the effect of various geometric configurations of sheet-gyroid structures on the efficiency of heat transfer in thermal energy storage systems utilizing sodium acetate trihydrate as a phase change material. The primary objective was to propose a solution to compensate for the low thermal conductivity of SAT in its solid phase, which significantly limits the rate of heat accumulation in such systems. The integration of a three-dimensional metallic sheet-gyroid structure made from aluminum 6061 was identified as a promising strategy for enhancing heat distribution throughout the PCM volume and accelerating the charging phase.

Four distinct geometric variants of the structure, differing in the degree of torsional deformation (0° , 90° , 180° , and 360°), were evaluated through simulation, along with a reference model without an embedded skeletal structure. The main evaluated output was the time required to raise the entire SAT volume to the minimum temperature of 58°C , which marks the onset of the phase transition—a key milestone in latent heat storage. The results demonstrate that all four configurations with embedded structures significantly reduced the heating time compared with the reference case. While the blank model without a structure reached the threshold temperature after approximately 1560 s, the 360° twisted configuration achieved it in just about 202.5 s. The other geometries also exhibited high performance, reaching 58°C in 213.5 s (180°), 216.0 s (90°), and 217.0 s (0°).

Supplementary analyses revealed that torsional modification not only affects the heating rate but also influences the temperature distribution within the PCM volume. Thermal maps from various cross-sections (XZ and YZ planes) demonstrated that configurations with greater torsion enable deeper spatial penetration of heat, a more uniform thermal energy distribution, and the minimization of cold zones. The visualization of surface temperatures on the structures confirmed that higher torsion resulted in higher local surface temperatures, indicating an increased instantaneous energy flux into the SAT. This observation was supported by quantitative heat flux data: the 360° configuration reached a thermal transfer rate of 9.596 W, followed by 8.995 W (180°), 8.849 W (90°), and 8.799 W (0°). The reference model without a structure yielded only 1.168 W, indicating significantly lower heat transfer efficiency into the PCM.

Despite the enhanced performance in terms of heat transfer and faster heating associated with higher torsion, a slight increase in the maximum temperature within the SAT was observed, suggesting the presence of increased thermal gradients. This phenomenon must be considered in the design of systems requiring high thermal homogeneity, such as those intended to prevent localized degradation of PCM or structural materials.

Based on the findings, it can be concluded that geometric optimization of TPMS structures—particularly through torsional deformation—represents an effective and viable approach for enhancing the performance of phase change thermal energy storage systems. The results demonstrate that the shape and spatial arrangement of the metallic insert are just as critical as its mere presence. From an application standpoint, this opens new opportunities for customized 3D-printed structures tailored to specific operational conditions and performance requirements. In the broader context of solar energy utilization, the demon-

strated improvements in charging time and heat distribution position the investigated TPMS-based design as a promising candidate for latent heat storage units operating in solar thermal systems. The efficient and compact integration of these structures can support thermal buffering and load shifting in domestic or small-scale industrial solar applications, thereby contributing to more reliable and flexible use of renewable solar resources. In addition to solar thermal energy systems, the results of this study can be extrapolated to other application domains that require efficient and compact thermal regulation. For example, the enhanced heat transfer dynamics demonstrated by the torsionally modified TPMS structures are particularly beneficial in electronics cooling, where localized heat buildup must be rapidly dissipated, and in HVAC systems, where smart thermal buffering can help stabilize temperature fluctuations. The adaptability of the gyroid design and the scalability of additive manufacturing support the integration of this concept into modular systems across a wide range of operating temperatures and spatial constraints.

From an industrial point of view, the use of aluminum alloys such as Al 6061 is fully compatible with modern additive manufacturing processes, particularly selective laser melting (SLM), which allows for the fabrication of complex geometries like the sheet-gyroid with high precision. Regarding geometry, the proposed wall thickness of 0.5 mm lies near the lower limit of manufacturability for most metal AM systems, but remains feasible under controlled conditions. The torsional deformation introduced by the twist operation increases surface complexity, which may affect powder removal and support strategies during fabrication. Therefore, while technically achievable, such manufacturing requires careful orientation planning, laser path optimization, and possibly segmentation of the geometry for post-assembly. These considerations are critical for translating simulation concepts into physical prototypes and will be addressed in subsequent experimental work. The geometric flexibility offered by AM enables design-driven performance optimization without the limitations of traditional casting or machining. Furthermore, sodium acetate trihydrate is a commercially available and chemically stable PCM that has already found practical use in low- to medium-temperature thermal storage. Its well-documented safety, affordability, and recyclability make it suitable for large-scale deployment. Together, the choice of material and manufacturing method supports the practical realization of the proposed thermal storage concept in various industrial and residential energy systems.

It should be acknowledged that the current study does not include direct validation against analytical or experimental benchmarks. Due to the exclusion of latent heat modeling, the simulation represents a transient conduction problem in a complex 3D domain. While analytical or semi-analytical solutions exist for canonical cases, the highly intricate geometry of the embedded TPMS and the inclusion of conjugate heat transfer effects prevent straightforward comparison. Therefore, the presented results are intended for comparative evaluation across the investigated geometries rather than for absolute thermal prediction. In future work, experimental validation using 3D-printed gyroid structures and embedded thermocouples will be conducted to confirm the observed numerical trends.

Future research should focus on the experimental validation of the simulation results, particularly in the areas of the cyclic stability, repeated melting, and solidification behavior of PCM, and verification of thermal field predictions via thermographic analysis. Further development could also explore the integration of torsionally modified structures with multi-material inserts, gradient geometries, or the design of hybrid storage systems employing multiphase mixtures.

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