A Comprehensive Review of Miscellaneous Heat Transfer Enhancement Designs of Phase Change Material Integrated Heat Exchanger

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Abstract:

This comprehensive review focuses on the specific investigation of heat transfer enhancement with a primary objective of achieving more uniform melting/solidification within heat exchangers employing phase change materials (PCM). The paper begins highlighting the crucial role of heat exchangers and introduces the unique studies associated with achieving uniform phase changes. The main body of the paper seeks to explore heat transfer enhancement strategies, particularly within shell-and-tube structures and plate heat exchanger (PHE). Moreover, the study discusses the role of these strategies in achieving more uniform melting/solidification in phase change materials. Special attention is applied to examining advancements and methodologies aimed at optimising heat transfer for improved performance in applications requiring control of phase changes. As a new contribution, the paper examines the application of PCM in PHEs, providing insights into their effectiveness in facilitating more uniform phase change and PCM usage in these heat exchangers. Notable improvements were also observed from literature studies with specific fin geometries, where longitudinal and spider-web-like structures reduced solidification times by as much as 63% and enhanced melting uniformity by 47.9%. Operational parameter optimization, particularly through increasing heat transfer fluid (HTF) inlet temperature by 10°C, resulted in a 35% decrease in charging time, underscoring the importance of temperature control in Thermal energy storage (TES) applications. The literature studies mentioned that enhanced PHE configurations, including corrugated and zigzag plate designs, have demonstrated up to nine times faster charging and discharging rates compared to traditional concentric systems due to increased surface area. This study provides essential insights for researchers and practitioners aiming to enhance heat exchanger designs for critical applications in thermal energy storages.

Keywords: Phase change materials, Shell-and-tube heat exchanger, Energy storage, Plate heat exchanger, Heat transfer enhancement.

Abbreviations:

HTF	heat transfer fluid
LHTES	latent heat thermal energy storage
PCM	phase change material
PHE	plate heat exchangers
TES	thermal energy storage

1. Introduction

Economic progress, rapid industrialisation, population growth, and increasing comfort standards contribute to rising global energy demand and fossil fuel consumption. This escalation in fossil fuel use for energy production leads to an increase in greenhouse gas emissions. Consequently, to maintain economic and environmental feasibility, there are incentives for effectively utilising of various renewable energy sources. Another critical consideration is the storage of this energy in forms that are quickly and conveniently convertible into necessary formats. Energy storage is essential for maintaining energy balance and improving the performance and reliability of future energy systems. It can also help mitigate one of the biggest challenges of renewable energy sources [1].

PCMs are substances that undergo transitions between different phases, typically during the absorption or release of heat. The significant advantage of these materials lies in their large surface area, which increases the efficiency of energy transfer and phase change processes. This characteristic allows for wider interaction between the material and its surroundings. The larger surface area of these materials helps them a more uniform behaviour during the phase change. This is especially useful in heat storage applications. Furthermore, the additional surface area allows the material to respond more uniform temperature variations. This responsiveness is important for effectively maintaining and controlling desired conditions, making it valuable in various practical applications. In summary, the large surface area in PCMs not only optimises energy transfer but also enhances their versatility in meeting specific thermal management requirements.

TES systems are classified into sensible, latent, and thermochemical methods based on the energy stored per unit volume. Sensible heat storage is popular because its low cost and commercial-scale use, but it suffers from a major disadvantage like low energy density [2]. On the other hand, the latent heat storage method, utilising PCMs, allows heat storage at a constant temperature during phase change and can hold higher energy storage density in smaller volumes compared to the sensible heat storage. PCMs also enable the isothermal transfer of thermal energy throughout the phase change process [2].

Historically, the first application of PCMs dates back to the 1800s, when British railways to keep passengers' seats warm on trains during cold winter months [3]. The world's first experimental application was pioneered by Telkes, who aimed to use PCM for buildings. In the work, the researcher led the design and construction of a solar energy laboratory which incorporated several hydrate-based storage systems[4]. Nowadays, PCMs are preferred in many areas, ranging from heating and cooling to spacecraft thermal control applications, with the application areas illustrated in Figure 1. The information presented in Figure 1 is synthesised from reference [5].

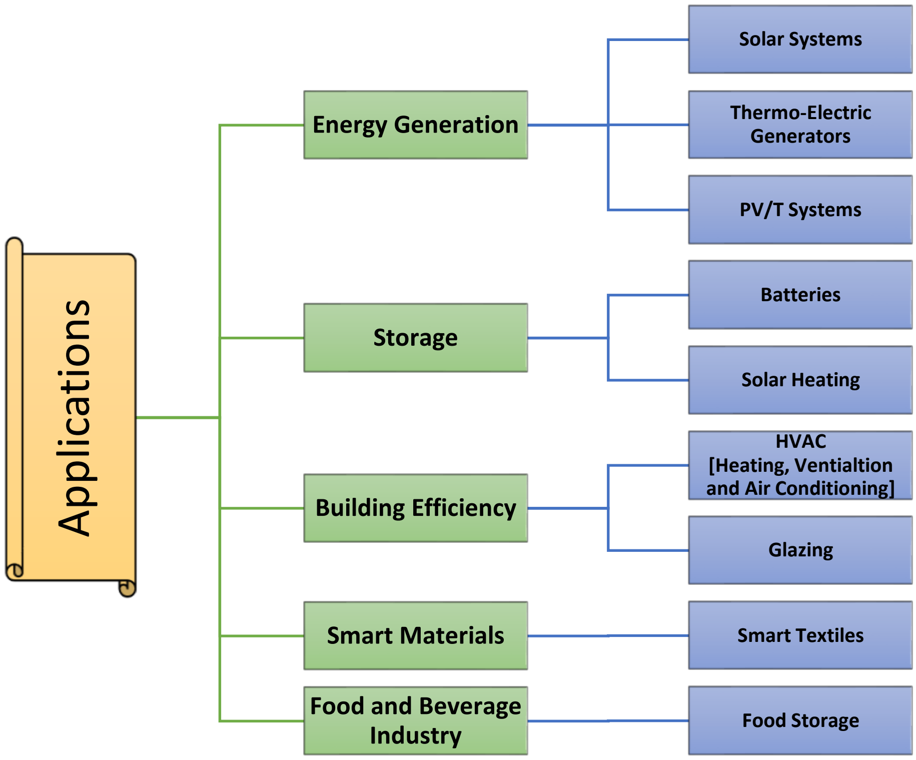

Figure 1. Application of PCMs in various area [5]

In any PCM latent heat storage system, three fundamental components are necessary: the heat storage material with the desired operating temperature range, the container for storing this material, and the heat exchangers that will facilitate the necessary thermal transformations within the system [6]. Among these components, heat exchangers are particularly crucial. This is because PCMs inherently lack the thermal conductivity required for effective heat transfer between the heat exchanger and the heat transfer fluid. However, this limitation, which leads to slow thermal responses of PCMs, can be offset by employing a suitably designed heat exchanger.

As industries seek energy-efficient and sustainable solutions, the investigation into heat transfer enhancement for uniform phase changes becomes as a critical area of research. The primary challenge in PCM-based heat exchangers is overcoming PCMs' low thermal conductivity, which limits heat transfer efficiency. This review addresses these challenges by examining different design approaches aimed at enhancing PCM heat transfer within heat exchangers.

2. Scope of This Review

PCMs have revealed unique advancements in thermal management systems, particularly in heat exchangers. The integration PCMs into heat exchangers has opened new energy efficiency and sustainable thermal control ways. As mentioned before, these advancements are not just confined to enhancing the core functionality of heat exchangers but also extend to various applications ranging from industrial processes to residential heating and cooling systems.

PCM-based heat exchangers can be categorised based on structural configuration, application purposes, or system's operating temperature. This review aims to provide valuable insights into the current state of knowledge, technological developments, and potential ways for further advancements in the search of optimal heat exchanger designs for applications requiring precise control over PCM melting and solidification processes. The advancements made in the field of PCM-based heat exchangers in recent years provide a detailed review of the influential operational and design parameters that are crucial to the efficiency of energy storage systems. The study shows an extensive analysis of how these parameters impact the performance and efficiency of thermal management solutions. The paper further provides a systematic classification of heat exchanger types. This sets the stage for a thorough discussion of various operational and design factors that play a significant role in optimising the performance of PCM-based heat exchangers, thereby contributing to the advancement of sustainable energy technologies. The scope of this study is shown in Figure 2.

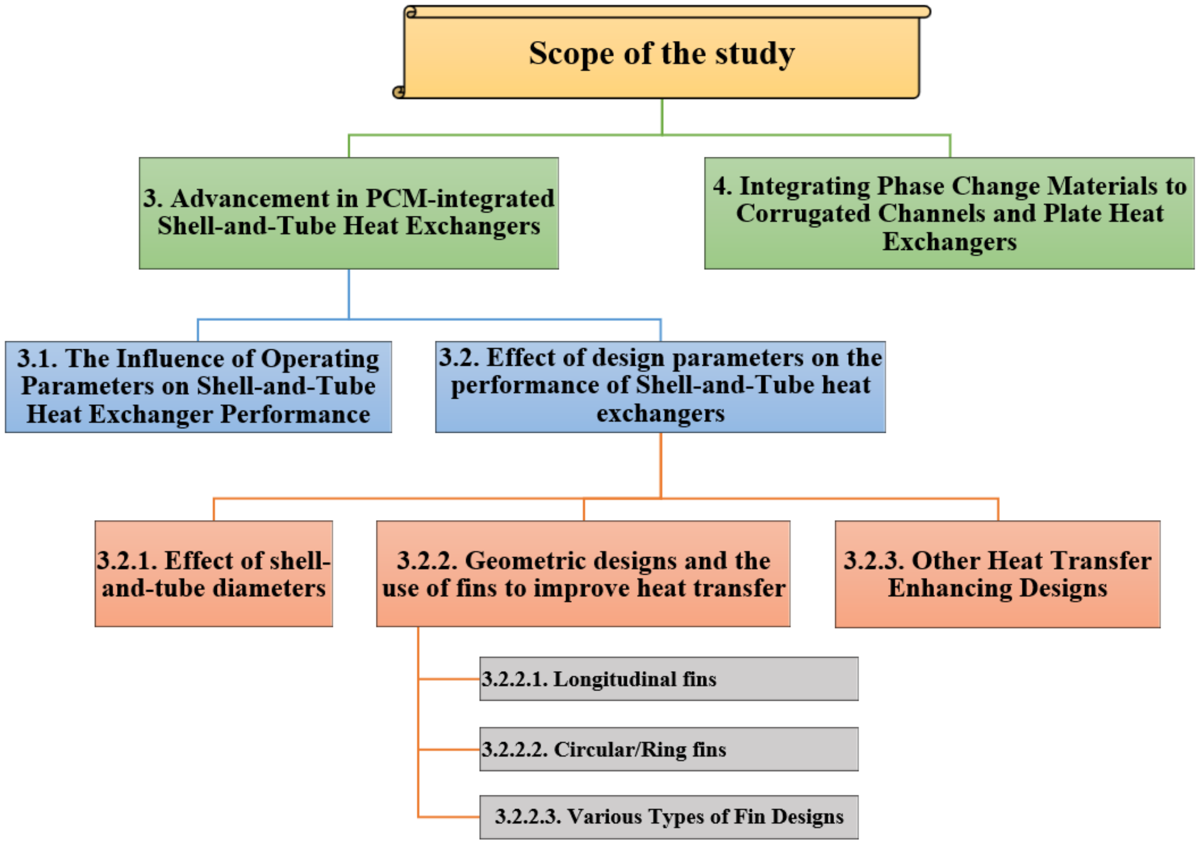

Figure 2. The scope and structure of the present review work with relevant sections

There have been many review papers related to the PCMs and each exploring various aspects of their applications and performance enhancements. Kalapala and Devanuri [7] reviewed different operating conditions and design parameters critical for PCM-based heat exchangers. They investigated the shell-and-tube and triple concentric tube configurations highlighting heat transfer techniques utilized in both types of exchangers. They evaluated the key factors such as fluid flow rates, material properties, and thermal conductivity to optimize the design process. Roy and Pant [8] discussed advancement of PCM properties to improve heat transfer performance. Hamidi et al. [9] examined the current studies and developments in computational techniques used to simulate heat transfer within latent heat TES systems incorporating metal foams to enhance the thermal conductivity of PCMs. Their study addressed the complexities inherent in such systems and focused on recent developments aimed at improving accuracy and efficiency. Huang et al. [10] provided a comprehensive summary and comparison of the thermal properties associated with various encapsulation methods for PCMs.

Saqib and Andrzejczyk [11] examined some methodologies to enhance heat storage utilizing PCMs and various extended surface configurations designed for optimal PCM performance. They reviewed innovative techniques and materials that improve the efficiency and applicability of PCM-based TES systems as well. Ma et al., [12] reviewed various fin geometries, such as rectangular, annular, and spiral fins, and compared their effectiveness in PCM applications. Y. B. Tao & He [13] focused on the advancements in PCMs and techniques to enhance the performance of TES systems. They evaluated new approaches of literature studies aimed at improving the efficiency and reliability of PCMs in storing and releasing thermal energy. Zalba et al. [14] examined PCMs and specifically addressed the challenges related to their long-term stability and encapsulation. Various issues related to the durability and containment of these materials were thoroughly discussed and analysed within the scope of the study. Q. Li et al. [15] reviewed some techniques related to heat transfer and performance enhancement in existing literature, particularly their characteristics and practical application within shell and tube heat exchangers. Saha et al. [16] conducted a comprehensive review of TES systems using PCMs in building and tube designs, covering testing methodologies, applications, and heat transfer enhancement methods. Diaconu et al. [17] investigated recent techniques including both passive and active methods for improving heat transfer efficiency in PCM-based heat storage systems. Ghoghaei et al. [18] extensively examined the applications of micro- or nano-encapsulated phase change slurries and impact of them on TES and heat transfer enhancement. Togun et al. [19] reviewed the practical use of LHTES systems with highlighting the transformative potential of LHTES systems in various applications and provided insights into their effectiveness and versatility in real-world scenarios. The authors stated that hybrid systems incorporating multiple PCMs, heat pipes, and nanofluids can offer enhanced thermal management. Zayed et al. [20] focused on different designs of PCM-finned storage systems and analysed their key parameters to determine the optimal design to obtain the best melting and solidification rates of PCM. The study investigated various design configurations to understand how specific parameters effect the performance of these systems in managing PCMs. Yang et al. [21] provided an overview of PCMs by discussing their properties, advantages, and disadvantages. Their study also covers the heat transfer modelling and enhancement techniques used during the melting and solidification processes of PCMs. Radomska et al. [22] presented and organized the existing knowledge on heat exchangers employed in LHTES systems. The study investigated the operational parameters that impact the phase change duration of phase change materials within these heat exchangers.

Table 1 summarizes some of recent review papers. The current study expands on this literature by covering a wide range of heat transfer enhancement strategies for shell-and-tube heat exchangers. As a novel contribution, it also examines the application of these strategies in plate heat exchangers, which offer a larger heat transfer surface area and improved thermal performance.

Table 1. Some recent review papers related to PCMs.

Study		Focuses			
	Year	**Shell and Tube Heat Exchangers**	**Fin Designs**	**Gasketed Plate Heat Exchangers**	**Main Focus**
Kalapala and Devanuri [7]	2018	✓	✓	✗	Shell and tube type heat exchanger
Zayed et al. [20]	2020	✓	✓	✗	Shell and tube exchanger and fin designs
Khademy et al. [23]	2022	✓	✓	✗	Hybrid with nanoparticles
Raut et al. [24]	2022	✓	✓	✓	Solar integration
Sagip and Andrzejczyk [11]	2023	✓	✓	✗	Kinds of PCM and extended surfaces
Mahmoudinezhad et al. [25]	2023	✓	✗	✓	High-temperature heat exchangers
Diaconu et al. [17]	2023	✓	✓	✗	Passive and active techniques
Rashid et al. [26]	2024	✓	✓	✗	L-shaped fins
Togun et al.[19]	2024	✓	✓	✗	Hybrid designs
Salami et al. [27]	2024	✓	✓	✗	Fin placement optimization
Tian et al. [28]	2024	✓	✗	✗	Optimized Heat transfer interface
This work	2025	✓	✓	✓	Shell and tube exchanger, corrugated channel and plate heat exchanger

3. Advancement in PCM-integrated Shell-and-Tube Heat Exchangers

Having reviewed PCM properties and their integration challenges, this section explores various heat exchanger configurations designed to optimize PCM performance. This section discusses common designs, such as shell-and-tube and plate heat exchangers, and compares their effectiveness in PCM applications. Shell-and-tube heat exchangers commonly preferred types in LES systems due to their compact structure and high heat transfer efficiency, consisting of two concentric pipe structures [25,29]. These heat exchangers are categorised into three types according to the PCM arrangement and the number of tubes: cylindrical, tubular, and multi-tube models. In the tubular model, the HTF flows through the inner tube, which is situated within the PCM in the shell part of the heat exchanger, as illustrated in Figure 3. Conversely, in the cylindrical model, the PCM is contained within the inner tube while the HTF flows through the shell. Esen et al. [30] conducted a theoretical study comparing both models, considering various PCM types and geometric parameters. The tubular model facilitates faster melting due to the thinner PCM layer, allowing better heat penetration from the HTF. The multi-tube model is another variation of the shell-and-tube heat exchanger, featuring multiple inner tubes for the flow of HTF within the shell. Agyenim et al. [31] performed an experimental analysis of a shell-and-tube storage system using Erythritol (with a melting point of 117.7°C) as the PCM, demonstrating the impact of this model on heat transfer and melting. Their findings indicated that an increased number of inner tubes (four tubes) enhanced heat transfer and decreased the melting time from 8 to 5 hours, compared to the cylindrical model, which utilised a single inner tube.

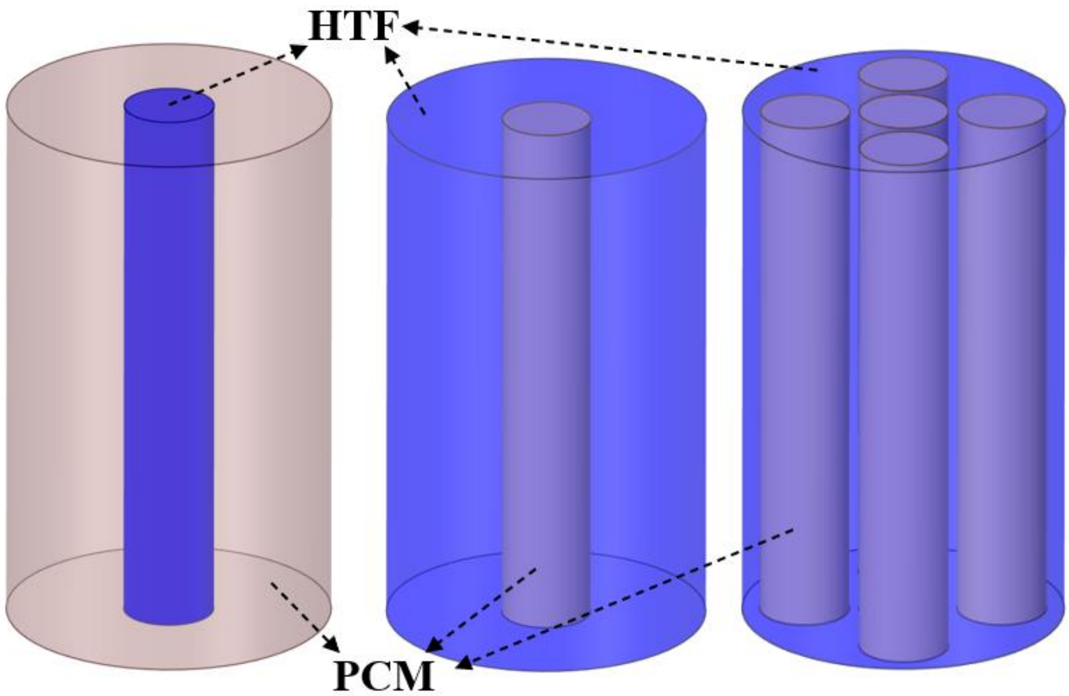

Figure 3. Type of Shell-and-Tube heat exchangers: a) cylindrical model, b) tubular model, c) multi-tube model (adopted from [32])

3.1. The Influence of Operating Parameters on Shell-and-Tube Heat Exchanger Performance

The duration required for phase change (melting and solidification) processes is predominantly influenced by two key factors: the mass flow rate and the inlet temperature of the heat transfer fluid. They have significantly impact on the heat transfer as they determine the overall heat transfer coefficient between the HTF and the PCM. Depending on the cooling or heating application, a change in mass flow rate and inlet temperature can raise the temperature difference, thereby increasing the heat transfer rate, consequently reducing the total melting and solidification times critical for energy storage and recovery. This section explores how variables like mass flow rate, inlet temperature, and Reynolds and Stefan numbers affect heat transfer rates and phase change efficiency.

Y. Cao & Faghri [33] conducted the first parametric study on the performance of PCM-based heat exchangers. They examined the melting interface for different Reynolds numbers, and they found an increase in the melting interface with higher Reynolds numbers, indicating that mass flow rate increment enhances the heat transfer. W.-W. Wang et al. [34] determined that an increase in mass flow rate does not have as significant an impact on storage capacity as the inlet temperature. However, they reported that heat transfer increases with increase in mass flow rate, thus reducing melting and solidification times. They also identified that the temperature change in PCM during the charging and discharging processes occurs in three stages: a rapidly changing period, a slowly changing period, and an even slower changing period. These three periodic conditions are also mentioned in a numerical study by [35] using water and air as HTF.

Nene & Ramachandran [36] conducted an experimental study of a system using a shell-and-tube heat exchanger filled with PCM to ensure the availability of hot water during the night. Their study concluded that the HTF mass flow rate strongly affects the charging and discharging processes of the PCM. They found that an increase in the mass flow rate of the HTF leads to a higher equilibrium temperature, while a HTF with a lower mass flow rate resulted in less PCM charging at a lower equilibrium temperature. Therefore, they suggested that an optimal amount of HTF is required for the system. Trp et al. [37] investigated the impact of the inlet temperature of the HTF on both stored and recovered energy within a shell-and-tube TES system during the phases of melting and solidification. Their results showed a direct relationship between the temperature difference encompassing the phase change temperatures of the PCM and the inlet temperature of the HTF and the total energy stored as well as energy density. In particular, they observed that elevating the temperature difference between the melting and solidification points of the PCM and the inlet temperature of the HTF leads to a proportional increase in both the overall stored energy and energy density. This shows the importance of optimising the HTF inlet temperature to enhance the efficiency and performance of TES systems.

The same findings were also reported by Fath [38]. Consequently, it is possible to say that an increase in the inlet temperature and mass flow rate of HTF leads to an increase in the amount of energy stored due to the increased temperature difference and heat transfer coefficient. Hosseini et al. [39,40] observed that natural convection dominated during the melting of the PCM by studying the melting behaviour of phase-change material within a shell-and-tube heat exchanger. They suggested that the rate of heat transfer and the duration required to complete the melting process were directly dependent on the inlet temperature of the HTF. In their work, increasing the inlet temperature of water from 70°C to 80 °C reduced the total melting time by 37%. In a similar study, Avci & Yazici [41] observed an asymmetric radial temperature field developing towards the upper parts of a shell-and-tube latent heat storage system, resulting in the upper region reaching melting temperatures earlier than the lower region. These results indicate that changes in the inlet temperature of the HTF can significantly affect the melting and solidification behaviour. Jesumathy et al. [42] studied heat transfer and temperature distribution in PCM during phase change and reached a conclusion supporting other studies. They noted that during melting, PCM moved from the top to the bottom of the storage system, and during solidification, it moved from the bottom to the top along the axial distances. Seddegh et al. [43] analysed the thermal behaviour of horizontally and vertically positioned shell-and-tube latent heat storage units and reported that increasing the inlet temperature significantly reduced the total melting time for both storage positions, but increasing the mass flow rate did not produce noticeable results in the melting and solidification processes. Their findings revealed that during the charging phase in a horizontal orientation, convective heat transfer notably influences the melting of the upper section of the solid PCM, while its impact decreases for the lower half. Conversely, in the vertical orientation, convective heat transfer remains consistently effective throughout the charging process. However, in the discharging phase, there are no noticeable thermal differences between horizontal and vertical systems. Furthermore, they highlighted that the horizontal orientation exhibits superior thermal efficiency during charging, particularly evident during part-load energy charging.

Kousha et al. [44] studied the effect of inclination angles ranging from 0° to 90° on the melting and solidification performance of the storage system. They found that the melting process accelerated as the inlet temperature increased and the total melting time decreased. Additionally, they observed that the melting rate in the initial half of the process was higher in horizontal systems compared to other inclination angles. Lacroix [45] investigated the phase change of PCM in a shell-and-tube latent heat storage system where the shell was filled with PCM and the HTF flowed through the inner tube. He determined that the stored energy increased linearly with the increase in the inlet temperature and mass flow rate of HTF. Akgün et al. [46] reported that in a latent heat storage system using paraffin as the PCM, the melting time decreased with increased inlet temperature and mass flow rate of HTF due to the increased enthalpy flow. However, they suggested selecting lower mass flow rates in TES units requiring energy efficiency, because higher mass flow rates require higher pumping power. Seddegh et al. [47] observed that the phase change performance of a vertical cylindrical shell-and-tube latent heat storage unit largely depended on the inlet temperature of HTF. However, the mass flow rate did not significantly impact the total heat transfer from the HTF to the PCM, thus minimally affecting on the melting and solidification processes. Gong & Mujumdar [48] investigated the effect of supplying hot and cold HTF from different ends in a shell-and-tube TES unit by considering variations in mass flow rate and inlet temperatures. They observed that supplying the hot and cold fluids from the same ends of the heat exchanger and increasing the mass flow rate enhanced the energy storage and recovery process. In solar collectors, the phase change process in Phase Change TES units occurs under unstable inlet boundary conditions due to variations in solar radiation intensity. Tao and He [49] analysed the effect of unstable inlet conditions of the HTF on the phase change process. An increase in the inlet temperature and mass flow rate of the HTF reduced the time required for the complete melting of the PCM. Agarwal & Sarviya [50] conducted an experimental analysis of a shell-and-tube latent heat storage unit used in a solar dryer employing air as the HTF for drying food products during hours with no sunlight or very low solar energy intensity. They observed that the heat transfer during melting and solidification was affected by natural convection and conduction, respectively. And they mentioned that melting occurring faster at the top of the storage unit. Furthermore, they concluded that an increase in inlet temperature reduced the melting time, and an increase in mass flow rate decreased the solidification time. They also determined that the time required during solidification in the latent heat storage unit was longer than melting due to the low heat transfer rate between the PCM and HTF.

Murthy et al. [51] analysed the thermal performance of the selected HTF Therminol®-55 utilizing shellac wax as a bio-PCM instead of the conventional PCM in their vertically oriented shell-and-tube latent heat storage unit designed for medium-temperature solar energy applications. They determined that increasing inlet temperature and mass flow rate of the HTF reduced the total melting time by 42.2% and 43.6%, respectively. However, they found that further increment in mass flow rate adversely affected the overall heat transfer coefficient and did not significantly improve the melting time. They determined that during solidification process and the dominant mode of heat transfer was conduction and changes in mass flow rate had no noticeable impact.

G. Shen et al. [52] analysed the impact of variations in the operating parameters of the HTF on the energy storage and recovery performance in a vertically oriented shell-and-tube latent heat storage system with different inclined lateral surface angles (0° to 7°). They observed that an increase in the difference between the inlet temperature of HTF and the average melting temperature of PCM significantly reduced the duration of both melting and solidification processes. Furthermore, they found that an increase in Reynolds number decreased melting and solidification times in the laminar and transitional flow regions but had a negligible effect when the turbulent heat transfer fluid flowed. In order to create an optimum design for a shell-and-tube thermal energy storage unit, [53] conducted a numerical study of a dimensionless parameter called energy efficiency and represented the ratio of stored energy to the energy consumed in pumping the HTF They found that this dimensionless parameter was minimally affected by increases in the inlet temperature of HTF, which initially increased but then decreased with rising Reynolds numbers. The Stefan number, positively correlated with the temperature gradient between the PCM and the HTF, implies that higher Stefan numbers lead to faster melting of the PCM with creating more significant temperature gradients [54].

Esen et al. [30] studied the melting behaviour of four different PCMs in a latent heat storage tank under various operating conditions. They found an increase in the Reynolds number reduced the melting time for all PCMs. Ismail & Abugderah [55] examined the impact of phase change temperature range, Reynolds number, and Stefan number on the performance and design of a vertically positioned shell-and-tube thermal energy storage system. They stated that increasing Stefan and Reynolds numbers could improve the thermal performance of the system. An increase in the Stefan number led to better heat transfer and increased the total amount of energy stored in the system due to the resulting more considerable temperature difference between the HTF and the PCM. Similarly, they found that high Reynolds numbers for convective heat transfer positively affected energy dispersion. The phase change temperature range did not have as significant an impact on system performance as the Reynolds and Stefan numbers.

Sari & Kaygusuz [56] observed that doubling the Reynolds number, dependent on mass flow rate and temperature difference resulted in a 28% reduction in total melting time due to the increased temperature gradient in a LES using a eutectic mixture of lauric and stearic acid as PCM. They also found that the increase in the Stefan number, associated with the increased temperature gradient, had a more significant impact on the melting time of PCM at higher positions than lower ones. However, these parameters did not affect the total solidification time as much as the total melting time.

Fang et al., [57] designed for radiant cooling applications in buildings under various operating conditions analysing a latent heat thermal energy storage unit filled with four different PCMs of varying thermal conductivities and they observed that an increase in Reynolds number monotonically decreased the effective storage rate for low thermal conductivity PCM composites. In contrast, for high thermal conductivity PCM composites, the effective storage rate peaked at a Reynolds number of 4000. They also reported that an increase in Reynolds number negatively affected the storage capacity as the mass flow rate increased.

In addition to traditional shell-and-tube heat exchanger models, PCM is placed inside the inner tube in some applications to increase the heat transfer area and thus achieve higher melting and solidification rates. Y. B. Tao et al. [58] compared two models under the same conditions, one with PCM in the shell and the other with PCM in the inner tube. They observed that using PCM in the inner tube increased the melting rate compared to its use in the shell, regardless of whether natural convection was considered or not. For similar models, G.-S. Han et al. [59] studied the melting behaviour of horizontally and vertically positioned shell-and-tube heat exchangers, also considering the direction of HTF inlet into the heat exchanger. They found that horizontal and vertical models with PCM in the inner tube and HTF entering from the bottom had nearly the same melting times. Moreover, this model reduced the melting time by 23.5% compared to the model with PCM in a horizontally positioned shell.

Longeon et al. [60] presented an experimental and numerical analysis examining the effect of the HTF injection direction on the melting and solidification processes. Their studies found that natural convection played a significant role during melting and that injecting the HTF from the bottom created a complex situation for melting. Therefore, they suggested injecting the HTF from the bottom during solidification and the opposite during the melting process. Xiao and Zhang examined the effect of various parameters on the thermal performance of a shell-and-tube latent heat storage unit with PCM inside the inner tube [61,62]. They determined that increment in the mass flow rate and inlet temperature of HTF effectively enhanced heat transfer during melting and solidification. However, they noted that an increased mass flow rate during solidification led to lower exit temperatures of the HTF, which was not beneficial for use in latent heat storage units. Table 2 presents other researchers' works about the impact of operating parameters on the performance of shell-and-tube heat exchangers.

As seen above increasing the mass flow rate in PCM systems generally accelerates heat transfer, allowing faster PCM melting and solidification. However, there exists an optimal flow rate where energy transfer is maximized without excessive pumping power requirements. Inlet temperature has a significant impact on PCM performance. Higher HTF inlet temperatures increase stored energy by raising the temperature gradient, leading to quicker melting and solidification of PCM. Reynolds and Stefan numbers are key indicators of the convective and conductive behaviours within PCM systems. Higher values improve energy transfer efficiency, but the optimal range must be determined based on the PCM type and heat exchanger configuration.

Table 2. Impact of operating parameters on the performance of Shell-and-Tube heat exchangers

Study	**Material**	**Configuration**		**Method**		**Findings**
		Horizantal	**Vertical**	**Numerical**	**Experimental**	
Ezan et al. [63]	Water	✓	✗	✗	✓	The temperature of the HTF inlet exerts a more significant influence on both melting and solidification durations compared to the mass flow rate.
Kibria et al. [64]	Paraffin Wax	✓	✗	✓	✓	Determined that inlet temperature and mass flow rate increment slightly increase the heat transfer rate, resulting in reduced melting and solidification times.
Rathod & Banerjee [65,66]	Paraffin	✗	✓	✗	✓	It has been observed that a reduction in the inlet temperature and mass flow rate of the HTF leads to an increase in the total melting time of PCM. Among these factors, the inlet temperature appears to have a greater influence on the duration of PCM melting compared to the mass flow rate.
Y. Wang et al. [67]	Erythritol	✗	✓	✗	✓	Found that free convection plays an important role in the melting behaviour, and changes in mass flow rate and inlet temperature can significantly increase the heat transfer in PCM.
Y.-B. Tao et al. [68])	Molten Salt	✓	✗	✓	✗	Increasing HTF inlet temperature from 1,070 K to 1,110 K and a doubling of the flow rate resulted in approximately 53% and 45.4% reductions in melting time, respectively.

3.2. Effect of design parameters on the performance of Shell-and-Tube heat exchangers

In the investigation for efficient TES, the role of design parameters should be considered. These parameters are essential in optimising the functionality and efficiency of PCM integrated shell-and-tube heat exchangers. PCMs need high thermal conductivity and latent heat capacity for efficient TES. However, numerous PCMs suffer from low thermal conductivity, limiting the impact of heat transfer between the heat exchanger and the HTF. Consequently, many methods have been suggested to enhance heat transfer within latent heat TES systems [69]. The following sections detail these methods. The interaction between design elements and the physical properties of PCMs determines the overall performance of TES systems. This section introduces the design parameters that affect the thermal behaviour of PCM-based heat exchangers and examines innovations aimed at maximizing energy storage.

3.2.1. Effect of shell-and-tube diameters

One method to increase heat transfer involves using different geometric designs in heat exchangers. Many researchers have considered the shell and inner tube diameters in addition to operating parameters to evaluate the overall performance of PCM-based shell-and-tube heat exchangers. Erek & Dincer [70] studied the effect of changing the shell diameter while keeping the inner tube diameter constant and determined that a smaller shell diameter resulted in faster melting and lower storage capacity. Y.-B. Tao et al. [68] performed numerical modelling on the entropy and energy efficiency analysis during the melting process of a shell-and-tube latent heat storage unit and they found that a decrease in the shell radius and the length of the storage unit increased the heat gain per volume and heat transfer rate. They also suggested that the shell radius is the most critical design parameter. Y.-B. Tao et al. [68] increased the shell radius while keeping the circular cross-sectional area between the shell and inner tube constant. They observed that this increase caused a decrease in the velocity of the HTF, and it leads to an increase in melting time and a decrease in heat transfer rate. However, they reported that a larger shell diameter could be beneficial in reducing the flow resistance of the HTF and homogenising the solid-liquid interface. Bellecci & Conti [71] studied the performance of a latent heat storage system integrated with a space-based solar receiver unit and reported that fluctuations in the exit temperature of the HTF could be mitigated with an increase in the PCM mass. They concluded that these fluctuations were reduced due to the increased shell diameters allowing a more significant amount of PCM.

Y. Cao & Faghri [33] observed that an increase in the ratio of shell radius to inner tube diameter reduced the melting time and caused a significant decrease in energy storage density. Trp et al. [37] obtained similar energy curves and reported that the outer tube diameter is a parameter that significantly affects the amounts of stored and transferred thermal energy. W.-W. Wang et al. [53] determined that this ratio increased the quantity of PCM in the tube and the thermal storage capacity. Ismail & Abugderah [55] reported that increasing the ratio of shell radius to inner tube diameter associated with increasing Reynolds and Stefan numbers reduced the melting time. Ismail & Goncalves [72] found that an increase in the ratio of the radii of the inner tube to the shell increased the complete melting and solidification times and suggested a ratio of about 4 for design purposes to achieve the highest efficiency. A similar result was obtained by Ismail & Melo [73] and they reported that an increase in this ratio led to an increase in the total melting time. Seddegh et al. [47] observed that as the ratio of shell to tube radius decreased, solidification time was reduced due to the increased heat transfer area and increasing radius ratios resulted in a higher rate of energy storage. The inner tube diameter is closely related to the flow regime of the HTF and is considered a parameter worthy of research. Liang et al. [74] proposed that a decrease in the inner tube diameter allowed the HTF to enter at lower velocities, transferring more heat to the PCM and thereby increasing the energy storage rate. In their studies, they found that inner tube diameters greater than 6 mm had a negative impact on energy storage. Guo & Zhang [75] analysed the performance of a high-temperature latent heat storage system. This system was specifically designed to integrate solar energy systems that employ direct steam generation technology. They reported that increasing the radius of the inner tube (carries the HTF) resulted in an increased heat transfer area. This increment of the heat transfer area was observed to facilitate rapid solidification. Kibria et al. [64] obtained similar results and presented that this reduction in melting and solidification times was due to the increased heat transfer area and the reduced use of PCM within the shell. Shen et al. [76] examined shell and inner tube radii changes in two separate configurations. In the first configuration, they kept the inner tube radius constant and varied the shell radius (R/r_f). In the second, they kept the shell radius constant and varied the inner tube radius (R_f_r). They observed that a rise in radius ratios increased the melting and solidification times for both configurations. Based on the evaluation of stored energy, they noted that the optimal radius ratio was around these values.

3.2.2. Geometric designs and the use of fins to improve heat transfer

The use of fins is one of the most effective and well-known methods to incorporate various fins into the PCM. This approach, which increases the contact area, improves the heat transfer between the PCM and the HTF. Materials with the highest thermal conductivity such as copper (350 W/mK), aluminium (200 W/mK), graphite foil (150 W/mK), carbon steel and stainless steel are preferred as fin materials. Various parameters such as the number of fins, fin spacing, types of fins, and fin dimensions, have been researched to improve or in other words shorten the duration of melting and solidification processes [77]. Longitudinal and circular fin types are commonly used in shell-and-tube heat exchangers and researchers have investigated different fin designs, such as plate, pin, and fractal, in subsequent studies.

3.2.2.1. Longitudinal fins

Longitudinal fins increase the surface area within PCM systems, enhancing the rate of melting and solidification. Their ease of design and manufacture make them a preferred choice in PCM-based heat exchangers. In 1985, Kalhori & Ramadhyani [78] observed that adding longitudinal fins significantly increased heat transfer rates compared to a finless situation. Castell et al. [79] studied the solidification in a latent heat storage unit and successfully increased the heat transfer using extended surface area with vertically positioned longitudinal fins on the HTF side. Shokouhmand & Kamkari [80] determined that longitudinal fins enhanced natural convection in the melted region, thus increasing the melting rate of the PCM, leading to faster melting in the upper half of the cylinder compared to the lower half. Numerous researchers have studied the effect of various parameters, such as the number of fins, fin thickness, or fin spacing, on heat transfer and have observed that system performance is strongly influenced by the geometric dimensions of the fins [81]. Velraj et al. [82] found that fins increased heat transfer and surface heat flux, with the number of fins having a more significant effect on surface heat flux by investigating fins in a latent heat storage system for solar energy applications. Ismail et al. [83] noted that fin thickness had a minor impact on solidification time in their experimental investigation of PCM solidification around a finned tube. However, the quantity of fins significantly influenced both the complete solidification process and its rate. Furthermore, they highlighted that employing fins could decrease the negative effects of natural convection during phase change.

Y. B. Tao & He [84] numerically investigated the impact of free convection in a storage system utilising a mixture of fluoride salts as the PCM. They observed the influence of fin usage on the solid-liquid interface and the homogeneity of temperature distribution within the PCM during melting. The use of fins was found to promote homogeneity during melting, but it was suggested that fin parameters should be chosen to enhance the heat storage capacity. Kazemi et al. [85] researched how changing the angle between longitudinal fins affects the total melting time, melting rate, and temperature distribution. Their study in a shell-and-tube exchanger with two and three fins found that increasing the angle between two longitudinal fins prevents natural convection, thus reducing the angle from 150° to 45° decreasing the total melting time. Increasing the angle from 60° to 120° for three longitudinal fins achieved the same effect. Yuan et al. [86] analysed the effect of different mounting angles of fins embedded within the PCM (Figure 4) at three fixed wall temperatures (60℃, 70℃, and 80℃). They observed that a fin mounting angle of 0° provided the maximum melting rate throughout the melting process, while a 45° angle did not significantly change the rate. The effect of wall temperature was determined by noting a 59.24% decrease in melting time when the temperature was raised from 60℃ to 80℃. Yu et al. [54] observed the melting behaviour for four different configurations with longitudinal fins distributed at uniform and gradient angles as illustrated in Figure 5. Gradient fins were found to increase the melting rate compared to a uniform fin distribution and created a more homogeneous temperature distribution. They also suggest a latent heat storage unit for engineering applications that uses thinner fins at the top and thicker fins at the bottom.

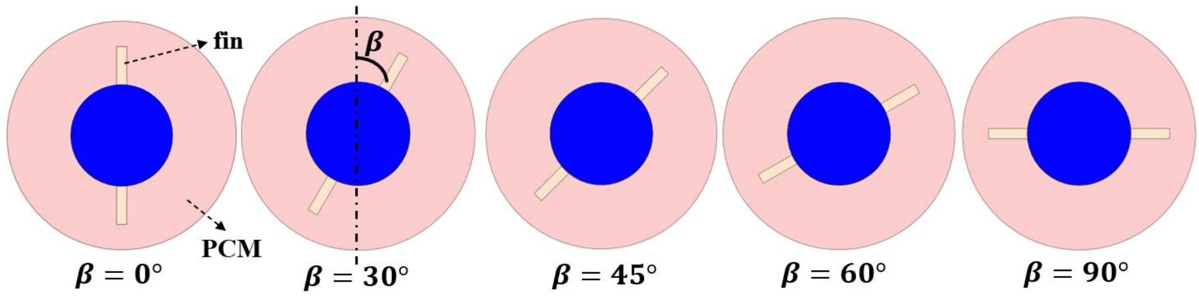

Figure 4. Positions of fins according to mounting angles (adopted from [86])

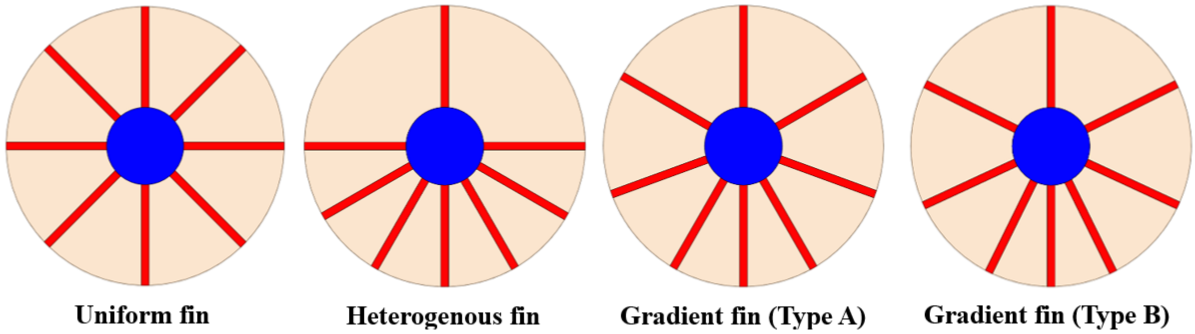

Figure 5. Schematic representation of four fin configurations (adopted from [54])

Compared to other studies, Y. Zhang & Faghri [87] utilised longitudinal internal fins in the tube through which the heat transfer fluid passed in a latent heat storage system and they observed that increasing the thickness, height, and number of fins significantly increased the volume ratio of melting. Furthermore, they presented that using internal fins was an efficient technique for enhancing heat transfer during melting, especially for heat transfer fluids with low Reynolds numbers and thermal conductivities. Studies examining the impact of longitudinal fin parameters on the performance of shell-and-tube heat exchangers are listed in Table 3.

Table 3. Enhancing thermal performance through longitudinal fin integration in shell-and-tube heat exchangers

Study	PCM	Configuration		Method		Findings
		Horizontal	Vertical	Numerical	Experimental	
Rathod & Banerjee [88]	Stearic Acid	✕	✓	✕	✓	Usage of fins at fluid inlet temperatures of 80°C and 85°C reduced the melting time by 12.5% and 24.52%, respectively. It also found that placing three longitudinal fins during the solidification process resulted in a reduction of approximately 43.6%.
Gasia et al. [89]	RT58	✓	✕	✕	✓	It was seen that better results were obtained in systems with a higher number of fins when the gap between the fins was reduced, larger fins were used, or fins made of materials with higher thermal conductivity were utilised.
X. Cao et al. [90]	Lauric Acid	✓	✕	✓	✕	They optimised the number of fins for a particular wall temperature and determined that the appropriate number of fins to compensate for the decreasing heat transfer coefficient.
Yagci et al. [91]	Paraffin	✕	✓	✕	✓	Determined that conditions with 1/3 and 0 edge lengths reduced the total melting time by 58% and 62%, respectively, compared to a finless situation.
Khan & Khan [92]	Stearic Acid	✓	✕	✕	✓	Observed that the heat transfer increase in the Y-fin configuration reduced the melting time by 50.7% compared to the λ-fin configuration and increased the total energy capacity of the LHTES by 10%.

Nie et al. [93]	Lauric Acid	✓	✕	✓	✕	Found that the lower fin design accelerated the melting of the PCM while significantly delaying the solidification. The augmentation in both the quantity and size of fins exerted a more significant influence on the solidification phase compared to the melting phase.
Tang et al. [94]	RT50	✓	✕	✓	✕	At a fin angle of 25° and a fin length of 40 mm, the time required for melting decreased significantly by 83.9%, while the thermal storage density experienced a remarkable increment, increasing by 466%. This indicates a substantial enhancement in heat transfer efficiency and thermal energy storage capabilities under these specific conditions. Compared to a finless situation, the most significant reduction in total melting time (83.9%) was achieved with lower fins,
H. Li, Hu, He, Tang, & Wang [95]	RT52	✓	✕	✓	✕	Concluded that thickening the lower fins and thinning the upper fins could effectively enhance heat transfer in the system. They achieved a 54.1% reduction in total melting time.
Modi et al. [96]	RT50	✓	✕	✓	✕	Presented that longer fins, both in number and thickness, provided more beneficial results for a fixed fin volume than shorter fins.
Z.-G. Shen et al. [97]	Sodium Nitrate	✓	✕	✓	✕	Proposed a heat exchanger design with 0° angle, 1.0 dimensionless length, and 48 fins to improve the heat transfer performance of the unit.
X. Yang et al. [98]	Paraffin	✓	✕	✓	✕	Achieved a maximum reduction of 72.85% in total melting time with an optimised condition of 52 fins compared to a 4-fin scenario.

3.2.2.2. Circular/Ring fins

Another fin geometry preferred in shell-and-tube heat exchangers to expand the heat transfer surface between the HTF and the PCM and to enhance heat transfer involves circular/ring fins. Circular and ring fins improve heat transfer by maximizing the contact area between PCM and the heat transfer fluid, which enhances thermal conductivity and storage efficiency. Choi & Kim [99] have achieved a 3.5 times greater improvement in the heat transfer coefficient with this fin type compared to the finless case. Y. Zhang & Faghri [100] have reported that using these fins can improve the situation if initial supercooling is present in the PCM. Lacroix [101] considered the phase change in a shell-and-tube heat exchanger equipped with a ring fin structure filled with PCM, addressing both axial and radial directions. The author observed an increase in the amount of heat transferred through the fins across the radial direction at moderate mass flow rates (0.0015 kg s^{-1} $\leq \dot{m} \leq$0.015 kg s^{-1})) and low inlet temperatures (ΔT_{in}= +5 K).

One of the effective geometric parameters for circular and ring fins is the number of fins. Seeniraj et al. [102] have presented a numerical model utilizing the enthalpy method to investigate the impact of different parameters on the energy storage process. They found that changes in the number of fins significantly influence the storage process, where an increase in the number and radius of fins raises the heat transfer area, therefore increasing the heat transfer rate. However, this decreases the amount of PCM in the heat exchanger or storage system, thus reducing the amount of stored energy. Hence, optimising these parameters, considering both the heat transfer rate and the stored energy, is essential.

W.-W. Wang et al. [103] suggest choosing smaller fin spacings to improve heat transfer in latent heat storage systems, noting that the effect of the fin radius becomes negligible when the fin spacing is four times larger than the inner diameter of the tube and that smaller spacings should be accompanied by increased fin radius. Some researchers have reported that increasing these parameters (number and radius of fins) can restrict natural convection. Therefore, in order to eliminate this effect, they have recommended changing operational parameters, such as the mass flow rate and inlet temperature of HTF.

D. Zhao & Tan [104] developed a numerical model for a proposed latent heat storage system integrated with a conventional air conditioning system by considering the effects of natural convection during the PCM melting process. They observed that higher HTF inlet temperatures, mass flow rates, and fin heights led to a higher PCM charge rate and a shorter total charge time. Groulx & Ogoh [105] optimised the number of fins needed for the complete melting of PCM during a 12-hour charging time in a latent heat storage system used with a solar collector by considering the HTF inlet temperature and velocity. They concluded that complete melting was achieved with 13 fins when the fluid inlet velocity was 0.6 or 1 m/s.

Paria et al. [106] have concluded that in addition to the significant enhancement in heat transfer due to an increase in the number of fins, changes in the velocity of the heat transfer fluid also impacted the melting process of PCM. In their study, increasing the number of fins and the velocity of the HTF reduced the melting time by 58% and 76%, respectively. Heat transfer occurs through conduction in solid PCM, and fins utilisation has a more important effect on solidification than melting [107]. Mosaffa et al. [108] applied an approximate analytical model to study solidification within a shell-and-tube heat storage system utilizing circular fins. They compared the solidification process of PCM in a rectangular heat storage unit with the same volume and heat transfer surface areas. They discovered that the solidification rate of PCM in the existing storage unit was higher than that in the rectangular storage unit. Kuboth et al. [109] analysed the effect of different fin arrangements on the solidification performance in a shell-and-tube latent heat storage system, keeping the number of fins and the amount of PCM constant. They achieved a 3% improvement in solidification by considering a 10% growth factor in fin density along the tube length.

Table 4. Use of circular fins in shell-and-tube heat exchangers

Study	PCM	Configuration		Method		Findings
		Horizontal	Vertical	Numerical	Experimental	
Erek et al., [110]	Pure Water	✓	✕	✓	✓	Found that stored energy increased with decreasing fin spacing, increasing fin radius and Reynolds and Stefan numbers, but beyond a Reynolds number of about 5000, the total stored energy did not change significantly.
Ermis et al. [111]	Pure Water	✓	✕	✕	✓	Achieved near-results to the total heat amount prediction with an artificial neural network model having an absolute average relative error of 5.58% and observed that adding fins increased heat transfer.
Agyenim et al. [112]	Erythritol	✓	✕	✕	✓	Observed that increased melting near circular fins but noted that complete melting was not achieved within an 8-hour charging period in their studies.
Kozak et al. [113]	Eicosane ($C_{20}H_{42}$)	✕	✓	✓	✓	Observed that providing heat to the outer tube of a latent heat storage system is appropriate for achieving high heat transfer rates.
Hosseini et al. [114]	RT50	✓	✕	✕	✓	Found that increasing fin height and Stefan number significantly reduced melting time. They also observed that increasing fin height affected the solidification process more than melting process.
Thirunavukkarasu et al. [115]	Paraffin Wax	✕	✓	✕	✓	Observed that the heat transfer rate increases with the number of fins, but no significant increase after 13 fins.

X. Yang et al. [116]	RT35	✕	✓	✓	✕	Achieved a 65% reduction in total melting time by adding fins and recommended 31 fins, 0.0248 fin thickness, and 0.0313 fin spacing for maximum heat transfer.
Cheng et al. [117]	Paraffin	✕	✓	✕	✓	Observed possible improvements in melting time with the use of fins, but changes in the mass flow rate of the heat transfer fluid had minimal impact.
Pu et al. [118]	RT35	✕	✓	✓	✕	Achieved the best improvement results in melting time by 48.8% and 38.9%, respectively, with a dimensionless fin height of 64.2% and arithmetic fin arrangement.
X. Yang et al. [119]	RT35	✕	✓	✓	✕	Achieved significant reductions in melting and solidification times with the use of finned and metal foam tubes and an increase in the mass flow rate of the heat transfer fluid.
H. Li, Hu, He, Tang, Wang, et al. [120]	Paraffin Wax	✕	✓	✓	✕	Suggested determining the optimal hole diameter as perforated circular fins increased natural convection while weakening thermal conduction; the optimum model (L=8mm, D=2mm, and n=6mm) increased the heat storage capacity by 0.21%.

3.2.2.3. Various Types of Fin Designs

As previously discussed, fins, being simple structures with low cost, are widely used in industrial products and commonly appear in longitudinal and circular types. However, in recent years, researchers have designed various fins to improve heat transfer and increase surface area in heat exchangers. New fin designs, such as tree-shaped, spider-web-like, and fractal fins, show promising improvements in PCM heat transfer. As illustrated in Figure 6, Sciacovelli et al. [121] have explored a tree-shaped fin design to maximise the performance of a shell-and-tube latent heat storage system. They selected the angles and lengths of branches in single- and double-branched configurations of Y-shaped fins as design variables to determine the optimum fin design. They observed that a fin design with a double-branching structure increased the discharge efficiency by approximately 24%. They also found that the operating duration of the system depends on the angles between branches and recommended wide angles for short operating times.

Hosseinzadeh et al. [122] examined a thermal energy storage system with tree-shaped branching fins, where TiO2-Cu nanoparticles were added to water, which is used as the phase change material to increase the system's thermal conductivity. They observed that increasing the branching angles of the fins accelerated the solidification process due to increased heat penetration. Pizzolato et al. [123] investigated the determination of appropriate fin design to reduce melting and solidification times and examined scenarios where the lower part of the heat exchanger body was densely populated with fins while only a few were placed at the top. They found that the current fin design reduced the time required to charge up to 95% of the total storage capacity by 27%. Additionally, they reported that the absence of branching or variable branch lengths resulted in an 11% decrease in solidification time.

Walter et al. [124] numerically analysed the effect of radial branches placed on broad Y-shaped longitudinal main fins on the charging and discharging process. They determined that these radial branches decreased the melting and solidification rates towards the outer shell.

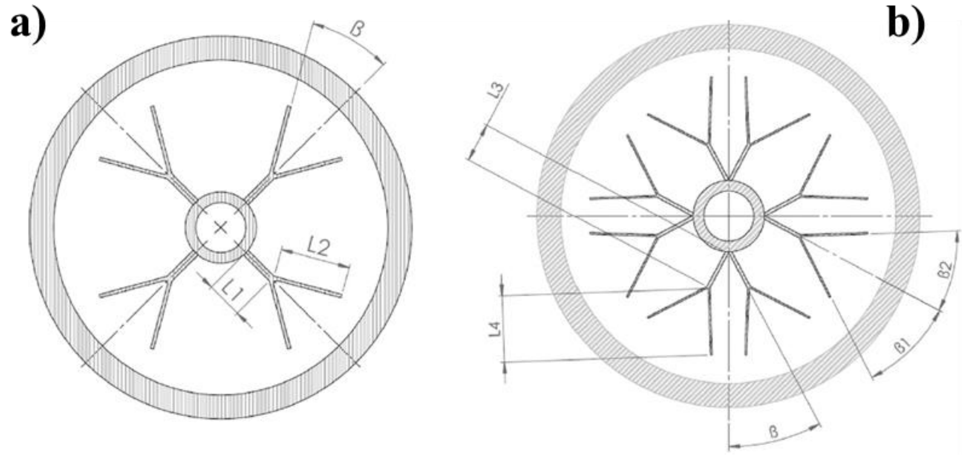

Figure 6. Fin configurations: a) single branching b) double branching [121]

Vogel & Johnson [125] analysed four different fin designs with varying tube spacings and fin widths by considering the effects of natural convection. Among the fin designs shown in Figure 7, they observed that natural convection is negligible in designs with small tube spacing and high fin ratio. It significantly affects designs with wide tube spacing and low fin ratio. Additionally, they determined that larger fin heights reduce the increase of heat transfer due to natural convection. Borhani et al. [126] focused on the melting process of the PCM in a spiral-finned heat exchanger, where the varying parameters were fin thickness and fin spacing. They found that an increase in fin spacing reduced the total melting time, but an increase in fin thickness avoided the heat transfer from the heat transfer fluid to the PCM, thereby increasing the total melting time. Positioning the heat exchanger from 0° to 90° resulted in a 56% improvement in total melting time. Therefore, they concluded that a vertical heat storage system exhibits a more acceptable performance than a horizontal heat storage system. Additionally, the researchers observed that each change in the effective parameters at a fixed PCM mass caused a change in fin height.

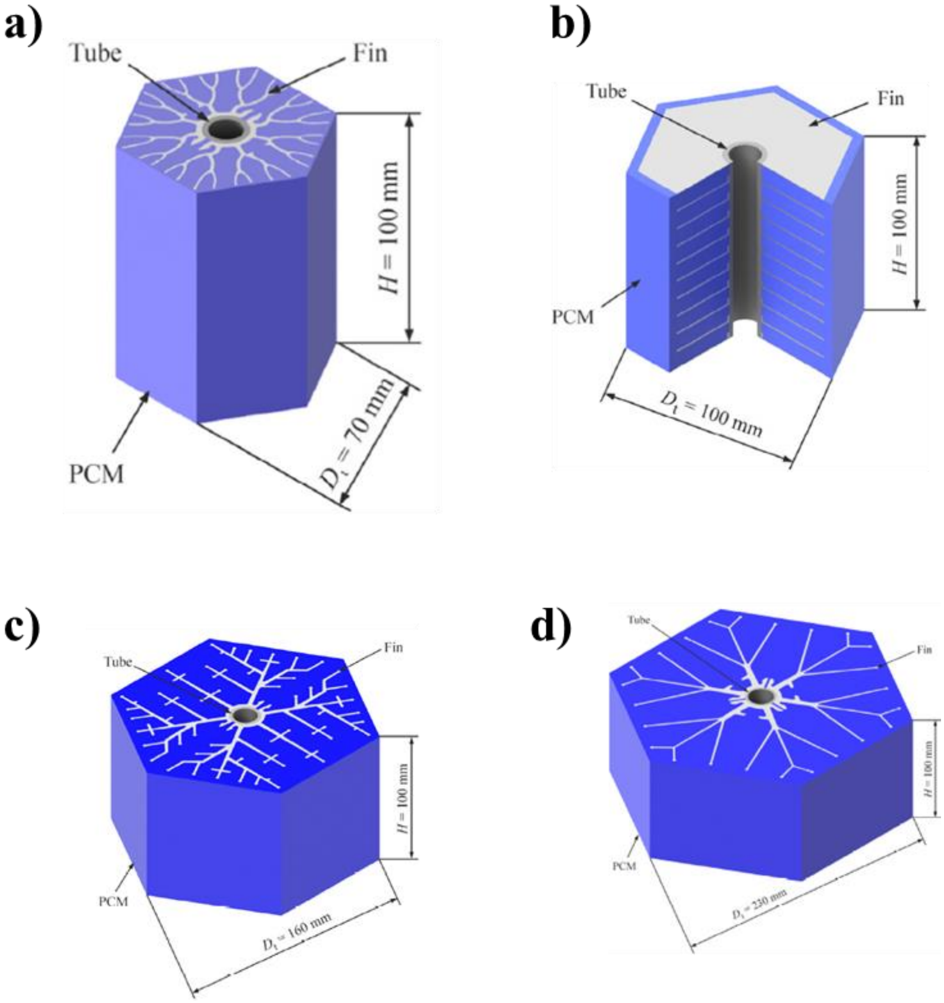

Figure 7. Geometries of four different fin designs: a) organic b) plate c) snowflake d) eco [125]

J. Li et al. [127] proposed to use a Koch-fractal fin design inspired by the geometry of the Koch snowflake in a latent heat storage system and compared the results of this fin structure with the result of radial fin designs. They observed that the Koch-fractal fins with higher fin efficiency create a more homogeneous temperature distribution during solidification compared to radial fins and facilitated faster heat flow from point to surface with this fin design.

Aly et al. [128] investigated the use of longitudinal corrugated fins installed in the inner tube to improve the solidification rate of PCM by using numerical modelling to study the effects of the number of corrugations and their height for each of these fins. Figure 8 shows the varying numbers of corrugations and height values per fin. They discovered that the existing design decreased solidification time by 30-35% when compared to a conventional straight longitudinal fin configuration. This improvement suggests a significant enhancement in efficiency, offering notable time savings during the solidification process. They also found that the solidification time decreased with increased fin length and the number of corrugations or height per fin. Additionally, the researchers noted that if these fins are used, it is recommended to minimize the number of corrugations per fin and position the fins close together. The average distance between adjacent fins should approximate the height of the corrugations.

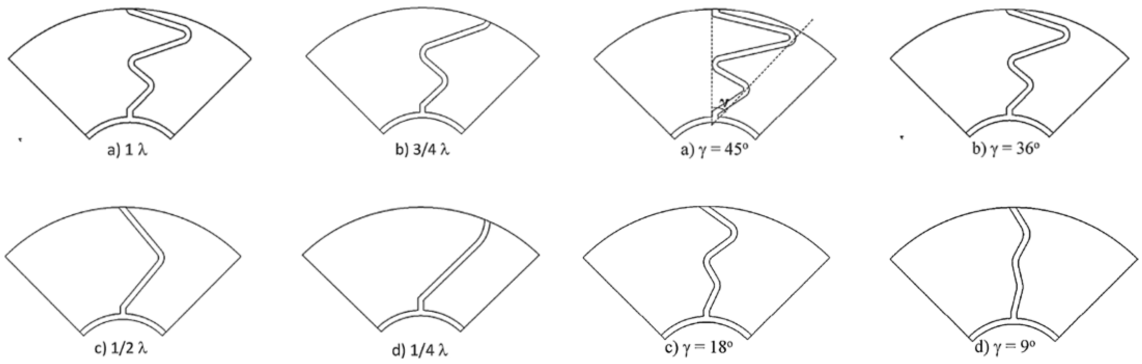

Figure 8. The examined corrugated fins [128]

Another different fin design studied by Ding & Liu [129] focused on the melting rate in a shell-and-tube heat exchanger using punched-fin and slit-fin designs. They observed that compared to a straight fin design at various Stefan numbers, the slit fin reduced the total melting time by 14% and the punched fin by 10.1%. They noted that both types of fins provided a noticeable improvement in performance in the heat exchanger. However, the slit fin reduced the blockage effect while simultaneously maintaining the heat transfer area and thus performed better than the punched fin.

L. Wu et al. [130] have designed a fin configuration resembling a spider-web-like in a latent heat storage system and compared the results obtained from the current study with those from longitudinal fins covering the same volume. They observed that the spider-web-like fins reduced the total solidification time by 47.9% compared to longitudinal fins. They also recommended using spider-web-like fins with eight branches to achieve maximum performance during the solidification process.

Ge et al. [131] placed longitudinal fins on the upper surface of each of the four inner tubes in a shell-and-tube heat storage system, placing short branches at the endpoints of each longitudinal fin structure. The geometric design of the study is shown in Figure 9. They demonstrated that the current fin design exhibited better performance with a 57.1% reduction in solidification time compared to the study using only longitudinal fins. Other studies related to various new fin designs are presented in Table 5.

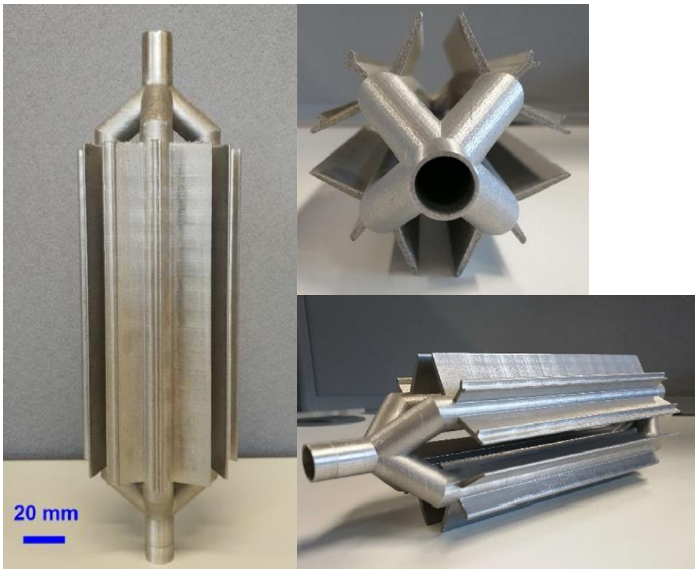

Figure 6. Optimised topology design of a shell-and-tube heat exchanger [131]

Table 5. Use of different fin designs in shell-and-tube heat exchangers

Study	PCM	Type of Fin	Method		Findings
			Numerical	Experimental	
M. Zhao et al. [132]	RT82	Y-shaped fins	✓	✕	Determined that the designed fin structure reduced the heat storage and release times by 70% and 81%, respectively.
Z. Liu et al. [133]	RT56	Y-shaped fins	✓	✕	Found that the use of Y-shaped fins at the bottom and short, straight longitudinal fins at the top reduced the total melting time by 21.5%.
C. Zhang et al. [134]	Lauric Acid	Fractal tree-shaped fins	✓	✕	Observed a reduction of 66.2% in total solidification time and 4.4% in total melting time compared to latent heat storage systems with radial fins.
Al-Mudhafar et al. [135]	RT82	T-shaped/tree-shaped fins	✓	✕	Found that tree-shaped fins achieved complete melting in 3.5 hours, while T-shaped fins improved melting time by 35%.
S. Wu et al. [136]	Lauric Acid	Tree-shaped fins	✓	✕	While a significant reduction in melting time was not achieved compared to wheel-shaped fins, significant improvements were made in solidification time. Suggested an optimal number of 16 fins for good melting performance.
T. Zhang et al. [137]	-	longitudinal and topology-optimized fins	✓	✕	Recommended an optimal fin volume ratio of 20% for the system. Achieved improvements of 46.8% and 47.1% in charge and discharge times, respectively, compared to longitudinal fins.

S. Liu et al. [138]	Triple hybrid molten salt (Li_2CO_3-K_2CO_3-Na_2CO_3)	Triangular fin	✓	✕	In the Fin-C model, where fin heights continuously decrease, they achieved a 38.30% reduction in solidification time compared to traditional longitudinal fins.
Lohrasbi et al. [139]	Water	V-shaped fin	✓	✕	Determined that optimised V-shaped fins accelerated solidification by 5.749, 3.741, and 3.742 times compared to scenarios using no fins, longitudinal fins, and circular fins, respectively.
(Liu et al. [140,141]	Stearic Acid	Spiral-shaped fin	✕	✓	Presented that the fin design significantly improved heat conduction and natural convection, particularly achieving a threefold increase in equivalent thermal conductivity.
S. Zhang et al. [142]	RT35	Helical-shaped fin	✓	✕	Achieved the best heat transfer performance with vertical double spiral and horizontal quadruple-helical fins, improving melting time by 31% and 10%, respectively, compared to traditional fins.
Huang et al. [143]	RT82	Hierarchical fin	✓	✕	Reported that optimised hierarchical fins reduced the total melting time by up to 41.1% compared to tree-shaped fin designs.

3.2.3. Other Heat Transfer Enhancing Designs

In addition to the methods mentioned in previous sections, various approaches have been implemented in heat exchanger designs to increase heat transfer; these include the use of multiple PCMs in the flow or radial direction, eccentricities, and changes in the sections of the shell or inner tube. Multi-PCM systems involve using multiple PCMs with different melting points, arranged to optimize thermal management. This method addresses the limitations of single PCM systems by providing a more gradual temperature response. In this method, considering the temperature difference decreases along the flow direction during melting, it is suggested to arrange the PCMs from high to low melting temperatures, and vice versa during solidification [144].

Gong & Mujumdar [145] examined a storage system with 5 different composite PCMs arranged as recommended. They observed a significant reduction in the fluctuations in the outlet temperature of the HTF and an increase in the charge and discharge rates compared to systems using a single PCM. Similarly, Cui et al. [146] presented a study for applications with 3 different PCMs. The researchers have shown that the use of multiple PCMs can enhance system performance. Michels & Pitz-Paal [147] observed the impact of using multiple PCMs on the phase change process in a shell-and-tube heat storage unit designed for use in solar power plants and using synthetic oil as the HTF. They found that it is possible to achieve a higher phase change fraction and charge/discharge capacity over a certain period compared to the storage unit using a single PCM with a higher melting temperature.

Seeniraj & Narasimhan [148] reported that a multi-PCM heat exchanger with circular fins provided an equal exit temperature of the heat transfer fluid over an extended period. [149] conducted a numerical study presenting the impact of the inlet temperature and mass flow rate of the heat transfer fluid on the performance of latent heat storage systems using the multi-PCM method. They achieved maximum storage efficiency at the lowest mass flow rate in the multi-PCM system, this value was determined to be a maximum of 0.98.

Kurnia et al. [150] have presented various configurations of multi-PCM arrangements in a new heat storage system named "Festoon" as shown in Figure 10. They found that placing a PCM with a higher melting temperature on the inlet side during solidification improves heat transfer while showing lower performance during melting. Hu et al. [151] analysed the use of multiple PCMs in a shell-and-tube storage system with frustum-shaped bodies of different length ratios. They found it appropriate to arrange multiple PCMs in the storage system according to increasing melting temperatures from top to bottom.

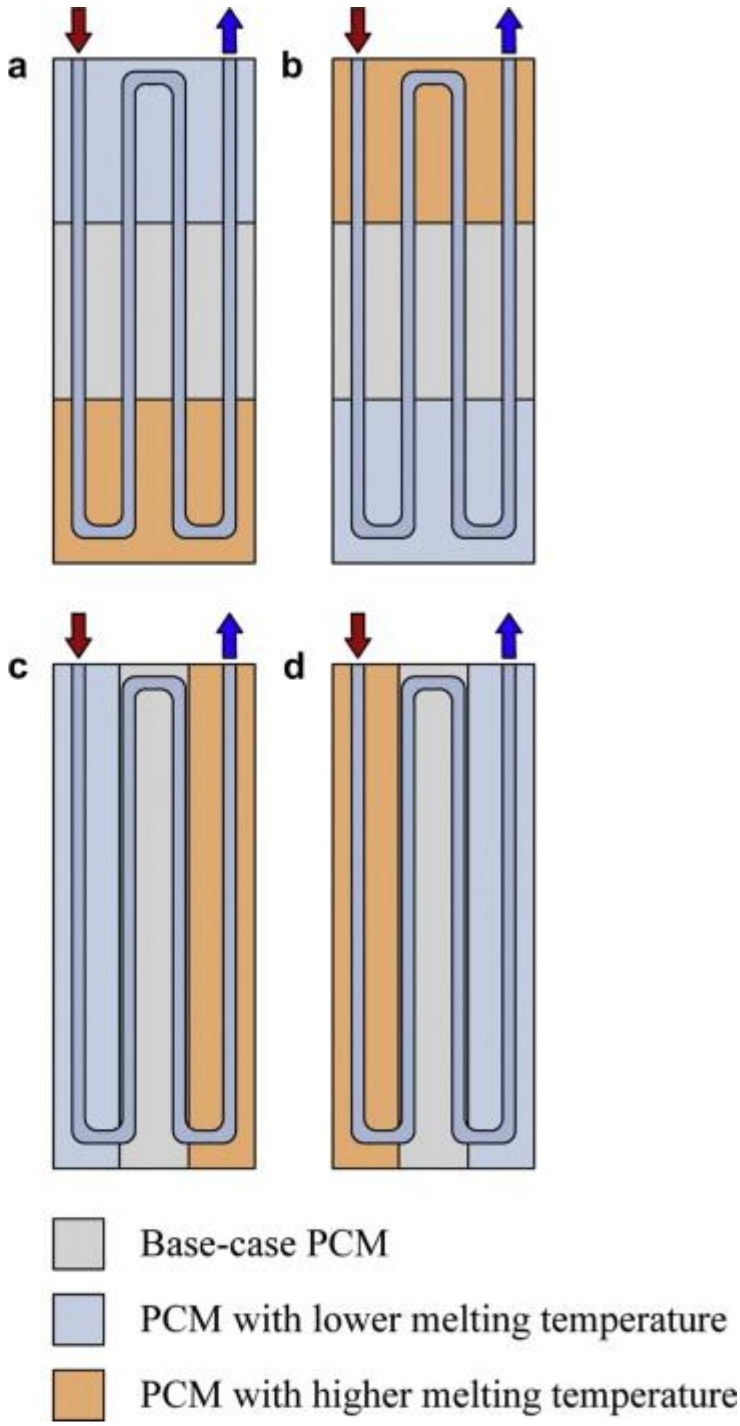

Figure 7. Schematic representation of various configurations of multiple PCMs [150]

Eccentricity refers to variations in the position of the inner tube within shell-and-tube heat exchangers and significant changes have been observed in melting or solidification times due to tube eccentricity. This is because eccentricity changes the heat transfer areas associated with convection. In 1980, Yao & Chen [152] presented an analytical study examining melting behaviour in an eccentric inner tube, while in 1997, Y. Zhang & Faghri [153] expanded the field by analysing solidification behaviour. They did not recommend eccentricity in latent heat thermal energy storage systems due to its adverse effect on the solidification rate. Yazici et al. Yazıcı et al. [154] and A. R. Darzi et al. [155] investigated the impact of changes in inner tube eccentricity on melting behaviour. They observed that heat conduction was dominant just before melting, but after a few minutes, natural convection became more prevalent. They also noticed that as eccentricity increased downwards from the centre, the natural convection area expanded and melting rate increased significantly. Specifically, they determined that an eccentricity of ε=30 mm resulted in a reduction of about 67% in total melting time compared to the concentric condition. They also noted that eccentricity increased the solidification time of the PCM, recommended that the inner and outer tubes should be positioned concentrically for situations requiring quick energy transfer [154].

Y. Liu & Tao [156] found that moving the inner tube downward in an eccentric configuration significantly increased the melting rate, reducing the duration by 29.8% compared to the concentric condition. They suggested moving the eccentricity upward to increase the rate of solidification. Dutta et al. [157] presented a computational model showing the effects of both eccentricity and the inclination angle on the thermal behaviour during melting. They observed that the net circulation of melted PCM increased when the inclination angle of eccentricity was not vertical, especially reaching a maximum value when the inclination angle approached -30° for a certain eccentricity. Pahamli et al. [158] studied the effects of changes in the position of the inner tube (Eccentricity (ε)=0.25, 0.5, and 0.75), different Reynolds numbers (1000, 1500, 2000) of the heat transfer fluid, and varying Stefan numbers (0.67 and 0.80) on the melting behaviour of PCM. They observed the reductions in melting time by 33%, 57%, and 64% as eccentricity increased to 0.25, 0.5, and 0.75, respectively, and they found the lowest total stored heat result for ε=0.75. They also identified that an increase in the Stefan number which is from 0.54 to 0.67 and then 0.8 created a significant temperature difference between the heat transfer fluid and the PCM, leading to reductions in melting time by 16% and 27%, respectively. They also found that an increase in Reynolds number had no significant effect on the melting process even when the inner tube was positioned eccentrically. Zheng et al. [159] examined the effects of eccentricity on melting and solidification performances and the impacts of Rayleigh numbers on optimal eccentricities. They found that increasing eccentricity reduced the melting process time but noted better melting times could not be achieved at large eccentricity values. They discovered that the optimal eccentricity for the melting process was linearly related to the Rayleigh number and observed that the optimal eccentricity for the melting-solidification process increased as the Rayleigh number ratio increased from 2.0 to 3.0, but the increase in optimal eccentricity slowed when the Rayleigh number ratio exceeded 3.0. They reduced the total melting-solidification times by 0.4% to 27% when the Rayleigh number ratio (Ra_m/Ra_s) varied between 2.0 and 7.4 compared to the concentric conditions of the inner and outer tubes. [160] analysed the melting rate in a latent heat storage system with longitudinal fins covering 36% of the shell, considering different eccentric positions (E=0.0, E=0.33, E=0.5, and E=0.7) and different angles (60°, 120°, and 180°) between fins located at the bottom of the system. They found that a 60° fin angle improved melting performance by 6% and 7% compared to other angles (120° and 180°), especially noting further improvements with eccentric positions.

Khan et al. [161] investigated five different eccentric positions in vertically downward Y-shaped longitudinal fin designs while maintaining the PCM volume constant adding Al_2O_3 and CuO nanoparticles to increase the thermal conductivity within PCM. They focused on performance determining parameters such as melting time, heat storage rate, and total thermal energy storage. They identified an optimal eccentric position of e=0.42 that resulted in a 34.14% reduction in melting time and a 30.7% improvement in thermal energy storage rate compared to the concentric (e=0) condition. Furthermore, they have found that adding 1% Al_2O_3 nanoparticles optimises the melting and energy storage performances by 10%.

Safari et al. [162] have investigated both experimentally and numerically the combined effects of fin configurations and eccentricity on the melting process in a shell-and-tube heat exchanger equipped with straight and bifurcated fins. They observed that, compared to a straight fin design, bifurcated fins diverted convection flows from the top of the body towards the lower parts, thus creating a higher melting rate. Moreover, they found that the heat exchanger with a 0.5 eccentricity factor and fork-shaped fins at the top reduced the melting time by 54% compared to the heat exchanger with a flat fin design.

Modi et al. [163] presented a study aiming to determine the optimal eccentricity position that would accelerate both melting and solidification times. They designed a latent heat storage system with a semi-rotational structure providing lower eccentricity during melting and upper eccentricity during solidification. According to this new concept, they determined that the optimal eccentricity position for the desired performance of the latent heat storage system should be 0.3. The common main conclusion from the studies reviewed above is that eccentricity applied to the lower part of horizontally oriented shell-and-tube heat exchangers or latent heat storage systems accelerates the melting time, while eccentricity applied to the upper part speeds up the solidification time. As previously mentioned, enhancing natural convection in shell-and-tube heat exchangers affects the melting speed and duration of the PCM. Therefore, researchers have designed different shell and inner tube shapes to increase the melting rate. Akgün et al. [164] developed a new heat exchanger design with a vertical conical shell by applying a 5° tilt angle to the shell of a shell-and-tube heat exchanger. Compared to traditional shell-and-tube heat exchangers with a 0° body angle, this new design reduced the melting time by 20%. Korawan et al. [165] examined the melting behaviours of heat exchanger designs composed of three different shell models using both numerical and experimental approaches. Among the three models, they observed that complete melting occurred the quickest (in 6,130 seconds) in the nozzle and shell model due to strong convection effects and took the longest (in 12,280 seconds) in the reducer and shell model.

A. A. R. Darzi et al. [166] explored the melting and solidification behaviours of N-Eicosane with added nanoparticles as a phase change material in a circular shell with three different internal tube designs: concentric circular, elliptical, and finned. While the use of vertically oriented elliptical inner tubes within the circular shell reduced the melting time, no significant results were obtained for solidification. Moreover, among the selected methods, the best results for both melting and solidification were achieved by adding fins to the hot or cold inner tubes. Faghani et al. [167] worked on nine different configurations, where both the shell and the inner tubes have elliptical shapes, examining the horizontal and vertical orientations of the elliptical inner tubes. They observed that, regardless of the shape of the inner tube, choosing a horizontal elliptical shell enhanced heat absorption and therefore reduced the total melting time. For the inner tube, the vertical elliptical structure achieved shorter melting times, but the simultaneous application of a vertical elliptical inner tube within a horizontal elliptical shell led to the maximum melting duration.

4. Integrating Phase Change Materials to Corrugated Channels and Plate Heat Exchangers

Corrugated heat exchangers are known for their higher surface area and efficient heat transfer coefficients. Their ability to facilitate enhanced heat exchange has attracted the attention of researchers, and focused exploration into the integration of PCM within the corrugated design. Plate heat exchangers (PHEs) are among the most widely used heat exchangers to perform heat transfer between two fluids. They are preferred due to their high level of heat exchange efficiency, small volume, easy maintenance, sufficient pressure and temperature resistance in a wide range of systems like HVAC+R and waste heat recovery. The use of such heat exchangers is rapidly becoming widespread. Chevron type plate heat exchangers are the most commonly used PHEs. There are lots of numerical and experimental studies about chevron type PHEs. The PHE have been used since 1923 [168]. Comprehensive information on PHE is given by Wang et al. [168] and Kakaç et. al [169]. Design methods are explained by Martin [170]. Most commonly used PHE type is chevron-type PHE, which is shown in 01.

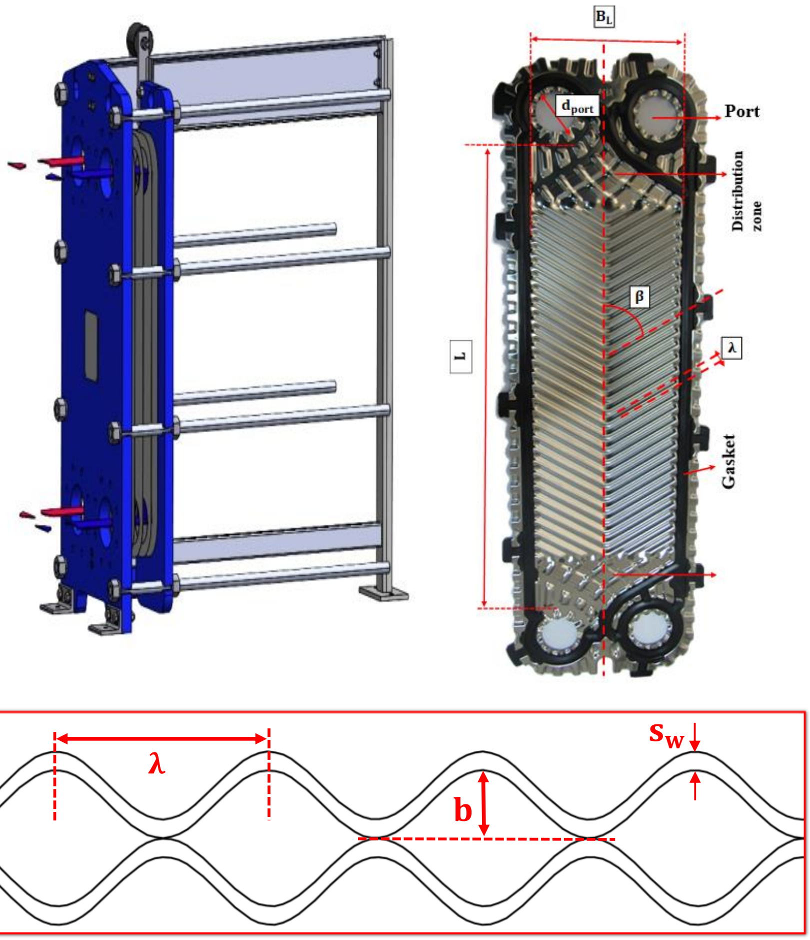

Figure 11. Chevron type PHE [171]

The integration of PCMs into gasketed or brazed plate heat exchangers presents a different set of opportunities. The smaller plate gaps compared to shell-and-tube configurations initially limit direct PCM use and require advances in plate geometries. However, PHEs have higher heat transfer coefficients and increased surface areas, and these make them efficient for heat exchange between fluids. To benefit from these advantages of PCM integration, researchers are focusing on innovative plate configurations that effectively utilize limited space between plates. In particular, the use of advanced plate designs on the plates improves convective heat transfer and enhances contact between PCMs and plate surfaces. These strategies underscore the ongoing commitment to research and development aimed at optimizing PCM applications within PHE and ensuring efficient and effective heat transfer in variety TES systems. The schematical representation of the PCM integrated PHE is illustrated in Fig. 12. Here one side filled with PCM and other side the HTF is flowing. That means both side of the PCM the fluid flows and this decrease the melting and solidification processes.

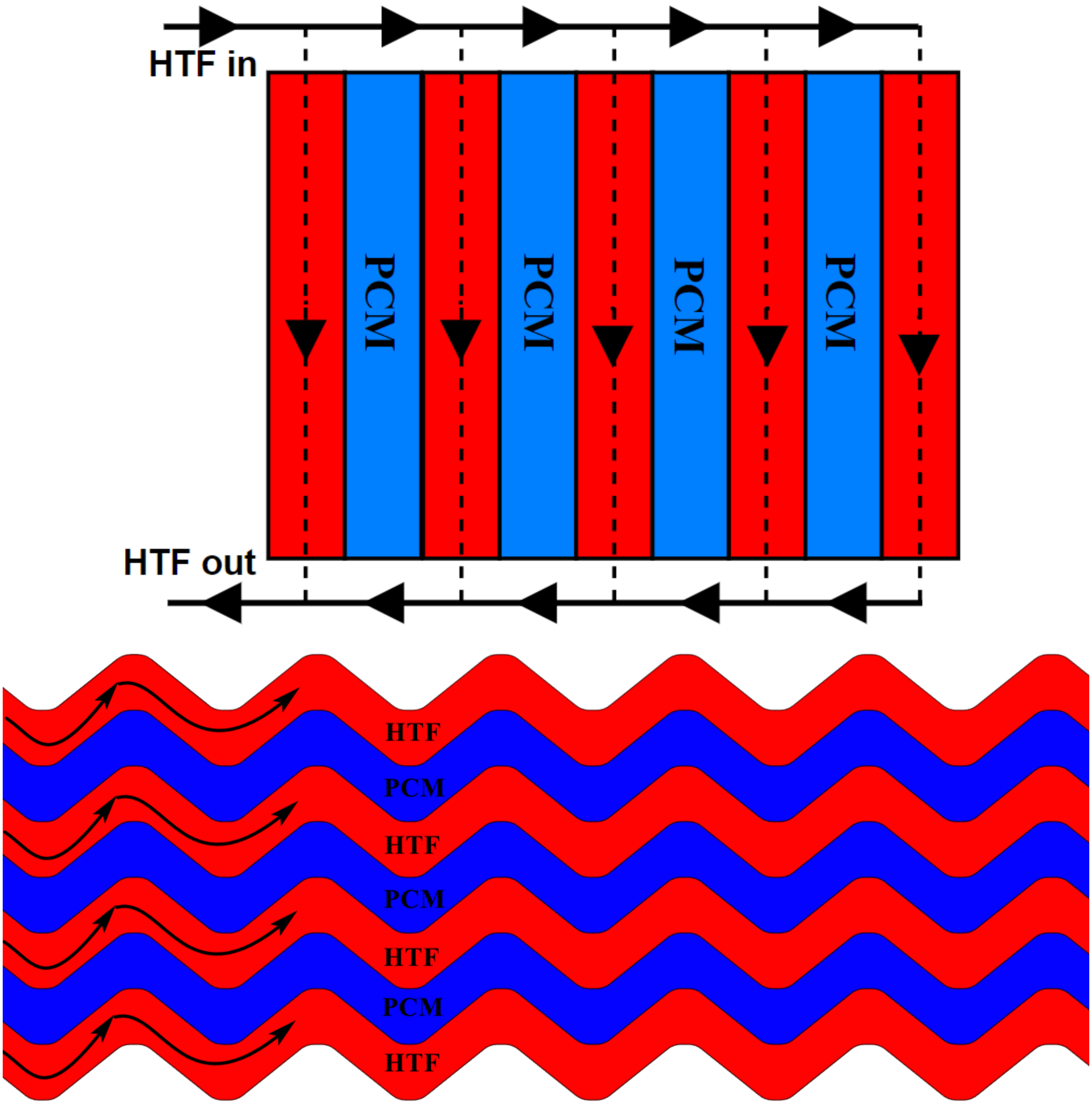

Fig. 12. The schematical representation of the PCM integrated PHE

In an experimental investigation conducted by Languri et al. [172], the effectiveness of a recently designed TES system characterized by a high surface-to-volume ratio and significant aspect ratio was examined. Various parameters such as Reynolds number, Stefan number, and the direction of HTF were investigated in the study. The TES system consisted sealed corrugated copper panels housing octadecane and arranged vertically to encourage a self-induced internal natural convection mechanism. The outcomes of the experiment showed an improvement in both charging and discharging rates reaching up to 9 times faster compared to concentric systems. This enhancement can be attributed to the superior surface-to-volume ratio found in the PCM panels used.

P. Wang et al. [173] examined a zigzag-configured heat exchanger incorporating multi-phase change materials (m-PCMs) using a two-dimensional mathematical model. By performing experimental validation, they mentioned that integrating m-PCMs improves the charging process compared to using a single PCM. Under similar conditions, a larger temperature difference during phase change between the m-PCMs leads to a more important enhancement in the charging process. Furthermore, using m-PCMs with unequal mass ratios further enhances this improvement. Their results also indicate that maintaining an optimal fluid velocity for a given input power is crucial for achieving a high melting rate.

Younis et al. [174] studied the thermal performance among five different tube configurations including flat, sinusoidal wave, square wave, triangular wave, and sawtooth wave. The study used nano-enhanced PCM for TES and they examined the influence of inlet temperature and velocity on the heat transfer process under a given input power. The results indicated that the sawtooth wave configuration showed better performance. At the highest values of Reynolds number, inlet temperature, and volume fraction, the sawtooth plate demonstrated a melting time reduction of 12%, 11%, and 12% compared to the flat plate, respectively. The study highlighted the potential of applying optimization techniques such as genetic algorithms and response surface methods in various geometries. Additionally, the authors suggested exploring alternative PCMs and nanoparticles to achieve enhanced results in future studies.

Kumirai et al. [175] studied the melting behaviour of three commercially available plate-encapsulated PCMs designed for passive cooling in air duct systems. The materials studied consistent of two paraffin-type PCMs and one of them is salt hydrate PCM, each with melting temperatures ranging from 22 °C to 28 °C. The study focused on vertically oriented plate-type encapsulations, each with a thickness of 10 mm and spaced at a pitch of 15 mm. Various experiments were conducted using air inlet temperatures ranging from 30 °C to 35 °C and upstream air velocities varying between 0.4 m/s and 0.9 m/s. The results indicated that the average thermal effectiveness decreased with higher air velocities. Moreover, the cooling power increased with increased air flow rates and inlet air temperatures. Utilizing the collected data, the they developed an empirical correlation model to describe the cooling capacity of the in-duct PCM plates.

Saeed et al. [176] noted that a literature review revealed that the key factor significantly affects the performance of TES units is the appropriate design of the heat exchange surface between the PCM and the HTF. While alternative methods such as increasing the thermal conductivity of the PCM or macro encapsulation, they are constrained by additional costs, increased weight, and reduced storage density due to additive presence. In response, the authors introduced a novel heat storage vessel, an innovative plate-type heat exchanger unit utilizing water as the working fluid and a PCM as the energy storage medium for load-shifting purposes. The thermal characteristics of this heat exchanger were experimentally evaluated across various inlet conditions. The compact parallel plate design demonstrated superior performance compared to conventional storage systems, achieving an effectiveness of up to 83.1% even when a low thermal conductivity PCM was used.

Gürel [177] conducted a numerical investigation of PHE integrated with latent heat TES. The objective of this research was to determine the ideal geometric configurations and operational parameters for enhancing the solidification process. The study evaluated three different plate geometries, various HTF inlet temperatures (12 °C, 17 °C, and 22 °C), a range of steel plate thicknesses (0.4 mm, 0.6 mm, and 0.8 mm), and different PCMs including RT-35 and n-octadecane. Numerical simulations using the finite volume method were simplified to two dimensions. The research reveals that under identical conditions, including phase change material type, boundary conditions, and geometric parameters, the solidification time of the PCM decreased significantly by up to 63% in a PHE-latent TES system using geometry-A for the PCM layer. This is in compared to a cylindrical latent heat TES system containing the same volume of PCM. Additionally, Gürel [177] observed that reducing the thickness of the PCM layer resulted in decreased solidification time for the PCM volume, simultaneously increases the heat transfer generated by solidification. In another study, Gürel [178] discovered that the TES system could experience a 75% reduction in heat losses when various geometries are used compared to a cylindrical latent heat TES system with equivalent PCM volume.

Juaifer et al. [179] undertook a research that aimed at enhancing the thermal efficiency of flat PHE TES systems while concurrently minimizing or sustaining costs. This was achieved using fixed dimensions and paraffin wax with a melting temperature of approximately 60 °C. The study revealed that the charging time could be reduced by as much as 35% by increasing the inlet high temperature fluid temperature from 343 K to 348 K and then to 353 K, In addition to the chevron-type plate heat exchanger, Ghasemi et al. [180] conducted a study on the performance and life cycle assessment of a pillow plate heat exchanger employing a slurry of microencapsulated PCM (MPCM). They observed a 6.2% improvement in the heat transfer rate with a 15% MPCM concentration. The life cycle assessment revealed a slight increase in emissions with rising MPCM concentration; however, the overall environmental impact remained minimal. Taghavi et al. [181] conducted a multi-objective optimization of PHE using PCM. They mentioned that using the optimization effectiveness can be enhanced by 21.4% compared to the normal design. Table 6 summarizes the literature studies related to PCM usage in corrugated channel and PHE.

Table 6. The studies related to thermal energy storage in corrugated channels and plate heat exchangers

Study	Year	PCM	Heat Exchanger Type	Flow Regime		Observed Trends	Key Findings
				Laminar	Turbulent		
Languri et al.[182]	2013	Octadecane	Corrugated copper panels	✕	✓	Upward HTF flow enhances buoyancy effects, reducing charging time by 70% and discharging time by over 3 times compared to downward flow. Heat transfer improved with higher flow rates and inlet temperatures.	Corrugated design with high surface-to-volume ratio significantly improves heat transfer rates, reducing charging/discharging times by up to 9 times compared to concentric systems.
Talebizadehsardari et al. [183]	2021	Paraffin RT-35	Zigzag Plate	✓	✕	Higher Re enhances storage rate and zigzag efficient	60° zigzag improves storage rate by 32.6% and higher Reynolds number accelerate phase change
Wang et al. [184]	2015	$NaCl - MgCl_2$ (4:6 mass ratio)	Zigzag Plate	✕	✓	Use of m-PCMs improved charging by up to 20% compared to single PCM; optimal inlet velocity and ΔT led to shorter melting times and higher thermal efficiency	Zigzag plate design with m-PCMs intensifies heat transfer; an optimal inlet velocity exists to balance pressure drop and heat transfer, achieving the best performance.
Younis et al. [185]	2022	Nano-enhanced PCM (Cu-Paraffin)	Corrugated Plate	✓	✕	Sawtooth geometry showed superior performance at higher Re values, reducing melting time by 12% compared to flat plates. Swirling flow enhanced heat transfer.	Corrugated geometries like sawtooth and triangular improved melting by up to 12%, with sawtooth being the best performer at high Re and temperatures.
Prieto et al. [186]	2016	Palmitic Acid, RT60 Paraffin	Flat Plate Heat Exchanger	N/A	N/A	Longer discharge time for Palmitic Acid (1.5 times RT60 Paraffin); higher thermal load demand coverage with fewer TES units.	Palmitic Acid outperformed RT60 Paraffin and water tanks, with better heat transfer rates, higher storage capacity, and fewer required TES units for peak load coverage.
Juaifer et al. [187]	2021	Paraffin Wax	Flat Plate Heat Exchanger	✓ (PCM)	✓ (HTF)	Natural convection dominated melting, and increasing HTF flow rate and temperature	Elevated HTF temperatures reduced charging time by up to 35%. Discharging time decreased by up to 19% when lowering HTF temperature

						improved charging and discharging performance	from 303 K to 293 K. Laminar PCM flow simplified thermal modeling.
Kumirai et al. [188]	2019	Paraffin RT25, RT27, Salt Hydrate SP24E	Plate encapsulated PCM in air ducts	✕	✓	Higher inlet air temperatures and mass flow rates improved cooling performance. SP24E (salt hydrate) had the highest energy absorption capacity due to its higher density.	SP24E modules achieved higher energy storage due to increased density and conductivity, while RT25 and RT27 showed higher instantaneous cooling power but shorter absorption times.
Saeed et al. [189]	2019	Hexadecane ($C_{16}H_{34}$)	Parallel plate type heat exchanger	N/A	N/A	Lower plate-plate spacing (1 inch) enhanced energy storage rate and reduced PCM shielding. Effectiveness exceeded 80% for optimized flow and temperature conditions.	1-inch spacing and controlled flow rates achieved higher effectiveness (>80%). Hexadecane demonstrated high latent heat storage capacity suitable for thermal energy storage systems.
Gürel [190]	2020	RT-35, n-Octadecane	Zigzag Plate Heat Exchange	✓	✕	Thin PCM layers and higher HTF inlet temperatures reduced melting time significantly; geometry optimization increased system efficiency.	Optimal melting time reduced by 75% compared to cylindrical systems; Geometry A achieved the best thermal performance with RT-35 at inlet temperature of 62∘C.
Gürel [191]	2020	RT-35, n-Octadecane	PHE	✕	✓	Lower inlet temperature (12 °C) and reduced PCM layer thickness improved solidification; Geometry A showed 63% faster solidification compared to cylindrical geometry.	Optimum conditions were achieved with Geometry A, n-Octadecane PCM, 0.6 mm plate thickness, and lower inlet HTF temperatures, significantly enhancing solidification performance.
Medrano et al. [192]	2009	Paraffin RT35	Double-pipe, compact, and PHE	✓	✓	Heat transfer enhanced significantly in turbulent flow regimes; compact heat exchanger had the highest performance; plate heat	Compact heat exchanger demonstrated the highest average thermal power (>1 kW), making it the best candidate for small-scale PCM applications. The plate heat exchanger

						exchanger had low storage efficiency.	was the least effective due to low PCM storage capacity.
Cerezo et al. [193]	2022	$MgCl_2 \cdot 6H_2O$	PHE	✕	✓	Higher Re numbers lead to improved charging/discharging rates; reducing PCM thickness increases heat transfer; corrugated plates show better performance compared to flat plates.	Corrugated plate enhances heat transfer; thicker PCM prolongs operation, and main thermal resistance is the PCM.
Taghavi et al. [194]	2023	Paraffin RT64HC	PHE	✓	✕	Stable HTF outlet temperature for up to 100 minutes during melting; reduced phase change time with thin PCM sections; enhanced performance with downward HTF flow during charging.	Their PHE demonstrated 75% higher thermal storage capacity per unit volume and 28.6% higher average effectiveness compared to roll-bonded one.
Ghasemi et al.	2024	Microencapsulated PCM (15% concentration)	Pillow Plate Heat Exchanger	✕	✓	Adding MPCM improved cooling performance, with 6.2% higher heat transfer rate. Increased flow rate and MPCM concentration reduced outlet temperature and enhanced heat capacity.	Pillow plates improve thermal performance through turbulence. A 15% MPCM concentration significantly enhances cooling but increases pressure drop by up to 48%.

5. Future Scope

While significant progress has been made in enhancing heat transfer and efficiency in PCM-based TES systems, there remain several areas where further research and innovation are needed. The following points outline potential directions for future work:

- Although various fin configurations have been studied, there is potential in exploring hybrid fin designs that combine the benefits of multiple shapes and materials. For instance, integrating fractal or hierarchical fin structures with conventional longitudinal or circular fins could improve heat transfer rates and reduce material costs.
- Research into advanced PCM materials, such as nano-enhanced PCMs or composite PCMs, can help overcome the inherent low thermal conductivity of standard materials. Nanoparticles and other additives can be used to enhance thermal properties, but the long-term stability and cost-effectiveness of these materials require further study.
- While modifications to shell geometries have shown to improve natural convection, adaptive or reconfigurable shell structures could further enhance efficiency. This approach might include variable geometry systems that adapt based on operating conditions, providing flexibility in energy storage applications with fluctuating loads.
- There are many valuable studies related to shell and tube and plate heat exchangers in the literature. And these can be applied the usage of the PCM in these heat exchangers. For the integration of PCM into the shell and tube heat exchangers the future trends should be focused on the intelligent techniques as given by Nazari et al.[195]. Also new types of fins can be integrated the PCM integrated shell and tube heat exchangers using X-truss vortex generators [196], helical fin with perforations[197], ellipsoidal protrusions on fin surfaces [198], tree-shaped fin structures[199], solid and hollow cylindrical fins [200], curved winglets and usage a multi-objective optimization approaches for different types of fins [201].
- Optimization studies like Taghavi et al. [181] are very important as well. Optimizing plate spacing and surface geometries will enhance heat transfer efficiency, thereby improving system performance and optimizing energy storage capacity. Integrating PHE with renewable energy sources such as solar or geothermal will create a good relationship that enhances overall efficiency and sustainability.
- For the future trends of integration of PCM into PHE, wide gap PHEs [202] and free flow PHEs [203] will be more suitable for PCM usage in the existing PHEs. Addition the existing one, the dimensions of the PHE given in Fig.11 should be optimized for the PCM usage also. Also, the pillow type heat exchanger can be extended to usage of PCM [204,205].

6. Conclusions

This review has undertaken a focused exploration of heat transfer enhancement, specifically targeting the achievement of uniform melting and solidification within heat exchangers utilizing PCMs. The insights collected here are useful for researchers and practitioners involved in optimizing heat exchanger designs for applications TES plays a critical role.

- The enhanced surface area characteristic of PCM facilitates a more uniform response to temperature fluctuations, which is essential for effectively maintaining and controlling desired conditions in various practical scenarios.
- Operating conditions like mass flow rate, inlet temperature, and Reynolds and Stefan numbers significantly impact PCM performance. By adjusting HTF inlet temperatures, studies reveal charging time reductions of up to 35%. Identifying optimal parameters is essential for achieving efficient heat transfer and stable phase change behaviour in TES systems.
- Fins are shown to greatly influence the thermal performance of PCM-based systems. For instance, specific longitudinal and circular fin designs, as well as novel spider-web and fractal structures, reduced solidification times by up to 63% and improved melting uniformity by shortening melting times by as much as 47.9%. These fin configurations enhance thermal uniformity, which is essential for stable and efficient energy storage Adjustments in fin angle and spacing, as demonstrated in studies on longitudinal and circular fins, resulted in substantial time reductions. For example, by optimizing fin angles, melting time was reduced by up to 83.9%, demonstrating that even slight modifications in fin geometry can lead to significant improvements in thermal efficiency.
- The above studies show the significant potential of PHE in TES by positioning them as key components in the future energy and TES systems and thus comprehensive set of improvements are essential.

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