Review

Himanshu Kumar, Ankit Yadav, Gurjeet Singh, Sumit Taneja*

A detailed review of the design parameters for augmenting the latent heat in a thermal energy storage system

Abstract

Purpose – The purpose of this study is to critically analyze various parameters that improve the latent heat transfer in heat exchangers. There has been a continuous increase in greenhouse gases because of industrial activities across the world. Consequently, it has become critical to harness renewable energy as a powerful substitute for meeting future energy needs. Thus, phase change materials (PCM) and heat transfer fluids have been instituted as alternatives for activities related to heat transfer enhancement employing heat exchangers with different fin configurations.

Methodology – The present work deals with the comparative analysis of thermal performance of longitudinal and circular finned heat exchangers. For creating a detailed summary of various computational cum experimental endeavours, efforts have been made to compile a refined picture of design variations and thermal performances of PCM-based latent thermal energy storage system (PCM – LTESS).

Findings – The comparative analysis of longitudinal as well as circular finned tube arrangement revealed that the latter has better thermal characteristics. However, various fin arrangements have also been explored as part of this review.

Originality – A significant improvement in heat transfer is observed when heat sinks clubbed with PCM-based arrangement are integrated with pin fins. These are frequently instituted for heat transfer enhancement or thermal energy management of various electronic goods with optimum number and size of fins.

Keywords: thermal energy management, phase change material, latent thermal energy storage system, heat transfer enhancement and heat transfer fluid

Nomenclature

ANN	Artificial Neural Network
B_m	Bingham number
C_p	Specific heat (kJ/kg K)
D, d	Diameter (m)
F_o	Fourier Number
H	Heat Transfer coefficient (W/m^2 K)
HTF	Heat-transfer fluid
HXs	Heat exchangers
K	Thermal conductivity (W/m K)
L, l	Length (m)
LHTES	Latent heat thermal energy storage
LHTESS	Latent heat thermal energy storage system
M	Mass (kg)
m	Mass flow rate (kg/s)
NTU	Number of transfer units
Nu	Nusselt number
Pr	Prandtl number
PCM	Phase-change material
Ra	Rayleigh number
Re	Reynolds number
r	Tube radius (m)
SHTES	Sensible heat thermal energy storage
Ste	Stefan number
t	Time (s), thickness (m)
T	Temperature (°C or K)
TESS	Thermal energy storage system
TTHX	Triplex tube heat exchanger
T_m	Melting temperature (°C or K)
V	Velocity (m/s)

* Corresponding author: Sumit Taneja, Department of Mechanical Engineering, Manipal University Jaipur, Rajasthan 303007, India, e-mail: sumit.taneja@jaipur.manipal.edu
Himanshu Kumar: Department of Mechanical Engineering, Punjab Engineering College, Chandigarh 160012, India, e-mail: himanshukumar1907@gmail.com
Ankit Yadav: Department of Mechanical Engineering, Punjab Engineering College, Chandigarh 160012, India, e-mail: ankityadav@pec.edu.in
Gurjeet Singh: Department of Mechanical Engineering, Punjab Engineering College, Chandigarh 160012, India, e-mail: gurjeetsingh@pec.edu.in

x, y, z x, y, z-component in a Cartesian coordinate system

Z Fin height (m)

Greek Letters

α Thermal diffusivity of PCM (m^2/s)

β Coefficient of volumetric expansion (1/K)

ε Eemissivity, emittance

γ Liquid fraction

η Efficiency

Subscripts

eff   Effective

f   Fluid

fin   Fin

i   Inner (inlet)

I   Liquid

M   Melting

O   Outer

P   Phase-change material

Ref   References

s   Solid

1 Introduction

The present annual energy requirement (thermal and electrical) is recognised as 2.3×10^{11} MWh by the end of the year 2035 (Zhang et al. 2016). Various kinds of industrial and non-industrial entities are heavily dependent on fossil fuels as far as their daily needs are concerned. Quite intriguingly, the previous data show a huge amount of energy losses (31%) as a part of the conversion from raw form to useful version apart from several eco-related issues (Tian and Zhao 2013). Keeping this in view, the research community has been givev huge thrust upon achievement of the better degree of sustainability as far as the consumption of scarce thermal entities is concerned (Taneja et al. 2013, 2021). Further, solar being most cheapest renewable energy fuel, stands out as a better and a convenient option in comparison to other alternatives such as wind or geothermal for all types of domestic and non-domestic purposes. Also, to address night-time thermal energy requirements for a variety of applications, solar-integrated thermal units have become the talk of the days, with the help of which availability of thermal energy can be ensured throughout the complete year (Erek et al. 2005). In continuation of the

same, sensible and latent heat accumulations are the types of thermal energy storage systems (TESS) that are most commonly employed for harnessing the thermal content of solar energy (Fisch et al. 1998). Depending on the configuration of the storage system, there must be adherence to temperature and design-related specifications, and energy storage in huge quantities must be customized in nature as well (Fernandez et al. 2010).

In line with the same, Trp (2005) diagnosed the charging and discharging behaviour of phase change material (PCM) paraffin wax (RT30) for shell and tube heat exchanger configuration through detailed experimental and non-experimental approaches. Post comprehensive comparative exploration of different configurations like liquid–gas, solid–solid and solid–liquid are considered to identify charging/discharging properties (Regin et al. 2008). Despite many disadvantageous features of PCM, there is always a need for special care as far as appropriate selection of the same is concerned in line with the particular kind of application. Also, several research initiatives have been put in place such as the use of PCMs in blended mode in combination with nanoparticles, use of multiple tube arrangement, involving microencapsulation, and modified design of TESS to seek a better degree of thermal performance (Jegadheeswaran and Pohekar 2009, Ho and Gao 2009, Fan and Khodadadi 2012, Dhaidan et al. 2013, Mahdi and Nsofor 2016, Mozafari et al. 2022, Elbahjaoui and Qarnia 2017). In a similar row, most fruitful heat transfer calibre/abilities were adjudged to be associated with fin-based heat exchanger configurations. Therefore, the present approach not only compiles end results from various configurations/approaches, but also through a broad light on performance entities/derivatives such as thermal efficiency, geometrical parameters and few other conforming and some non-conforming design-related features (Agyenim et al. 2009, 2011, Mat et al. 2013, Al-Abidi et al. 2014, Rathod and Banerjee 2015).

2 PCM-assisted latent heat thermal energy storage system (LHTESS)

Basically, storage materials are used in two forms for the storage of energy, i.e. solid or liquid, which can be released or used in line with temperature–time combinations. The thermal energy is usually collected in the PCM-assisted latent energy storage device under certain specified temperature conditions. So, in view of space constraints, it seems highly imperative that latent thermal energy storage entities must be highly efficient as well as suitable for a variety of PCM materials owing to their being less conductive ($k \leq 0.2$ W/m K) and environment-dependent nature

particularly when it undergoes charging and discharging protocols and sometimes in case of overheating related problems (Morrison and Abdel-Khalik 1978, Ghoneim 1989). So, it makes good sense to develop such TESS which would undoubtedly assist in harnessing the highest possible energy potential associated with thermal performance.

2.1 Classification of PCMs

As far as the classification of PCM materials is concerned, they fall into the categories of solid, liquid and gas, and a combination of the mentioned types, i.e., solid–liquid and liquid–gas, etc., to find the most suitable combination/blend for a particular kind of heat exchanger configuration. The broad classification of PCMs is displayed in Figure 1.

2.2 Selection criterion of the PCM

There must be keen focus on the key characteristics/considerations of PCM materials as far as thermal energy storage applications are concerned, particularly features pertaining to thermodynamic as well as non-thermodynamic domain and of course economic considerations in accordance with charging and discharging behaviour. For example, there is a requirement for optimum value of thermal conductivity for domestic heating applications in the temperature range 0°–65°

(Abhat 1983). Besides, fulfilling crystal growth is immensely needed for recovery of heat content from LHTESS apart from securing better nucleation rate at high-temperature gradients, in line with chemical properties such as non-virulent, non-flammable and non-fulminating, and the availability of the same at low-cost value (Lamberg et al. 2004).

2.3 Design configuration of PCM-based LHTESS

It is paramount to note that the role of design parameters associated with PCM-assisted heat exchanger units has quite significant and impactful bearing on the energy conversion rate as well as the thermal behaviour of the entire system. Various configurations of the generally used PCM containers are represented in Figure 2.

Moreover, as far as the suitability of a PCM about its applications is concerned, it must have close conformation with the same. The characterization of PCM-based LHTESS, i.e., cylindrical (Figure 2a), rectangular (Figure 2b) and the spherical (Figure 2c) is shown in Figure 2. The cylindrical heat exchangers are employed for commercial purpose activities owing to small volumetric space and much higher efficiency (Tan et al. 2009, Venkata-chalapathy et al. 2015).

The cylindrical heat exchanger configuration is shown in Figure 2a, where, the PCM fills the outer shell while the heat transfer fluid (HTF) flows through the inner pipe. As
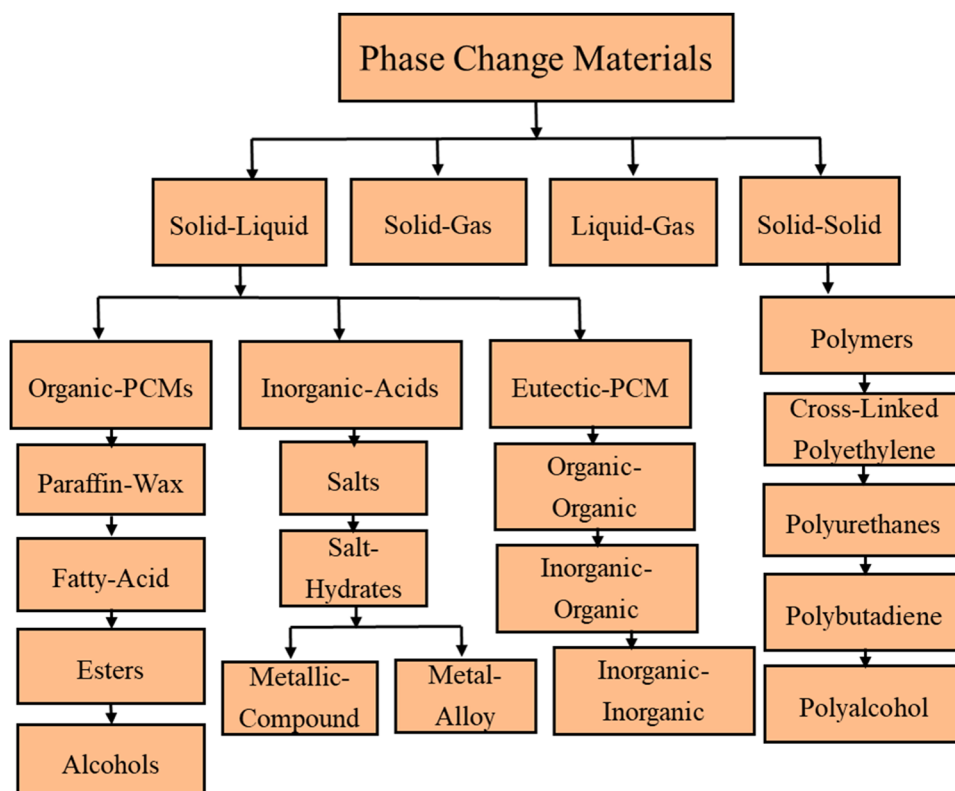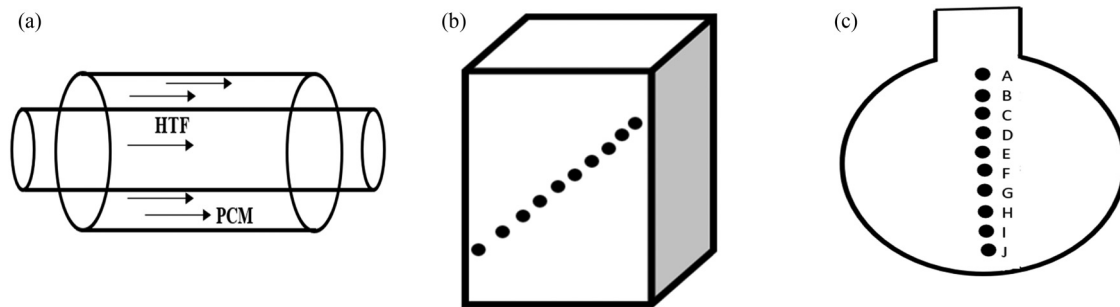

Figure 1: Classifications of PCMs (Podara et al. 2021, Sharma et al. 2009, Bruno et al. 2015).

Figure 2: Various types of generally used PCM containers. (a) Cylindrical (Agyenim et al. 2009). (b) Rectangular (Lamberg et al. 2004). (c) Spherical (Tan et al. 2009).

per the literature finding of Hosseini et al. (2014), it has been identified that upon raising the temperature of PCM from 70 to 75°C and 75 to 80°C, the efficiency of charging and discharging characteristics of PCM increases to 5.6 and 1.7%, respectively. Besides, the effect of the Reynolds Number has also been studied while exploring melting and solidification characteristics (Jesumathy et al. 2012). Among various configurations instituted to harness solar energy, the rectangular model was found to be of significant value, particularly in entities such as solar energy systems, nuclear reactors and geothermal energy units (Arasu and Mujumdar 2012, Jellouli et al. 2007). On a similar note, Lamberg et al. (2004) experimentally as well as numerically explored the discharging behaviour of the PCM in a rectangular enclosure, even in natural convection conditions where the PCM was found to exhibit a close match with analytical outcomes only in the beginning stage. In addition, as the melting proceeds, the experimental interface secures a position far ahead of its analytical counterpart (Stritih 2004). Thus, many researchers have shown deep interest in the rectangular configuration because of shape simplicity and easily implementable boundary conditions, making them ideal geometry for thermal energy storage purposes for a variety of applications.
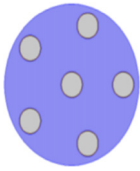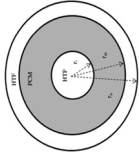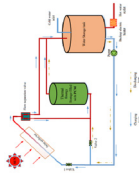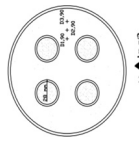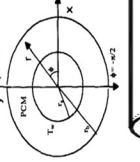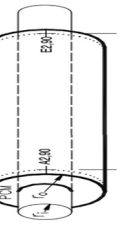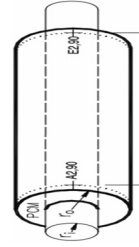
The configuration of the rectangular heat exchanger is shown in Figure 2b. Further, several research studies have been reported for the spherical shape type TESS also, as shown in Figure 2c. UmaMaheswari and Reddy (2004) performed some numerical investigation for spherical shape type heat exchangers. On a similar approach, Assis et al. (2007a) executed some numerical as well as experimental studies on determination of thermal properties of Paraffin Wax PCM (RT27) with 98% PCM packing in spherical container as a necessary condition simulation. The heat transfer rate was found to be significantly influenced by geometrical as well as thermal characteristics in case of normal PCM, whereas nano-particle assisted PCM improves the thermal

conductivity in line with a decrement in latent heat of fusion (Assis et al. 2009). Moreover, researchers have also reported that the role of random packing was more prominent as compared to customized packing, i.e., encapsulation properties have an important impact on thermal energy storage characteristics of heat exchanger (Xia et al. 2010). For further details, refer Tables 1–3.
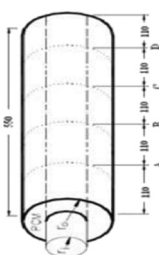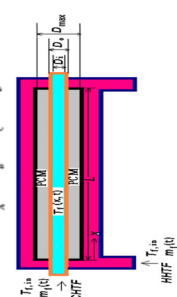
3 Heat transfer augmentation techniques

Rising energy costs and material costs have compelled academics all around the world to find new techniques to improve heat transfer performance in all types of heat exchangers over the last several decades (HXs). Enhancing heat transfer in a latent heat thermal storage can be done in a number of ways: enhancement of thermal conductivity using low-density materials such as carbon fibres and paraffin composites exchanger (Sun et al. 2007), porous materials such as metal foams (copper or aluminium) or porous materials like graphite exchanger (Jegadheeswaran and Pohekar 2009, Wang et al. 2009b, Tian and Zhao 2011), metal matrices exchanger (Srivatsa et al. 2014), and encapsulation methods using graphite (Trelles and Dufly 2003), polymers, or the nickel film coating of PCM copper spheres exchanger (Amaral et al. 2017), enhancement with fins (expanded surface of metal) exchanger (Sciacovelli et al. 2015), and multiple PCMs exchanger (Sun et al. 2007), and direct heat transfer procedures exchanger (Wang et al. 2009a). The utilization of expanded surfaces such as fins and multiple PCMs with various melting points is the most common improvement strategy. Ibrahim et al. (2017) conducted a general overview of some of these strategies. Details are shown in Figure 3.

Table 1: Different cylindrical configurations of PCM-based LHTESS

Refs.	Nature of study	Design configurations	Figure/geometry	PCM used	Materials of constructions	Varying parameter	Major findings
a. Condition: Cylindrical design configuration for charging							
Niyas and Muthukumar (2013)	Numerical (charging)	Shell and tube		Paraffin RT-50	Copper	Heat flux, PCM mass	Increasing charging rate
Mat et al. (2013)	Numerical (charging)	Triplex tube heat exchanger (TTHX)		Rubitherm GmbH-Germany (RT82)	Copper	Heat flux	Enhancing charging rate, Reducing charging time
Mahfuz et al. (2014)	Experimental (charging)	Shell and tube		Paraffin Wax	Copper	HTF mass flow rate, Energy, exergy	Enhancing mass flow rate, Reducing life cycle price
Agyenim et al. (2010a)	Experimental (charging)	Shell and multiple tubes		Erythritol	Aluminium and copper tube	HTF directions: Axil, radial and angular	Enhancing melting rate, Reducing melting time
Ng et al. (1998)	Numerical (charging)	Annulus		n-Octadecane	—	Heat flux	Improving charging and discharging rate
Agyenim et al. (2009)	Experimental (charging)	Concentric tube		Erythritol	Aluminium and copper	HTF mass flow rate, HTF initial temperature	For a specified (8-h) charge, melting was not complete
b. Condition: Cylindrical design configuration for discharging							
Hosseini et al. (2014)	Numerical and experimental (discharging)	Shell and tube		Paraffin RT50	Copper	HTF, Initial temperature	Enhancing heat transfer rate, reducing charging time, Decreasing heat transfer rate and charging fraction

(Continued)

Table 1: *Continued*

Refs.	Nature of study	Design configurations	Figure/geometry	PCM used	Materials of constructions	Varying parameter	Major findings
Akgün et al. (2007)	Experimental (discharging)	Concentric annulus		Paraffin wax	Mild steel and stainless steel	HTF mass flow rate -Re	Increasing Re and mass flow rate, Increasing heat transfer rate, melt fraction
Jian-you (2008)	Experimental and numerical (discharging)	TTHX		*n*-Hexacosane	Copper	HTF mass flow rate, HTF initial temperature	Improving mass flow rate, improving charging rate, reducing charging time

3.1 Fin-based heat transfer augmentation techniques

Since low thermal conductivity is a highly undesirable feature of most PCMs, it is quite pertinent to address this problem for seeking augmentation in heat transfer characteristics of PCMs. In order to seek fulfilment of the statement just mentioned above, various shapes of fins such as longitudinal, circular, spiral, plate and pin–fin arrangements are incorporated in PCMs to secure better thermal ratings of LHTESS. Moreover, the decision related to the use of a particular shape of fin depends on factors such as space, enhancement in heat transfer surface, low construction cost and most importantly ease of fabrication. The above-mentioned fins are shown in Figure 4.
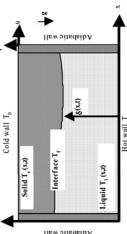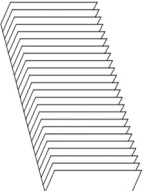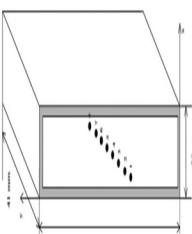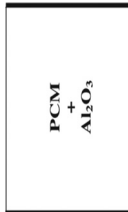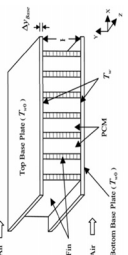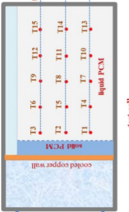
3.1.1 Longitudinal fins

It is interesting to note that most of the researchers have achieved significant success in understanding the thermodynamic behaviour of LHTESS wherein the fins are mounted on the circumference of the PCM container. Also, simplicity and ease of fabrication played a pivotal role in securing better thermal performance in line with the statement mentioned above. Similarly, Gharebaghi and Sezai (2007) performed the simulation exercises on a rectangular PCM container coupled with horizontal fins added to the vertical heated walls. Both (vertical or horizontal) the heated walls were maintained at a temperature higher than the melting point of PCMs. There has been an intriguing outcome of the above-mentioned technique, i.e., vertical walls in association with horizontal fins, which enhanced the overall heat transfer of the system. In another similar research initiative, Al-Abidi et al. (2014) identified the role of mass flow rates on PCM melting as well as the impact of steady/unsteady conditions on HTF inlet temperature. Further, Velraj et al. (1997) employed circular pipe having longitudinal fins on the inner surface to study the behaviour of PCM in terms of thermal resistance decreases.

Moreover, the time taken for solidification without fin arrangement was reported to be *n* times higher than that of fin arrangement. Besides, the same author has presented its study on outward cylindrical solidification for a double pipe heat exchanger system wherein the PCM employed in the free cooling arrangement was empirically examined. Therefore, this can be concluded that longitudinal fins increase the cooling rate thereby reducing the solidification time exchanger (Rathod and Banerjee 2015, Solomon and Velraj 2013). For all the sorts of fins configuration, i.e., internal, external or a combination thereof in the PCM
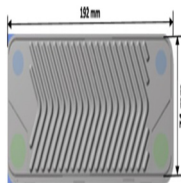
Table 2: Different rectangular configurations of PCM-based LHTESS

Refs.	Nature of study	Design configurations	Figure/geometry	PCM used	Materials of constructions	Varying parameter	Major findings
a. Condition: Rectangular design configuration for charging							
Jellouli et al. (2007)	Numerical (charging)	Rectangular		—	—	Heat flux	Enhancing natural convection
Stritih (2004)	Experimental and numerical (charging)	Rectangular		RUBITHERM, RT 30 Paraffin	Steel	Heat flux	Enhancing the conduction heat transfer
Lamberg et al. (2004)	Experimental and numerical (charging)	Rectangular		Technical grade paraffin	Solid aluminium, tufnol phenolic fabric, 6063-T5 aluminium	Heat flux	Enhancing natural convection
Arasu and Mujumdar (2012)	Numerical (charging)	Rectangular	PCM + Al$_2$O$_3$	Paraffin wax	—	Heat flux	Enhancing the thermal conductivity of heat transfer
b. Condition: Rectangular design configuration for discharging							
Gharebaghi and Sezai (2007)	Numerical (charging and discharging)	Rectangular		Rubitherm RT27	Aluminium	—	In a rectangular system, the minimum augmentation rate attained with widely separated fins was three times higher
Talukdar et al. (2019)	Numerical and experimental (charging and discharging)	Rectangular		Water	Stainless Steel	Compressor, a condenser, and an expansion valve	Enhancing heat transfer rate
Motahar et al. (2017)	Experimental (discharging)	Rectangular		n-Octadecane	Acrylic Glass	Fourier number (Fo), Rayleigh number (Ra), solid Stefan number (St), Bingham number and mass fraction of nanoparticles	Solidification rate was enhanced by dispersing nanoparticles

(Continued)

Table 2: *Continued*

Refs.	Nature of study	Design configurations	Figure/geometry	PCM used	Materials of constructions	Varying parameter	Major findings
Gürel (2020)	Numerical (discharging)	Rectangular plate		RT-35 and *n*-octadecane	Perspex	Plate geometry HTF initial temperature PCMs	Enhancing heat transfer rate and reduce solidification time

container, the preferred fin material primarily is copper exchanger (Solomon and Velraj 2013) as detailed in Table 4.

3.1.2 Circular fins

Extending the previous discussion, this section deals with the circular fins. In order to augment the heat transfer rates in different cylindrical containers, the circular fins were instituted to achieve the desired purpose. Mosaffa et al. (2012) suggested an analytical model for performance assessment of shell and finned based tube used in air conditioning exercise. The solidification characteristics found to have similar nature for cylindrical as well as rectangular PCM container bearing the same heat transfer area. In a separate kind of research initiative, Lacroix (1993) proposed a numerical approach to study the melting behaviour of PCM in a shell with annular fins around the tube's circumference. Jung and Boo (2014) proposed an analytical protocol to forecast unsteady/transient thermal characteristics of PCM-packed finned heat pipe-assisted LHTESS in the absence of natural convection.
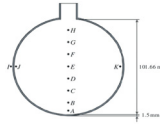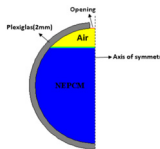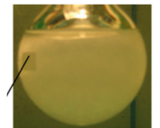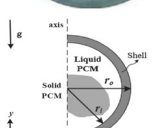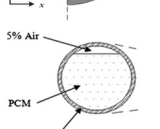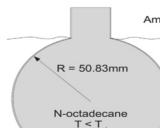
In an intriguing numerical exercise, Ermis et al. (2007) implemented artificial neural network (ANN) Feed Forward Back Propagation algorithm to solve the governing equations meant for HTF, Pipe Wall and PCM, to unearth or estimate the impact of fin and flow parameters upon overall performance of TESS. The results showed quite a close match of predicted values with simulated ones. Therefore, it could be perfectly concluded that upon addition of circular fins to the LHTESS, a substantial rise in heat transfer capabilities was reported for the said system apart from improved liquid fraction rate during melting and solidification process as given in Table 4.

3.1.3 Spiral fins

The compact shape and rapid heat transfer rates are the characteristics of spiral fins heat exchanger and thus their thermodynamic performance is excellent. In a similar di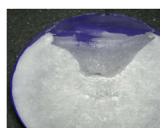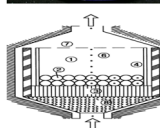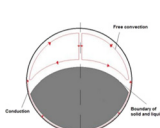rection, several research initiatives are going on to seek further improvement in their thermodynamic performances. Bharadwaj et al. (2009) investigated the pressure drop and heat transfer behaviour of a flow (Laminar/Turbulent) through a spirally grooved tube having twisted tape inserts inside it, wherein the heat transfer rates had a substantial rise. Further, Naphon (2011) performed experimental investigation of heat transfer and flow properties of a horizontal spiral coil tube arrangement wherein Nusselt number and pressure drop were found to have a higher

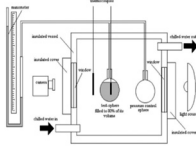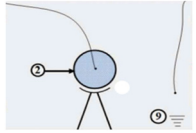**Table 3:** Different rectangular configurations of PCM-based LHTESS

Refs.	Nature of study	Design configurations	Figure/geometry	PCM used	Materials of constructions	Varying parameter	Major findings
a. Condition: Spherical design configuration for charging							
Tan et al. (2009)	Numerical and experimental (charging)	Spherical		*n*-Octadecane	Glass	Heat flux	For less charging point in capsule due to enhancing phase change rate
Hosseinizadeh et al. (2012)	Numerical (charging)	Spherical		RT27	Plexiglas	Heat flux	Enhancing PCM charging rate
Assis et al. (2007b)	Numerical and experimental (charging)	Spherical		RT27	—	Heat flux and operating temperature	Enhancing PCM charging rate
Gao et al. (2019)	Numerical (charging)	Spherical		*n*-Octadecane	—	Ra, Pr, α	Increasing PCM charging rate
Liao et al. (2018)	Numerical (charging)	Spherical		NaNO$_3$	Steel	Heat flux, encapsulations	Enhancing PCM charging rate
Amin et al. (2014)	Numerical (charging)	Spherical		Water	Medium-density polyethylene	Heat flux, encapsulations	Enhancing phase change rate
b. Condition: Spherical design configuration for discharging							
Assis et al. (2009)	Numerical and experimental (discharging)	Spherical		RT27	Plastic	Heat flux	Enhancing PCM charging rate
Cho and Choi (2000)	Experimental (discharging and charging)	Spherical		*n*-Tetradecane (C$_{14}$H$_{30}$), *n*-hexadecane (C$_{16}$H$_{34}$) and water	Acryl	Re, initial temperature	Enhancing heat transfer coefficient up to 40%
Singh et al. (2023)	Experimental and numerical (discharging)	Spherical		Paraffin wax	Pyrex, glass	Total time, Melt fractions	Enhancing heat transfer rate
Galione et al. (2015)	Experimental and numerical (charging and discharging)	Spherical		*n*-Octadecane	Glass	Flow pattern, thermophysical properties	Enhancing heat transfer rate

Table 3: *Continued*

| Refs.	Nature of study	Design configurations	Figure/geometry	PCM used	Materials of constructions	Varying parameter	Major findings
Eames and Adref (2002)	Experimental (discharging and charging)	Spherical		Water	Glass	HTF temperature	Enhancing the charging and discharging rate of spherical ice thermal storage elements
Lago et al. (2020)	Experimental (discharging)	Spherical		Pure water or a mixture of polyethylene glycol and water)	Polystyrene	Super cooling polyethylene glycol	Enhancing the diameter of the spherical shell is found to increase the time for complete solidification

magnitude in comparison with its straight tube counterpart as given in Table 4.

On the same lines, Li et al. (2012) devised an approach to improve heat transfer behaviour of a smooth helical tube wherein whirling motion was ascertained as the main reason responsible for the better degree of heat transfer at the cost of slightly higher pressure drop in the current system. Another similar research by Pongsoi et al. (2014) unearthed the air-side performance of spiral fin and tube heat exchangers. Moreover, the counter current spiral heat exchanger was studied by Nguyen and San (2016a). Also, the optimal Number of Transfer Units at maximum heat transfer effectiveness increases as the number of spiral turns increases exchanger (Nguyen and San 2016b). Besides, Nunez et al. (2009) presented a design approach for spiral heat exchanger wherein it was discovered that heat transfer coefficient, which was the main reason behind pressure drop owing to friction, was used as a parameter to decide the dimension of heat exchanger. In addition, the constant changes in the direction of fluid flow resulted in an increased magnitudes of heat transfer coefficient values exchanger (Son and Shin 2001). In another related study, the heat transfer characteristics of a spirally coiled circular fin-tube heat exchanger were examined (Altac and Altun 2014). Apart from the above-mentioned research, the researcher has also calculated parameters, such as frost thickness, pressure drop, heat transfer rate, and Nusselt number (Lee et al. 2011) as depicted in Table 4.

3.1.4 Plate fins

The plate fins generally made of aluminium exchanger (Ye et al. 2011) and stainless-steel exchanger (Rahimi et al. 2014) are widely employed for constructing LHTESS mainly because of properties such as high thermal conductivity. In addition, Campos-Celador et al. (2013) roped in three solver approaches, such as analytical, numerical and simpler numerical methods, for assessing the thermal performance of LHTESS with plate fins. Owing to the inability of analytical approach to comprehensively judge the thermal performance of long fins, a simpler numerical approach was designed which is easier for computation of thermal performances for a variety of fins. In the same direction, Ye et al. (2011) numerically explored the pattern of energy storage as well as release in plate fin-based LHTESS under uniform thermal conditions in heating as well as cooling mode.

Extending the similar exercise, Wang and Li (2016) investigated traditional design practices for multi–stream plate fin heat exchangers and dealt with the development of methods for layer pattern design. From the above-mentioned discussion, this could be concluded that finned plate technology is the best-suited approach for LHTESS, having rectangular shape as a key design configuration which not only facilitates space integration but also simplifies the production process owing to plane surfaces being used as depicted in Table 4.
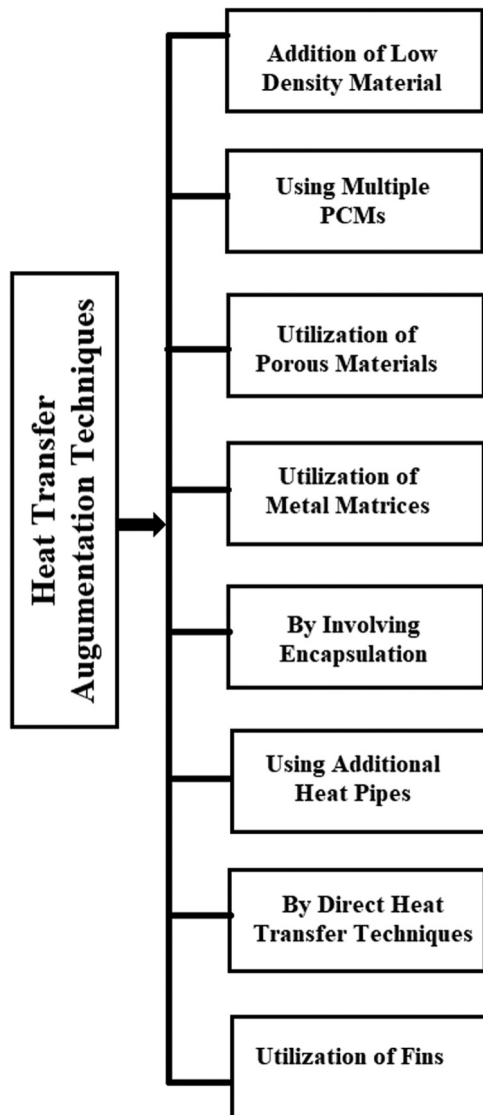
Figure 3: Classifications of heat transfer enhancement techniques (Ibrahim et al. 2017, Zayed et al. 2020, Sarbu and Dorca 2018, Mahdi et al. 2019, Gasia et al. 2016, Agyenim et al. 2010b, Al-Maghalseh and Mahkamov 2018, Taneja et al. 2018).

3.1.5 Pin fins

The thermal management has quite significant role as far as heat transmission in electrical as well as electronic components is concerned. The optimum heat transfer is the outcome of appropriate thermal management of equipment working within permissible temperature limits that too in line with robust design and construction of the same. Further, it is quite understandable that the low thermal conductivity value of PCM is the main deterrence in the design of PCM-assisted electrical cooling devices. However, to address the above deficiencies, the PCM-based heat sinks were modified by adding pin fins to bring qualitative improvement in the performance of LHTESS.

In line with the above discussion, Pakrouh et al. (2015) determined the energy transfer rates of pin fin heat sinks using PCMs to judge their effectiveness for electronics equipment. Some studies similar to Jaworski's (2012) assessed the performance characteristics of pin fin type heat sink having PCM injected into the tubes of heat exchanger. Additionally, Fok et al. (2010) conducted a series of experimentations on PCM-assisted cooling of electronic equipment using pin fin type heat sinks only to identify that the copper/aluminium made pin fins compensate for the low thermal conductivity value of PCM-assisted heat transfer operations as given in Table 4.

3.1.6 Novel fins

In some miscellaneous occurrences, few of the researchers identified some novel design combinations, using which the charging and discharging efficiency could be optimised. In the same line, Sciacovelli et al. (2015) involved single or double bifurcation tree-shaped fin to conclude that discharging efficiency is raised as high as up to 24%. Besides, Kurnia et al. (2013) quantitatively examined the PCM-based LHTESS in connection with design configurations, such as U-tube, U-tube with plane/staggered fins inside apart from an innovative festoon design as shown in Figure 5. The involvement of innovative design has led to higher heat transmission rate during charging and discharging conditions. The present review has compiled some of the novel studies that state that sometimes different shapes and designs play some crucial role in heat transfer enhancement as far as LHTESS is concerned as given in Table 5.

The schematic diagram of finned thermal storage system and plane tube are shown in Figures 6–8.

4 Parametric assessment of PCM-based LHTESS

Several investigators across the world studied the performances of PCM-based LHTESS in connection with variation of dimensional parameters of fins, number of fins, geometrical configurations of fins and size and shape of fins, etc., wherein it was found that a subtle relationship exists between variation of fin parameters and performance characteristic of the thermal energy storage unit. In an extension to the above statement, one study revealed that
– Increase in fin size does not increase heat transfer all the times
– Increasing number of fins does not improve the heat transfer considerably
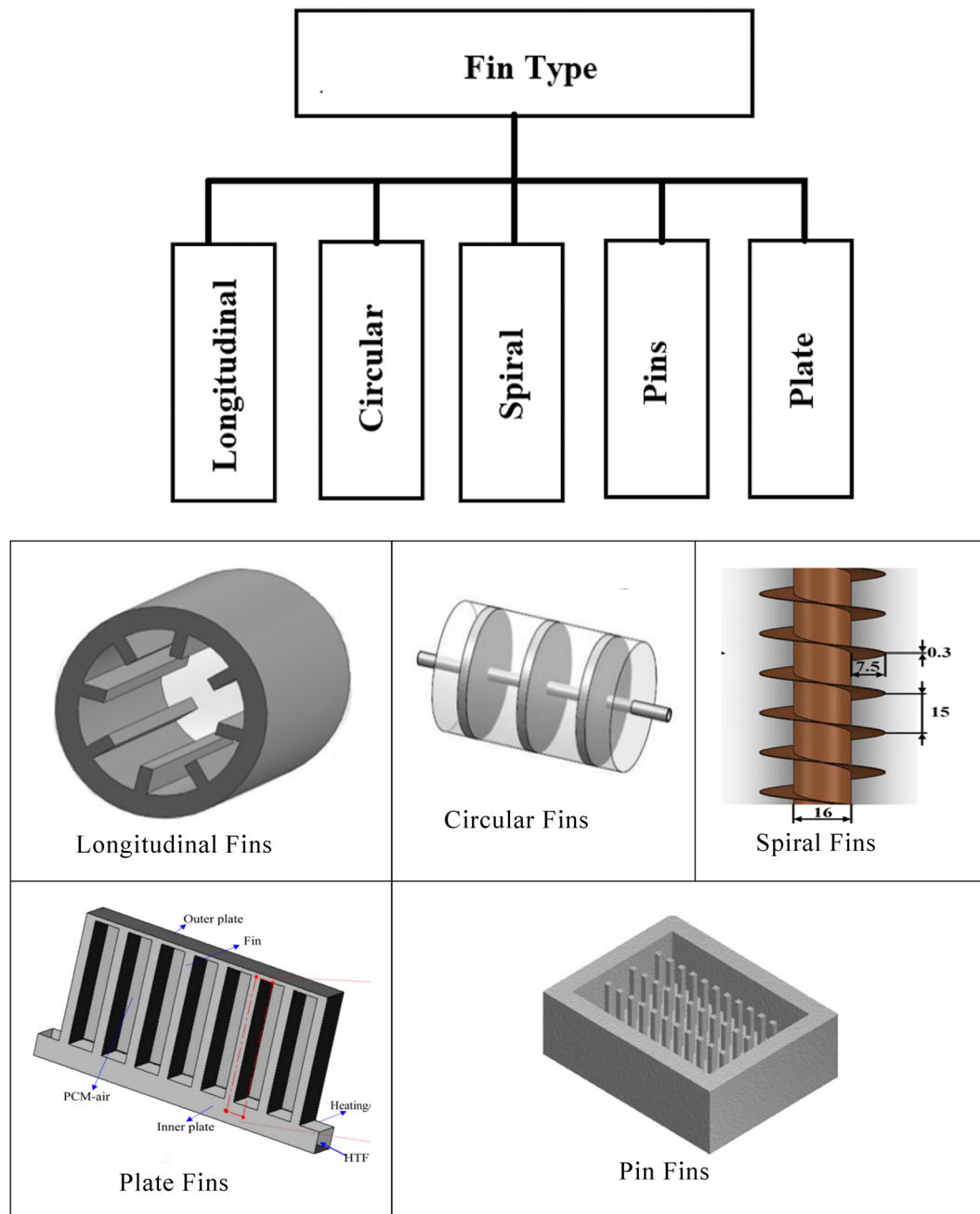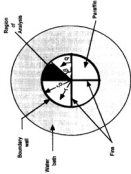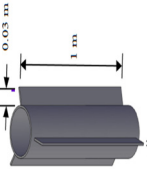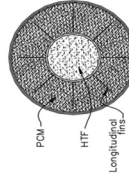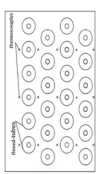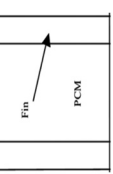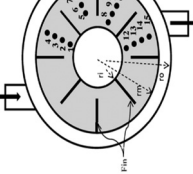
Figure 4: Various fin configuration techniques used in PCM-based LHTESS. Baba et al. (2018), Groulx and Ogoh (2009), Lu et al. (2021), Ye et al. (2011) and Baby and Balaji (2013).

- There is a strong impact of dimensionless quantities on thermal performances of LHTESS
- Thermal entity such as charging/discharging, melted volume fraction and temperature profile provides a comprehensive picture of results.

In line with the aforementioned discussions, Hosseini et al. (2015a) both experimentally and numerically explored the role of fin height as well as Stefan number on the thermal efficiency of pipe heat exchanger. In continuation of a similar exercise, Tiari et al. (2015) probed the effects of pipe spacing, fin length, fin number and natural convection upon the thermal performances of LHTESS. In addition, Al-Abidi et al. (2013a) studied the dependence of dimensionless quantities, fin parameters and PCM design module on operational characteristics of LHTESS. Following a similar approach, Ismail et al. (2001) looked into the impact of axial fins on solidification process in relation to quantities, such as fin parameters, annular spaces and aspect ratios. All these were found to significantly affect the fin characteristics.
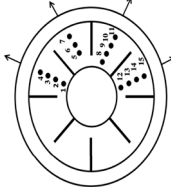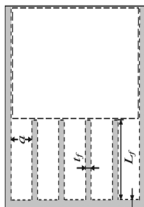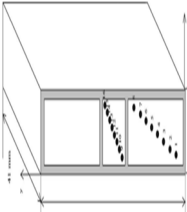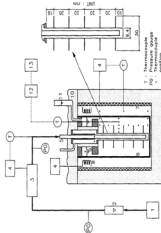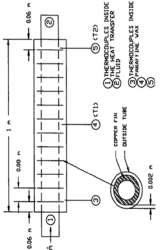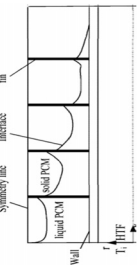
Table 4: Fin enhancement techniques in PCM-based LHTESS

Refs.	Nature of study	Design configurations	Figure/geometry of fin	Materials constructions of fin	Varying parameters	Major findings
Condition: Longitudinal fin configuration						
Velraj et al. (1997)	Experimental (discharging)	Cylindrical		Aluminium	Heat flux	Enhancing heat cooling rate and reducing discharging time
Rathod and Banerjee (2015)	Experimental (charging and discharging)	Shell and tube		Brass	Heat flux, HTF, initial temperature	Heat transmission rises as the HTF-initial temperature rises faster than the HTF mass flow rate
Baba et al. (2018)	Experimental study	Double pipe		Stainless steel	HTF, Reynolds number	Enhancing heat transfer rate in the finned tube HXs is 90–98% greater than the heat transfer rate in plain tube HXs
Agyenim et al. (2009)	Experimental (charging)	Concentric tube		Copper	HTF, mass flow rate, HTF, initial temperature	Using longitudinal fin PCM charging completed
Li et al. (2010)	Experimental (charging and discharging)	Circular tube		Copper	Heat flux	On the PCM, there is a consistent temperature range
Gharebaghi and Sezai (2007)	Numerical (charging)	Rectangular		Aluminium	Heat flux	Using longitudinal fin enhancing the heat transfer rate
Al-Abidi et al. (2014)	Experimental (charging and discharging)	TTHX		Copper	HTF, Mass flow rate, HTF, initial temperature	The temperature of the HTF's inlet has a greater impact than the temperature of the HTF mass flow rate on the PCM

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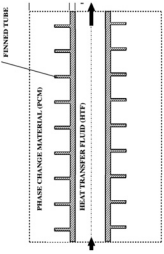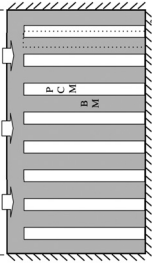
Table 4: *Continued*

Refs.	Nature of study	Design configurations	Figure/geometry of fin	Materials constructions of fin	Varying parameters	Major findings
Mat et al. (2013)	Numerical (charging)	TTHX		Copper	Heat flux	Enhancing charging rate utilizing the fin
Sharifi et al. (2011)	Numerical (charging)	Rectangular		Copper	Heat flux	Enhancing charging rate utilizing the fin
Lamberg et al. (2004)	Numerical (charging and discharging)	Rectangular		Aluminium	HTF, temperature	Using longitudinal fin enhancing the heat transfer rate
Condition: Circular fin configurations						
Choi and Kim (1995)	Experimental (discharging)	Shell and tube with annular fin		Stainless steel	HTF, mass flow rate, HTF, initial temperature	Enhancing cooling rate and radial temperature distribution
Lacroix (1993)	Numerical (charging)	Shell and tube with circular fin		Copper	HTF, mass flow rate, HTF, initial temperature	Increasing the PCM energy storage
Seeniraj et al. (2002)	Numerical (charging)	Shell and tube with circular fin		—	HTF, exit temperature	Enhancing the PCM energy storage
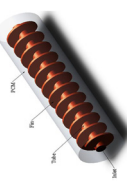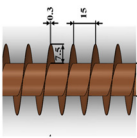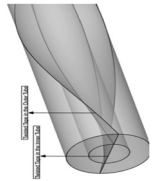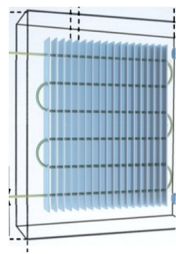
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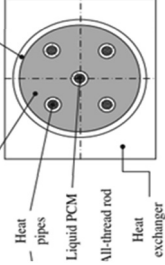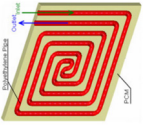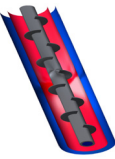| Refs.	Nature of study	Design configurations	Figure/geometry of fin	Materials constructions of fin	Varying parameters	Major findings
Ermis et al. (2007)	Experimental and numerical (charging and discharging)	Pipe circular fin		Bronze	HTF, mass flow rate, HTF, initial temperature	The ANN approach worked well in predicting the total quantity of heat stored.
Groulx and Ogoh (2009)	Numerical (charging)	Cylindrical with circular fin		Copper	Heat flux	Enhancing PCM phase change
Mosaffa et al. (2012)	Analytical (discharging)	Shell and tube with circular fin		Highly conductive base material	HTF, mass flow rate, HTF, initial temperature	Easily and fast solidify in cylindrical compared to rectangular container
Robak et al. (2011)	Experimental (charging)	Circular tube		Aluminium and copper	Heat flux	Fins did not work well.
Condition: Spiral fin configurations						
Banaszek et al. (1999)	Experimental (charging and discharging)	Cylindrical with spiral geometry		Copper	HTF, solid liquid phase change	Enhancing the charging and discharging rate
Erek and Ezan (2006)	Experimental and numerical (charging)	Spiral tube		Polyethylene	Flow rate and temperature	Obtain an optimum geometrical, flow and thermal conditions for TESS
Bahiraei et al. (2019)	Numerical (charging)	Helical coil tube		Aluminium	HTF initial temperature and Re	Enhancing the heat transfer rate
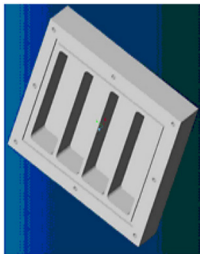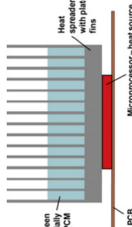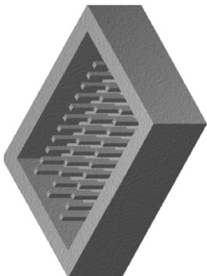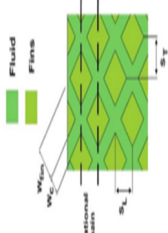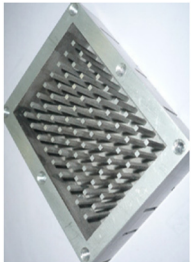
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Table 4: *Continued*

Refs.	Nature of study	Design configurations	Figure/geometry of fin	Materials constructions of fin	Varying parameters	Major findings
Borhani et al. (2019)	Numerical (charging)	Spiral fin tube		Copper	HTF initial temperature	Enhancing the charging rate
Lu et al. (2021)	Experimental (charging and discharging)	Vertical shell and spiral fin tube		Copper	HTF initial temperature charging and discharging time	Enhancing the charging and discharging rate
Noorbakhsh et al. (2020)	Numerical (charging)	Twisted tape in double pipe heat exchanger		—	Pressure drop, Nusselt number and coefficient of performance	Enhancing the heat transfer rate
Condition: Plate fin configurations						
Campos-Celador et al. (2013)	Numerical (charging)	Heat sink		Aluminium	Heat flux	PCM performance is influenced by the enclosure aspect ratio
Ye et al. (2011)	Numerical (charging and discharging)	Rectangular		Aluminium	Heat flux, HTF, initial temperature	Enhancement of heat transfer rate and storage of PCM
Rahimi et al. (2014)	Numerical (charging and discharging)	Rectangular		Aluminium and stainless steel	Operating temperature	Enhancing the storage of PCM
Saha and Dutta (2010)	Experimental (charging and discharging)	Shell and tube		Aluminium	HTF, initial temperature	Reducing the charging and discharging time

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Table 4: *Continued*

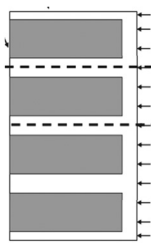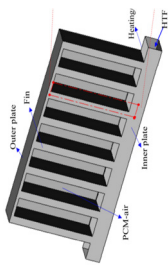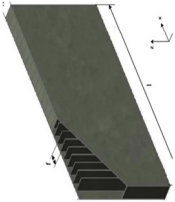| Refs.	Nature of study	Design configurations	Figure/geometry of fin	Materials constructions of fin	Varying parameters	Major findings
Condition: Pin fin configuration						
Fok et al. (2010)	Experimental (charging)	Heat sink		Aluminium	Heat flux	Enhancing heat transfer rate
Jaworski (2012)	Experimental and numerical (discharging)	Radiator		Copper and aluminium	Heat flux	Enhancing cooling rate
Baby and Balaji (2013)	Experimental and numerical (discharging)	Heat sink		Aluminium	Heat flux	Improvement of heat transfer rate
Rajabifar et al. (2016)	Numerical (charging)	Micro pin fin heat sink		Silicon	Heat flux	Enhancement of heat transfer rate due to nano encapsulation on the PCM
Srikanth and Balaji (2017)	Experimental (charging)	Heat sink with discrete heating		Silicon	Heat flux	Enhancement of heat transfer rate
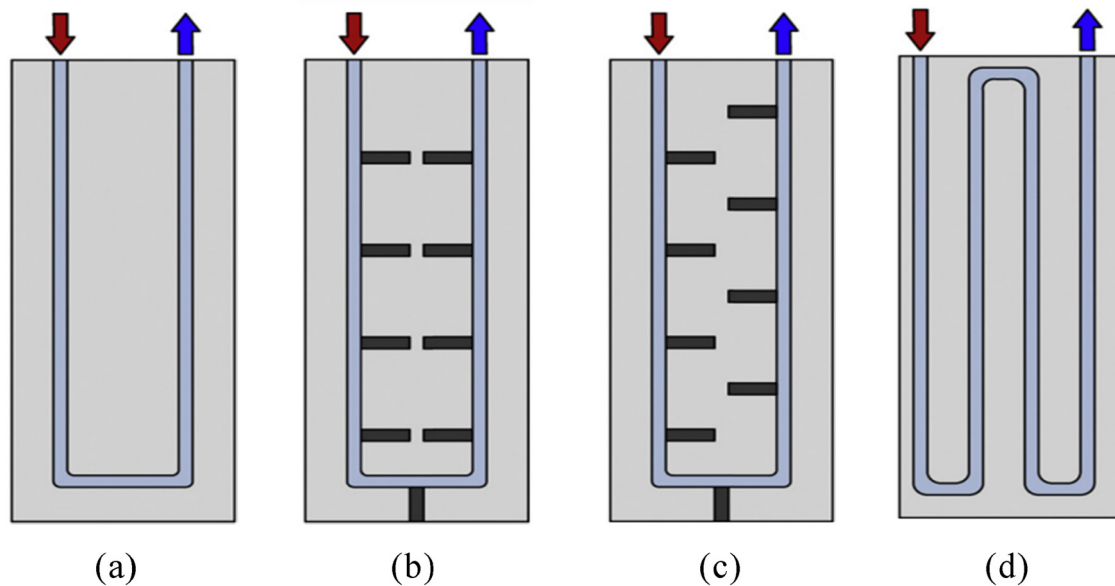
Figure 5: (a) U-tube, (b) U-tube with in-line fins, (c) U-tube with staggered fins and (d) Festoon design in the PCM-LHTESS (Kurnia et al. 2013).

4.1 Effect of fin geometry on thermodynamic performance of LHTESS

The present section provides a detailed coverage about geometrical aspects of extended surfaces or fin parameters on charging/discharging rate, total time for complete phase transition, molten or solidified mass percentage and stored energy potential, have been explored in this section.

Besides, this section is divided into four subsections for investigation:
(1) The impact of Fin number
(2) Thickness
(3) Length
(4) Distance between the fins: fin form and angle

4.1.1 Impact of fin count, width and lengths

The characteristics of fin count, width and lengths are linked to the heat transfer area and can thus have a significant impact on the performance characteristics pertaining to phase change process of PCM. However, the variation of properties depends upon whether the fins are horizontally mounted or vertically in relation to melting or solidification of PCM. Also, the presence of fins with variable geometrical features has a subtle bearing upon the temperature distribution and flow fields of the PCM in certain conditions. In line with the same Lacroix and Benmadda (1997) discovered that for a vertical rectangular tank having horizontal fins mounted on it (long as well as short fins), assist in heat transfer process mainly by way of conduction

mechanism in line with more number of fins in place. According to some previous research surveys (Zhang and Faghri 1996, Padmanabhan and Murthy 1986, Hosseini et al. 2015b), a definite increment in lengths of fins would develop a corresponding rise in melting rate of PCM.

However, Kamkari and Shokouhmand (2014) displayed that the involvement of partially horizontal fins are responsible for higher melting rates especially over the fin surfaces owing to the formation of a vortex. Besides that, the melting rate had experienced a subtle fall mainly because of increasing the fins width and decreasing the profile length. In addition, it was revealed that the melting time of PCM increases with increasing fin thickness in the presence of sunlight (Acır and Canlı 2018). Apart from that, for spirally twisted fins, reductions in fin width and fin pitch are some of the prominent ways to speed up the PCM melting process light (Liu et al. 2005a). Further, Ismail et al. (2001) investigated the impact of several parameters on the solidification process, i.e., reduction in solidification time owing to increases in the fin thickness. Furthermore, the solidification time is reduced by almost 60% when the wall temperature is raised from 5.4 to 20.1°C light (Nóbrega et al. 2019).

4.1.2 Impact of fin spacing

With regard to the aforementioned feature, Gharebaghi and Sezai (2007) examined the thermal performance of PCM–filled finned flat storage modules in melting and solidification modes under forced convection conditions to

Table 5: Novel fin configurations

Design configurations	Varying parameter	Nature of study	Major findings	Refs.
Rectangular, with straight fin	Operating temperature	Numerical (discharging)	Enhancement of heat transfer rate	Humphries and Griggs (1977)
Shell and tube, with spiral twisted	Heat flux	Experimental (charging)	Enhancement of heat transfer rate, reducing pre-charging time	Liu et al. (2005a)
Shell and tube, with spiral twisted	Heat flux	Experimental (discharging)	Enhancement of cooling rate, natural convection	Liu et al. (2005b)
u-tube, u-tube with inline fin, u-tube with staggered fin	Heat flux	Numerical (charging and discharging)	Enhancing the heat transfer rate	Kurnia et al. (2013)
Shell and tube, with tree fin	Heat flux	Numerical (discharging)	Enhancing the efficiency of LHTESS	Sciacovelli et al. (2015)
Rectangular, with stepped fins	Heat flux operating temperature	Numerical (charging)	Increasing the heat transfer rate	Nakhchi and Esfahani (2020)
Tapered shell and tube	Heat flux	Numerical (charging)	Enhancing the charging rate	Rudra Murthy et al. (2021)
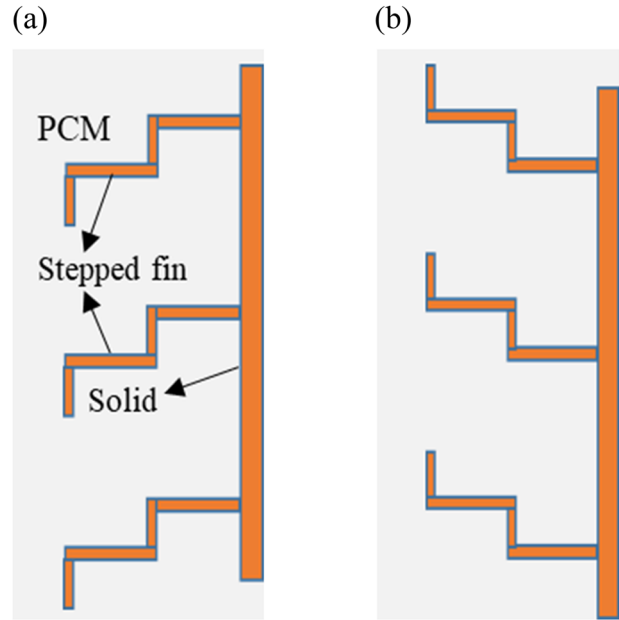
Figure 6: Schematic view of finned thermal storage system (Nakhchi and Esfahani, 2020). (a) Stepped fins downward. (b) Stepped fins upward.

conclude that for large fin spacing, it is always on the beneficial side to maintain a small gap between the fins to enhance heat transmission vis a vis thickness of modules, mainly because of the fact that smaller fin spacing leads to reduction in time it takes for both the modules to charge and discharge. Furthermore, decreasing the distance between the fins diminishes the strength of natural convection, which slows down the melting process (Lacroix and Benmadda 1998).

4.1.3 Impact of fin angle

The angle at which fins are mounted in a circular container plays an important role in estimation of phase change rate of PCM. In line of the same, the study on melting parameters of PCM in the horizontal circular enclosure was executed by Yuan et al. (2016) for five fin angles configurations to find optimum melting rate in purely vertically mounted fins. Post that, Kazemi et al. (2018) identified that increasing the fins angle from 60° to 120° for the triple–fin geometry and reducing the angle from 150° to 45° for double-fin arrangement decreases the melting time.

4.1.4 Impact of fin shape

Many researchers have proposed that the unique form of fin geometry can be used in a cylindrical or rectangular enclosure. In view of the same, Agyenim et al. (2007) recognised that a system with longitudinal fins is thermodynamically
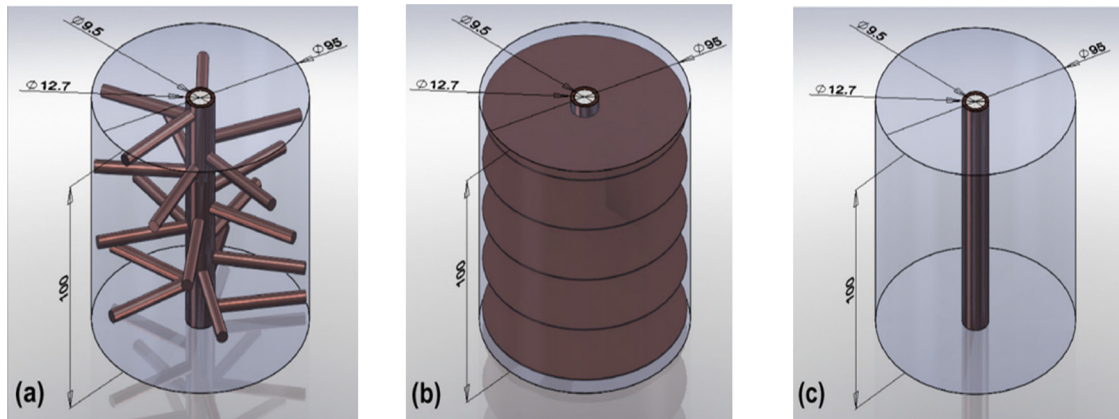
Figure 7: Plain tube with and without fins, cross-sectional views (Tay et al. 2013).

more stable in charging and discharging modes than that of the system with circular fins counterparts. Similarly, Eslami and Bahrami (2017) examined the thermal performance of I-shaped, V-shaped and Pencil-shaped fins in a rectangular enclosure with the same amount of material. Apart from the above-mentioned studies, single and double Y-shaped fins were installed in the LHTES unit to speed up the discharging process. In fact, adoption of multiple Y-shaped fins boosts discharging efficiency roughly by a percentage value of 24% (Sciacovelli et al. 2015, Lohrasbi et al. 2016b). Apart from the previous discussion, V-shaped fins were shown to have been solidified at a rate 1.5 times faster than their basic counterparts (Lohrasbi et al. 2016a). On a similar note, Abdulateef et al. (2017, 2018) recommended the use of triangular fins in the triplex tube storage system so as to improve the thermal behaviour. Quite intriguingly, in comparison to a

longitudinal fin arrangement, the results pertaining external triangular finned tube arrangement improve the solidification and melting processes by 18 and 15%, respectively.

4.1.5 Interactive effects between fin and HTF

Till date, the focus of aforementioned discussion was on the effect of fin number, size and shape on heat transfer behaviour of LHTES system, while geometrical aspects are understood in line with other parameters such as HTF flow rate and temperature. The magnitude of HTF mass flow rate has a significant bearing upon thermal energy stored capacity of the unit (Pakrouh et al. 2015). Other than that, in reality, raising the volumetric flow rate and switching from a laminar to a turbulent flow regime provides a sharp
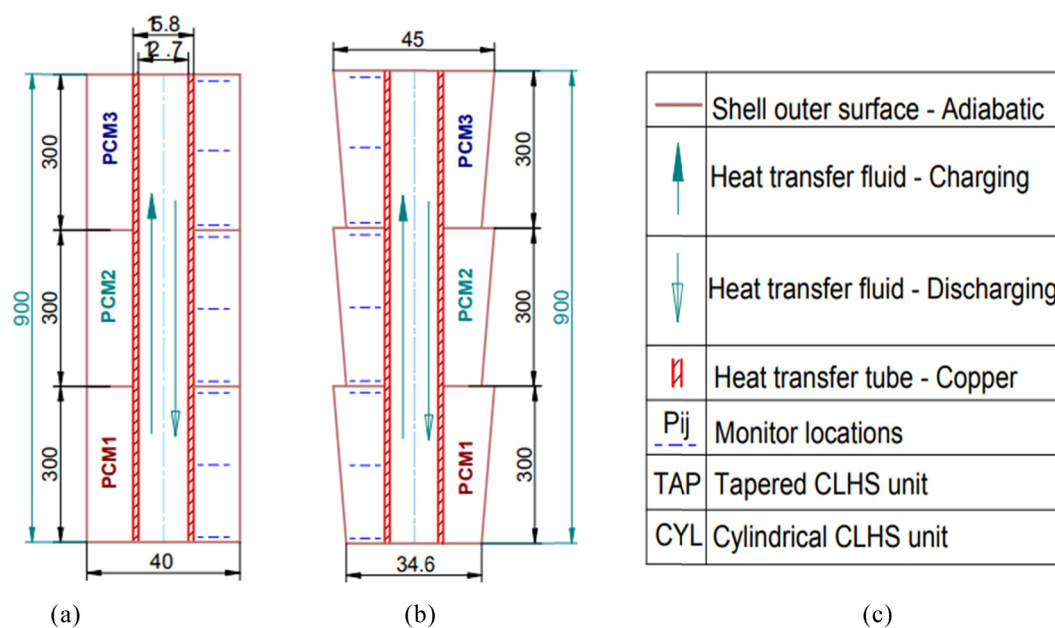
Figure 8: Dimensions, thermocouple location and notational of a cylindrical and tapered CLHS model (Rudra Murthy et al. 2021).

increment in convective heat transfer coefficient, which accelerates the heat transfer rate between the HTF and the PCM. Moreover, another interesting aspect of HTF is to bring about the positive impact on thermal performance of LTHESS by way of increasing HTF velocity accompanied by large number of fins (Ogoh and Groulx 2012). The importance of natural convection is certainly diminished in the present situation. Also, the position of the melting interface is greatly influenced by HTF velocity. Furthermore, an increase in the flow rate of cold HTF in a system leads to greater amount of energy recovery during simultaneous charging and discharging conditions (Murray and Groulx 2014a, b).

4.1.6 Impact of fin location

Depending upon the application of LHTESS, primarily two kinds of varieties of LHTESS are being employed for solar water heating as well as for electronic cooling. In both cases, the packed PCM system having HTF as working fluid is used, however in the latter case, hot/ cold boundary wall conditions are involved for analysis. Also, relative heat transfer is the parameter used for placement of fins in the storage system. Moreover, PCM-packed heat sinks involving pins or plate fins are being extensively utilised in cooling electronic equipment (Lacroix 1993, Akhilesh et al. 2005). Heat sinks with vertical and horizontal fins emerge from the heated vertical and bottom surface, respectively (Shatikian et al. 2005, 2008). Therefore, the discussion points to the fact that in PCM-based LHTESS, the design and inclination of the fins have a significant bearing on overall performance related to melting and solidification exercises of PCM.

5 Performance analysis of LHTESS with and without placement of fins

In the numerous studies performed so far, it has been exercised to ascertain the best possible fin structure to seek optimum phase change rate and a better quality of temperature distribution profile across various charging as well as discharging regimes. Additionally, Kumar et al. (2022) developed a comprehensive mathematical representation for estimation of thermal performance of LHTESS in conjunction with or without placement of longitudinal fins (external–internal) inside the storage structure. In addition, it was unearthed that there is a significant reduction in charging as well as discharging times (50–90 min) owing

to the placement of fins inside the storage structure. Further, there is substantial change in heat transfer characteristics of LHTESS, in line with consideration of entities such as number of fins, geometrical parameters of fins, heat exchanger material, Stefan Number and PCM design module. Besides that, Agyenim et al. (2009) examined three design configurations of LHTESS, such as no fins, circular fins and longitudinal fins, wherein it was found out that the thermal performance was recorded as best in the third case by way of enhancing thermal responsiveness during melting regime and decrement in sub-cooling behaviour upon solidification regime. Therefore, keeping in view the comprehensive discussion about fin and placement thereof in storage units, it was quite intriguing to reveal that placement of fins in an appropriate manner/number always assists in better thermal transmission while maintaining the same energy density and the same is adjudged as the most effective technique for a variety of shell and tube configurations (Al-Abidi et al. 2013b).

6 Conclusion

In recent times, several research works have been executed on PCM-assisted Latent Heat Thermal Energy Storage System (PCM – LHTESS) in connection with features such as unit design, behaviour of PCM during phase transition, optimization approaches in line with enrichment of heat transfer enhancement. The above set of researches provide a comprehensive information regarding restrictions and features of prolonged surface apart from in-depth study of charging and discharging behaviour of PCM during heat transfer phenomena. Owing to poor thermal conductivities of PCMs, the prominent technique of heat transfer enhancement is utilization of PCM-filled fins having variety of geometrical shapes such as longitudinal, circular and spiral. Besides, the present research endeavour provides subtle compilation of complex entities such as geometrical fin factors, HTF tube, enclosure shape, and flow parameters related to HTF. Consequently, the longitudinal fin configuration was adjudged as the most suitable/preferable fin configuration, mainly because of its simple design, less cost as well as ease of fabrication. For numerous shell and tube heat exchanger configurations, a circular finned tube configuration fin arrangement was ascertained to be more effective than its pinned counterpart.

- The optimization of the thermal performance of PCM-based LHTESS depends upon the careful selection of parameters such as geometrical entities, fin parameters, e.g. HTF tube and enclosure shape and flow parameters

associated with HTF. Consequently, the rate of heat transfer in a finned tube arrangement depends on the optimum numbers of fins as well as their geometrical dimension in the arrangement.

- Despite the fact, variation (usually increment) in the number and size of fin configuration results in better heat transmission, presence of more number of fins in the arrangement might lead to reduction in flow of convective current and thus restricting heat transfer augmentation.
- Besides the above discussed facts, it has also been unearthed that variation in fin length as well as increment in fin number, rather than fin thickness, has been found to have profound impact on thermal performance of system. In nutshell, fin thickness has a mild adverse effect on charging time with no major change in discharging time.
- The results of various empirical or computational studies are only available for a given system with its own set of characteristics, such as PCM type, enclosure size, HTF temperature and corresponding flow rates.
- Although, most novel fin shapes have been proved to have produced comparatively better charging/discharging rates than that of its simple longitudinal or radial counterparts. Also, selection of optimal fin shape for the melting or solidification process is no doubt a difficult exercise.
- The optimal value for fin number is based on mass flow rates of HTF and its temperature in line with the studies available on the interaction between fin qualities and HTF.
- In view of all the facts discussed in the present compilation, it has been understood primarily that design as well as optimization of fin parameters are in fact a complex activity apart from its being a computationally expensive given the transient nature of the system.
- Thus, designing of altogether a new model of fin is an indeed an important activity as far as heat transfer enhance is concerned particularly with regard to its extended applications in posterity, e.g. TESS and that too in connection with parameters such as mass flow rates, temperature and geometrical entities of the fin.

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References

Abdulateef A. M., Abdulateef J., Mat S., Sopian K., Elhub B., and Mussa M. A. (2018). "Experimental and numerical study of solidifying phase-change material in a triplex – tube heat exchanger with longitudinal/triangular fins," *Int. Commun. Heat Mass Transf.*, vol. 90, pp. 73–84, https://www.sciencedirect.com/science/article/abs/pii/S0735193317302658.

Abdulateef A. M., Mat S., Sopian K., Abdulateef J., and Gitan A. A. (2017). "Experimental and computational study of melting phase-change material in a triplex tube heat exchanger with longitudinal/triangular fins," *Sol. Energy*, vol. 155, pp. 142–153, https://www.sciencedirect.com/science/article/abs/pii/S0038092X17305273.

Abhat A. (1983). "Low temperature latent heat thermal energy storage: Heat storage materials," *Sol. Energy*, vol. 30, no. 4, pp. 313–332, https://www.sciencedirect.com/science/article/abs/pii/0038092X8390186X.

Acır A. and Canlı M. E. (2018). "Investigation of fin application effects on melting time in a latent thermal energy storage system with phase change material (PCM)," *Appl. Therm. Eng.*, vol. 144, p. 1071, https://www.sciencedirect.com/science/article/abs/pii/S1359431118310792.

Agyenim F., Eames P., and Smyth M. (2007). "A comparison of heat transfer enhancement in medium temperature thermal energy storage heat exchanger using fins and multitubes," *ISES Sol. World Congr.*, vol. 4, p. 2726, https://link.springer.com/chapter/10.1007/978-3-540-75997-3_550.

Agyenim F., Eames P., and Smyth M. (2009). "A comparison of heat transfer enhancement in a medium temperature thermal energy storage heat exchanger using fins," *Sol. Energy*, vol. 83, no. 9, pp. 1509–1520, https://www.sciencedirect.com/science/article/abs/pii/S0038092X09000942.

Agyenim F., Eames P., and Smyth M. (2010a). "Heat transfer enhancement in medium temperature thermal energy storage system using a multitube heat transfer array," *Renew. Energy*, vol. 35, no. 1, pp. 198–207, doi: 10.1016/j.renene.2009.03.010.

Agyenim F., Hewitt N., Eames P., and Smyth M. (2010b). "A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS)," *Renew. Sustain. Energy Rev.*, vol. 14, no. 2, pp. 615–628, https://www.sciencedirect.com/science/article/abs/pii/S1364032109002469.

Agyenim F., Eames P., and Smyth M. (2011). "Experimental study on the melting and solidification behaviour of a medium temperature phase change storage material (Erythritol) system augmented with fins to power a LiBr/H$_2$O absorption cooling system," *Renew. Energy*, vol. 36, no. 1, pp. 108–117, https://www.sciencedirect.com/science/article/abs/pii/S0960148110002612.

Akgün M., Aydin O., and Kaygusuz K. (2007). "Experimental study on melting/solidification characteristics of a paraffin as PCM," *Energy*

Convers. Manag., vol. 48, no. 2, pp. 669–678, https://www.sciencedirect.com/science/article/abs/pii/S0196890406001786.

Akhilesh R., Narasimhan A., and Balaji C. (2005). "Method to improve geometry for heat transfer enhancement in PCM composite heat sinks," *Int. J. Heat Mass Transf.*, vol. 48, no. 13, pp. 2759–2770, https://www.sciencedirect.com/science/article/abs/pii/S0017931005001419.

Al-Abidi A. A., Mat S., Sopian K., Sulaiman M. Y., and Mohammad A. T. (2013a). "Internal and external fin heat transfer enhancement technique for latent heat thermal energy storage in triplex tube heat exchangers," *Appl. Therm. Eng.*, vol. 53, no. 1, pp. 147–156, https://www.sciencedirect.com/science/article/abs/pii/S1359431113000410.

Al-Abidi A. A., Mat S., Sopian K., Sulaiman M. Y., and Mohammad A. T. (2013b). "Numerical study of PCM solidification in a triplex tube heat exchanger with internal and external fins," *Int. J. Heat Mass Transf.*, vol. 61, pp. 684–695, https://doi.org/10.1016/j.ijheatmasstransfer.2013.02.030.

Al-Abidi A., Mat S., Sopian K., Sulaiman M. Y., and Mohammad A. T. (2014). "Experimental study of melting and solidification of PCM in a triplex tube heat exchanger with fins," *Energy Build.*, vol. 68, pp. 33–41, https://www.sciencedirect.com/science/article/abs/pii/S0378778813005707.

Al-Maghalseh M. and Mahkamov K. (2018). "Methods of heat transfer intensification in PCM thermal storage systems: Review," *Renew. Sustain. Energy Rev.*, vol. 92, pp. 62–94, https://www.sciencedirect.com/science/article/abs/pii/S1364032109002469.

Altac Z. and Altun O. (2014). "Hydrodynamically and thermally developing laminar flow in spiral coil tubes," *Int. J. Therm. Sci.*, vol. 77, pp. 96–107, https://www.sciencedirect.com/science/article/abs/pii/S1290072913002561.

Amaral C., Vicente R., Marques P., and Timmons A. (2017). "Phase change materials and carbon nanostructures for thermal energy storage: A literature review," *Renew. Sustain. Energy Rev.*, vol. 79, pp. 1212–1228. https://sciencedirect.com/science/article/abs/pii/S1364032117307293.

Amin N. A., Bruno F., and Belusko M. (2014). "Effective thermal conductivity for melting in PCM encapsulated in a sphere," *Appl. Energy*, vol. 122, pp. 280–287, https://www.sciencedirect.com/science/article/abs/pii/S0306261914001020.

Arasu A. V. and Mujumdar A. S. (2012). "Numerical study on melting of paraffin wax with Al_2O_3 in a square enclosure," *Int. Commun. Heat Mass Transf.*, vol. 39, no. 1, pp. 8–16, https://www.sciencedirect.com/science/article/abs/pii/S0735193311002156.

Assis E., Katsman L., Ziskind G., and Letan R. (2007a). "Numerical and experimental study of melting in a spherical shell," *Int. J. Heat Mass Transf.*, vol. 50, no. 10, p. 1790, https://www.sciencedirect.com/science/article/abs/pii/S0017931006005503.

Assis E., Katsman L., Ziskind G., and Letan R. (2007b). "Numerical and experimental study of solidification in a spherical shell melting in a spherical shell," *Int. J. Heat Mass Transf.*, vol. 50, no. 9–10, pp. 1790–1804, https://www.sciencedirect.com/science/article/abs/pii/S0017931006005503.

Assis E., Ziskind G., and Letan R. (2009). "Numerical and experimental study of solidification in a spherical shell," *J. Heat Transf.*, vol. 131, no. 2, pp. 1–5, doi: 10.1115/1.2993543.

Baba M., Raju A. V., and Rao M. B. (2018). "Heat transfer enhancement and pressure drop of Fe_3O_4 -water nanofluid in a double tube counter flow heat exchanger with internal longitudinal fins," *Case Stud. Therm. Eng.*, vol. 12, pp. 600–607, https://www.sciencedirect.com/science/article/pii/S2214157X18301436.

Baby R. and Balaji C. (2013). "Thermal optimization of PCM based pin fin heat sinks: An experimental study," *Appl. Therm. Eng.*, vol. 54, no. 1, pp. 65–77, https://www.sciencedirect.com/science/article/abs/pii/S1359431113000045.

Bahiraei M., Mazaheri N., and Rizehvandi A. (2019). "Application of a hybrid nanofluid containing graphene nanoplatelet–platinum composite powder in a triple – tube heat exchanger equipped with inserted ribs," *Appl. Therm. Eng.*, vol. 149, pp. 588–601, https://www.sciencedirect.com/science/article/abs/pii/S1359431118359878.

Banaszek J., Domañski R., Rebow M., and El-Sagier F. (1999). "Experimental study of solid – liquid phase change in a spiral thermal energy storage unit," *Appl. Therm. Eng.*, vol. 19, no. 12, pp. 1253–1277, https://www.sciencedirect.com/science/article/abs/pii/S1359431198001203.

Bharadwaj P., Khondge A., and Date A. (2009). "Heat transfer and pressure drop in a spirally grooved tube with twisted tape insert," *Int. J. Heat Mass Transf.*, vol. 52, pp. 1938–1944, https://www.sciencedirect.com/science/article/abs/pii/S0017931008006066.

Borhani S. M., Hosseini M. J., Ranjbar A. A., and Bahrampoury R. (2019). "Investigation of phase change in a spiral-fin heat exchanger," *Appl. Math. Model.*, vol. 67, pp. 297–314, https://www.sciencedirect.com/science/article/pii/S0307904X18305213.

Bruno F., Belusko M., Liu M., and Tay N. H. S. (2015). *Using solid-liquid phase change materials (PCMs) in thermal energy storage systems*, Woodhead Publishing Limited. https://doi.org/10.1533/9781782420965.2.201.

Campos-Celador A., Diarce G., González I., and Sala J. (2013). "Development and comparative analysis of the modeling of an innovative finned-plate latent heat thermal energy storage system," *Energy*, vol. 58, pp. 438–447, https://www.sciencedirect.com/science/article/abs/pii/S0360544213005306.

Cho K. and Choi S. H. (2000). "Thermal characteristics of paraffin in a spherical capsule during freezing and melting processes," *Int. J. Heat Mass Transf.*, vol. 43, pp. 3183–3196, https://www.sciencedirect.com/science/article/abs/pii/S0017931099003294.

Choi J. C. and Kim S. D. (1995). "Heat – transfer characteristics of a latent heat storage system using $MgCl_2 \cdot 6H_2O$ at the melting point," *Energy*, vol. 20, no. 1, pp. 13–25, https://www.sciencedirect.com/science/article/abs/pii/0360544294000514.

Dhaidan N. S., Khodadadi J. M., Al-Hattab T. A., and Al-Mashat S. M. (2013). "Experimental and numerical investigation of melting of phase change material/nanoparticle suspensions in a square container subjected to a constant heat flux," *Int. J. Heat Mass Transf.*, vol. 6, pp. 672–683, https://www.sciencedirect.com/science/article/abs/pii/S0017931013005346.

Eames I. W. and Adref K. T. (2002). "Freezing and melting of water in spherical enclosures of the type used in thermal/ice storage systems," *Appl. Therm. Eng.*, vol. 22, no. 7, pp. 733–745, https://www.sciencedirect.com/science/article/abs/pii/S1359431102000261.

Elbahjaoui R. and Qarnia H. E. (2017). Transient behavior analysis of the melting of nanoparticle-enhanced phase change material inside a rectangular latent heat storage unit," *Appl. Therm. Eng.*, vol. 112, pp. 720–738, https://www.sciencedirect.com/science/article/abs/pii/S1359431116325662.

Erek A. and Ezan M. A. (2006). "Experimental and numerical study on charging processes of an ice-on-coil thermal energy storage system," *Int. J. Energy Res.*, vol. 31, no. 02, pp. 158–176, https://onlinelibrary.wiley.com/doi/abs/10.1002/er.1240.

Erek A., Ilken Z., and Acar M. A. (2005). "Experimental and numerical investigation of thermal energy storage with a finned tube," *Int. J.*

Energy Res., vol. 29, no. 4, pp. 283–301, https://onlinelibrary.wiley.com/doi/10.1002/er.1057.

Ermis K., Erek A., and Dincer I. (2007). "Heat transfer analysis of phase change process in a finned-tube thermal energy storage system using artificial neural network," *Int. J. Heat Mass Transf.*, vol. 50, pp. 3163–3175, https://www.sciencedirect.com/science/article/abs/pii/S001793100700052X.

Eslami M. and Bahrami M. A. (2017). "Sensible and latent thermal energy storage with constructal fins," *Int. J. Hydrog. Energy*, vol. 42, no. 28, p. 17681, https://www.sciencedirect.com/science/article/abs/pii/S0360319917314866.

Fan L. and Khodadadi J. M. (2012). "An experimental investigation of enhanced thermal conductivity and expedited unidirectional freezing of cyclohexane-based nanoparticle suspensions utilized as nano-enhanced phase change materials (NePCM)," *Int. J. Therm. Sci.*, vol. 62, pp. 120–126, https://www.sciencedirect.com/science/article/abs/pii/S1290072911003358.

Fernandez A. I., Martnez M., Segarra M., Martorell I., and Cabeza L. F. (2010). "Selection of materials with potential in sensible thermal energy storage," *Sol. Energy Mater. Sol. Cell*, vol. 94, no. 10, pp. 1723–1729, https://www.sciencedirect.com/science/article/abs/pii/S0927024810003296?via%3Dihub.

Fisch M. N., Guigas M., and Dalenbäck J. O. (1998). "A review of large-scale solar heating systems in Europe," *Sol. Energy*, vol. 63, no. 6, pp. 355–366, https://www.sciencedirect.com/science/article/abs/pii/S0038092X98001030?via%3Dihub.

Fok S., Shen W., and Tan F. (2010). "Cooling of portable hand-held electronic devices using phase change materials in finned heat sinks," *Int. J. Therm. Sci.*, vol. 49, pp. 109–117, https://www.sciencedirect.com/science/article/abs/pii/S1290072909001471.

Galione P. A., Lehmkuhl O., Rigola J., and Oliva A. (2015). "Fixed-grid numerical modeling of melting and solidification using variable thermo-physical properties- Application to the melting of n-Octadecane inside a spherical capsule," *Int. J. Heat Mass Transf.*, vol. 86, pp. 721–743, https://www.sciencedirect.com/science/article/abs/pii/S0017931015002914.

Gao Z., Yao Y., and Wu H. (2019). "Validation of a melting fraction-based effective thermal conductivity correlation for prediction of melting phase change inside a sphere," *Int. J. Therm. Sci.*, vol. 142, pp. 247–257, doi: 10.1016/j.ijthermalsci.2019.04.029.

Gasia J., Miró L., and Cabeza L. (2016). "Materials and system requirements of high temperature thermal energy storage systems: A review Thermal conductivity enhancement techniques," *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1584–1601, https://www.sciencedirect.com/science/article/abs/pii/S0017931019301449.

Gharebaghi M. and Sezai I. (2007). "Enhancement of heat transfer in latent heat storage modules with internal fins," *Numer. Heat Transf., Part. A: Appl.*, vol. 53, no. 7, pp. 749–765, doi: 10.1080/10407780701715786.

Ghoneim A. A. (1989). "Comparison of theoretical models of phase-change and sensible heat storage for air & water-based solar heating systems," *Sol. Energy*, vol. 42, no. 3, pp. 209–220, https://www.sciencedirect.com/science/article/abs/pii/0038092X89900133Accessed May 1, 2023.

Groulx D. and Ogoh W. (2009). "Solid-liquid phase change simulation applied to a cylindrical latent heat energy storage system," Proceedings of the 5th Annual COMSOL Conference, Boston USA, https://www.uk.comsol.com/papers/6414/download/Groulx.pdf.

Gürel B. (2020). "Thermal performance evaluation for solidification process of latent heat thermal energy storage in a corrugated plate heat exchanger," *Appl. Therm. Eng.*, vol. 174, p. 115312, doi: 10.1016/j.applthermaleng.2020.115312.

Ho J. C. and Gao J. Y. (2009). "Preparation and thermophysical properties of nanoparticle-in-paraffin emulsion as phase change material," *Int. Commun. Heat Mass Transf.*, vol. 36, no. 5, pp. 467–470, https://www.sciencedirect.com/science/article/abs/pii/S0735193309000414.

Hosseini M. J., Rahimi M., and Bahrampoury R. (2014). "Experimental and computational evolution of a shell and tube heat exchanger as a PCM thermal storage system," *Int. Commun. Heat Mass Transf.*, vol. 50, pp. 128–136, https://www.sciencedirect.com/science/article/abs/pii/S0735193313002194.

Hosseini M. J., Rahimi M., and Bahrampoury R. (2015a). "Thermal analysis of PCM containing heat exchanger enhanced with normal annular fines," *Mech. Sci.*, vol. 6, pp. 221–234, doi: 10.5194/ms-6-221-2015.

Hosseini M. J., Ranjbar A. A., Rahimi M., and Bahrampoury R. (2015b). "Experimental and numerical evaluation of longitudinally finned latent heat thermal storage systems," *Energy Build.*, vol. 99, p. 263, https://www.sciencedirect.com/science/article/abs/pii/S0378778815003448.

Hosseinizadeh S. F., Darzi A. A. R., and Tan F. L. (2012). "Numerical investigations of unconstrained melting of nano-enhanced phase change material (NEPCM) inside a spherical container," *Int. J. Therm. Sci.*, vol. 51, pp. 77–83, doi: 10.1016/j.ijthermalsci.2011.08.006.

Humphries W. R. and Griggs E. I. (1977). *A design handbook for phase change thermal control and energy storage devices*, NASA Technical Paper 1074, https://ntrs.nasa.gov/citations/19780007491.

Ibrahim N., Al-Sulaiman F., Rahman S., Yilbas B., and Sahin A. (2017). "Heat transfer enhancement of phase change materials for thermal energy storage application: A critical review," *Renew. & Sustain. Energy Rev.*, vol. 74, pp. 26–50, https://www.sciencedirect.com/science/article/abs/pii/S1364032117301739.

Ismail K. A. R., Alves C. L. F., and Modesto M. S. (2001). "Numerical and experimental study on the solidification of PCM around a vertical axially finned isothermal cylinder," *Appl. Therm. Eng.*, vol. 21, no. 1, pp. 53–77, https://www.sciencedirect.com/science/article/abs/pii/S1359431100000028.

Jaworski M. (2012). "Thermal performance of heat spreader for electronics cooling with incorporated phase change material," *Appl. Therm. Eng.*, vol. 35, pp. 212–219, https://www.sciencedirect.com/science/article/abs/pii/S1359431111005746.

Jegadheeswaran S. and Pohekar S. D. (2009). "Performance enhancement in latent heat thermal storage system: A review," *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2225–2244, https://www.sciencedirect.com/science/article/abs/pii/S1364032109001221.

Jellouli Y., Chouikh R., Guizani A., and Belghith A. (2007). "Numerical study of the moving boundary problem during melting process in a rectangular cavity heated from below," *Am. J. Appl. Sci.*, vol. 4, no. 4, pp. 251–256, https://thescipub.com/abstract/ajassp.2007.251.256.

Jesumathy S. P., Udayakumar M., and Suresh S. (2012). "Heat transfer characteristics in latent heat storage system using paraffin wax," *J. Mech. Sci. Technol.*, vol. 26, pp. 959–965, https://www.sciencedirect.com/science/article/abs/pii/S0735193313002194.

Jian-you L. (2008). "Numerical and experimental investigation for heat transfer in triplex concentric tube with phase change material for thermal energy storage," *Sol. Energy*, vol. 82, no. 11, pp. 977–985, https://www.sciencedirect.com/science/article/abs/pii/S0038092X08001096.

Jung E. G. and Boo J. H. (2014). "Thermal analytical model of latent thermal storage with heat pipe heat exchanger for concentrated solar power," *Sol. Energy*, vol. 102, pp. 318–332, https://www.sciencedirect.com/science/article/abs/pii/S0038092X13004805.

Kamkari B. and Shokouhmand H. (2014). "Experimental investigation of phase change material melting in rectangular enclosures with horizontal partial fins," *Int. J. Heat Mass Tranfer*, vol. 78, p. 839, https://www.sciencedirect.com/science/article/abs/pii/S0017931014006450.

Kazemi M., Hosseini M. J., Ranjbar A. A., and Bahrampoury R. (2018). "Improvement of longitudinal fins configuration in latent heat storage systems," *Renew. Energy*, vol. 116, p. 447, https://www.sciencedirect.com/science/article/abs/pii/S0960148117309679.

Kumar R., Rao Y. A., Yadav A. S., Balu A., Taneja S., and Sharma A. (2022). "Application of phase change material in thermal energy storage systems," *Mater. Today Proc.*, vol. 63, pp. 798–804, doi: 10.1016/j.matpr.2022.06.152.

Kurnia J. C., Sasmito A. P., Jangam S. V., and Mujumdar A. S. (2013). "Improved design for heat transfer performance of a novel phase change material (PCM) thermal energy storage (TES)," *Appl. Therm. Eng.*, vol. 50, no. 1, pp. 896–907, https://www.sciencedirect.com/science/article/abs/pii/S1359431112005376.

Lacroix M. (1993). "Study of the heat transfer behavior of a latent heat thermal energy storage unit with a finned tube," *Int. J. Heat Mass Transf.*, vol. 36, pp. 2083–2092, https://www.sciencedirect.com/science/article/abs/pii/S1364032109002469.

Lacroix M. and Benmadda M. (1997). "Numerical simulation of natural convection-dominated melting and solidification from a finned vertical wall," *Numer. Heat Transf. Part. A Appl.*, vol. 31, no. 1, pp. 71–86, https://www.tandfonline.com/doi/abs/10.1080/10407789708914026.

Lacroix M. and Benmadda M. (1998). "Analysis of natural convection melting from a heated wall with vertically oriented fins," *Int. J. Numer. Methods Heat Fluid Flow.*, vol. 8, no. 4, p. 465, https://www.emerald.com/insight/content/doi/10.1108/09615539810213241/full/html.

Lago T. G., Ismail K. A., Lino F. A., and Arabkoohsar A. (2020). "Experimental correlations for the solidification and fusion times of PCM encapsulated in spherical shells," *Exp. Heat Transf.*, vol. 33, no. 5, pp. 440–454, https://www.tandfonline.com/doi/pdf/10.1080/08916152.2019.1656301.

Lamberg P., Lehtiniemi R., and Henell A. M. (2004). "Numerical and experimental investigation of melting and freezing processes in phase change material storage," *Int. J. Therm. Sci.*, vol. 43, no. 3, pp. 277–287, https://www.sciencedirect.com/science/article/abs/pii/S1290072903001303.

Lee M., Kang T., Joo Y., and Kim Y. (2011). "Heat transfer characteristics of spirally-coiled circular fin-tube heat exchangers operating under frosting conditions," *Int. J. Refrig.*, vol. 34, no. 1, pp. 328–336, https://www.sciencedirect.com/science/article/abs/pii/S0140700710001854.

Li W., Li X., and Zhao J. (2010). "Experimental study of a finned-tubes phase change heat storage system," *Asia-Pacific Power Energy Engineering Conference APPEEC*, pp. 25–28, https://ieeexplore.ieee.org/document/5449502.

Li Y., Wu J., Wang H., Kou L., and Tian X. (2012). "Fluid flow and heat transfer characteristics in helical tubes cooperating with spiral corrugation," *Energy Procedia*, vol. 17, pp. 791–800, https://www.sciencedirect.com/science/article/pii/S1876610212005085.

Liao Z., Xu C., Ren Y., Gao F., and Du X. (2018). "A novel effective thermal conductivity correlation of the PCM melting in spherical PCM encapsulation for the packed bed TES system," *Appl. Therm. Eng.*, vol. 135, pp. 116–122, https://www.sciencedirect.com/science/article/abs/pii/S1359431117367741.

Liu Z., Sun X., and Ma C. (2005a). "Experimental investigations on the characteristics of melting processes of stearic acid in an annulus and its thermal conductivity enhancement by fins," *Energy Convers. Manag.*, vol. 46, no. 6, pp. 959–969, https://www.sciencedirect.com/science/article/abs/pii/S019689040400130X.

Liu Z., Sun X., and Ma C. (2005b). "Experimental study of the characteristics of solidification of stearic acid in an annulus and its thermal conductivity enhancement," *Energy Convers. Manang.*, vol. 46, no. 6, pp. 971–984, https://www.sciencedirect.com/science/article/abs/pii/S0196890404001293.

Lohrasbi S., Bandpy M. G., and Ganji D. D. (2016a). "Response surface method optimization of V-shaped fin assisted latent heat thermal energy storage system during discharging process," *Alex. Eng. J.*, vol. 55, no. 3, p. 2065, https://www.sciencedirect.com/science/article/pii/S1110016816301764.

Lohrasbi S., Sheikholeslami M., and Ganji D. D. (2016b). "Discharging process expedition of NEPCM in fin-assisted latent heat thermal energy storage system," *J. Mol. Liq.*, vol. 221, p. 833, https://www.sciencedirect.com/science/article/abs/pii/S0167732215313891.

Lu B., Zhang Y., Sun D., and Yang S. (2021). "Experimental investigation on thermal behavior of paraffin in a vertical shell and spiral fin tube latent heat thermal energy storage unit," *Appled Therm. Eng.*, vol. 187, p. 116575, https://www.sciencedirect.com/science/article/abs/pii/S1359431121000326.

Mahdi J. M. and Nsofor E. C. (2016). "Solidification of a PCM with nanoparticles in triplex-tube thermal energy storage system," *Appl. Therm. Eng.*, vol. 108, pp. 596–604, https://www.sciencedirect.com/science/article/abs/pii/S1359431116312613.

Mahdi J. M., Lohrasbi S., and Nsofor E. C. (2019). "Hybrid heat transfer enhancement for latent-heat thermal energy storage systems: A review," *Int. J. Heat Mass Transf.*, vol. 137, pp. 630–649, https://www.sciencedirect.com/science/article/abs/pii/S0017931019301449.

Mahfuz M. H., Anisur M. R., Kibria M. A., Saidur R., and Metselaar I. H. S. C. (2014). "Performance investigation of thermal energy storage system with Phase Change Material (PCM) for solar water heating application," *Int. Commun. Heat Mass Transf.*, vol. 57, pp. 132–139, https://www.sciencedirect.com/science/article/abs/pii/S0735193314001791.

Mat S., Al-Abidi A., Sopian K., Sulaiman M. Y., and Mohammad A. T. (2013). "Enhance heat transfer for PCM melting in triplex tube with internal-external fins," *Energy Convers. Manag.*, vol. 74, pp. 223–236, https://www.sciencedirect.com/science/article/abs/pii/S0196890413002501.

Morrison D. J. and Abdel-Khalik S. I. (1978). "Effects of phase-change energy storage on the performance of air-based and liquid-based solar heating systems," *Sol. Energy*, vol. 20, no. 1, pp. 57–67, https://www.sciencedirect.com/science/article/abs/pii/0038092X7890141X.

Mosaffa A. H., Talati F., Tabrizi H., and Rosen M. A. (2012). "Analytical modeling of PCM solidification in a shell and tube finned thermal storage for air conditioning systems," *Energy Build.*, vol. 49, pp. 356–361, https://www.sciencedirect.com/science/article/abs/pii/S0378778812001478.

Motahar S., Alemrajabi A. A., and Khodabandeh R. (2017). "Experimental study on solidification process of a phase change material

containing TiO$_2$ nanoparticles for thermal energy storage," *Energy Convers. Manag.*, vol. 138, pp. 162–170, https://www.sciencedirect.com/science/article/abs/pii/S0196890417300705.

Mozafari M., Lee A., and Cheng S. (2022). "A novel dual-PCM configuration to improve simultaneous energy storage & recovery in triplex-tube heat exchanger," *Int. J. Heat Mass Transf.*, vol. 186, pp. 412–420, https://www.sciencedirect.com/science/article/abs/pii/S0017931021015180.

Murray R. E. and Groulx D. (2014a). "Experimental study of the phase change and energy characteristics inside a cylindrical latent heat energy storage system: Part 2 simultaneous charging and discharging," *Renew. Energy*, vol. 63, pp. 724–734, https://www.sciencedirect.com/science/article/abs/pii/S096014811300534X.

Murray R. E. and Groulx D. (2014b). "Experimental study of the phase change and energy characteristics inside a cylindrical latent heat energy storage system: Part I consecutive charging and discharging," *Renew. Energy*, vol. 62, pp. 571–581, https://www.sciencedirect.com/science/article/abs/pii/S0960148113004084.

Nakhchi M. E. and Esfahani J. A. (2020). "Improving the melting performance of PCM thermal energy storage with novel stepped fins," *J. Energy Storage*, vol. 30, p. 101424, https://www.sciencedirect.com/science/article/abs/pii/S2352152X19316317.

Naphon P. (2011). "Study on the heat transfer and flow characteristics in a spiral-coil tube," *Int. Commun. Heat Mass Transf.*, vol. 38, no. 1, pp. 69–74, https://www.sciencedirect.com/science/article/abs/pii/S0735193310002502.

Ng K. W., Gong Z. X., and Mujumdar A. S. (1998). "Heat transfer in free convection-dominated melting of a phase change material in a horizontal annulus," *Int. Commun. Heat Mass Transf.*, vol. 25, no. 5, pp. 631–640, doi: 10.1016/S0735-1933(98)00050-5.

Nguyen D. K. and San J. Y. (2016a). "Decrement in heat transfer effectiveness due to solid heat conduction for a counter-current spiral heat exchanger," *Appl. Therm. Eng.*, vol. 103, pp. 821–831, https://www.sciencedirect.com/science/article/abs/pii/S1359431116305713.

Nguyen D. K. and San J. Y. (2016b). "Heat transfer and exergy analysis of a spiral heat exchanger," *Heat Transf. Eng.*, vol. 37, no. 12, pp. 1013–1026, https://www.tandfonline.com/doi/full/10.1080/01457632.2015.1104159.

Niyas H. and Muthukumar P. (2013). "Performance analysis of latent heat storage systems," *Int. J. Sci. Eng. Res.*, vol. 4, no. 12, pp. 74–79.

Nóbrega C. R. E. S., Ismail K. A. R., and Lino F. A. M. (2019). "Enhancement of ice formation around vertical finned tubes for cold storage applications," *Int. J. Refrig.*, vol. 99, p. 251, https://www.sciencedirect.com/science/article/abs/pii/S0140700718305176.

Noorbakhsh M., Zaboli M., and Mousavi Ajarostaghi S. S. (2020). "Numerical evaluation of the effect of using twisted tapes as turbulator with various geometries in both sides of a double-pipe heat exchanger," *J. Therm. Anal. Calorim.*, vol. 140, no. 3, pp. 1341–1353, https://link.springer.com/article/10.1007/s10973-019-08509-w.

Nunez M., Davalos L., and Fulores A. (2009). "Alternative sizing methodology for compact heat exchangers of spiral type," *Heat Transf. Eng.*, vol. 30, pp. 744–750, doi: 10.1080/01457630802678508.

Ogoh W. and Groulx D. (2012). "Effects of the number and distribution of fins on the storage characteristics of a cylindrical latent heat energy storage system: A Numerical Study," *Heat Mass Transf.*, vol. 48, no. 10, pp. 1825–1835, https://link.springer.com/article/10.1007/s00231-012-1029-3.

Padmanabhan P. V. and Murthy M. K. (1986). "Outward phase change in a cylindrical annulus with axial fins on the inner tube," *Int. J. Heat Mass Tranfer*, vol. 29, no. 12, p. 1855, https://www.sciencedirect.com/science/article/abs/pii/0017931086900049.

Pakrouh R., Hosseini M., and Ranjbar A. (2015). "A parametric investigation of a PCM-based pin fin heat sink," *Mech. Sci.*, vol. 6, no. 1, pp. 65–73, https://ms.copernicus.org/articles/6/65/2015/ms-6-65-2015.html.

Podara C. V., Kartsonakis I. A., and Charitidis C. A. (2021). "Towards phase change materials for thermal energy storage: classification, improvements and applications in the building sector," *Appl. Sci.*, vol. 11, no. 4, pp. 01–26, https://www.mdpi.com/2076-3417/11/4/1490.

Pongsoi P., Pikulkajorn S., and Wongwises S. (2014). "Heat transfer and flow characteristics of spiral fin-and-tube heat exchangers: A review," *Int. J. Heat Mass Transf.*, vol. 79, pp. 417–431, https://www.sciencedirect.com/science/article/abs/pii/S1364032109002469.

Rahimi M., Ranjbar A. A., Ganji D. D., Sedighi K., Hosseini M. J., and Bahrampoury R. (2014). "Analysis of geometrical and operational parameters of PCM in a fin and tube heat exchanger," *Int. Commun. Heat Mass Transf.*, vol. 53, pp. 109–115, https://www.sciencedirect.com/science/article/abs/pii/S0735193314000657.

Rajabifar B., Seyf H. R., Zhang Y., and Khanna S. K. (2016). "Flow and heat transfer in micro pin fin heat sinks with nano – encapsulated phase change materials," *J. Heat Transf.*, vol. 138, no. 6, pp. 1–8.

Rathod M. K. and Banerjee J. (2015). "Thermal performance enhancement of shell and tube Latent Heat Storage Unit using longitudinal fins," *Appl. Therm. Eng.*, vol. 75, pp. 1084–1092, https://www.sciencedirect.com/science/article/abs/pii/S1359431114009454.

Regin A. F., Solanki S. C., and Saini J. S. (2008). "Heat transfer characteristics of thermal energy storage system using PCM capsules: A review," *Renew. Sustain. Energy Rev.*, vol. 12, no. 9, pp. 2438–2458, https://www.sciencedirect.com/science/article/abs/pii/S1364032107001001.

Robak C. W., Bergman T. L., and Faghri A. (2011). "Enhancement of latent heat energy storage using embedded heat pipes," *Int. J. Heat Mass Transf.*, vol. 54, no. 15–16, pp. 3476–3484, https://www.sciencedirect.com/science/article/abs/pii/S0017931011001840.

Rudra Murthy B. V., Nidhul K., and Gumtapure V. (2021). "Performance evaluation of novel tapered shell and tube cascaded latent heat thermal energy storage," *Sol. Energy*, vol. 214, pp. 377–392, https://www.sciencedirect.com/science/article/abs/pii/S0038092X20312408.

Saha S. K. and Dutta P. (2010). "Heat transfer correlations for PCM – based heat sinks with plate fins," *Appl. Therm. Eng.*, vol. 30, no. 16, pp. 2485–2491, https://www.sciencedirect.com/science/article/abs/pii/S1359431110002681.

Sarbu I. and Dorca A. (2018). "Review on heat transfer analysis in thermal energy storage using latent heat storage systems and phase change materials," *Int. J. Energy Res.*, vol. 43, pp. 29–64, https://onlinelibrary.wiley.com/doi/abs/10.1002/er.4196.

Sciacovelli A., Gagliardi F., and Verda V. (2015). "Maximization of performance of a PCM latent heat storage system with innovative fins," *Appl. Energy*, vol. 137, pp. 707–715, https://sciencedirect.com/science/article/abs/pii/S0306261914006825.

Seeniraj R. V., Velraj R., and Narasimhan N. L. (2002). "Thermal analysis of a finned – tube LHTS module for a solar dynamic power system," *Heat Mass Transf.*, vol. 38, no. 4–5, p. 409, https://link.springer.com/article/10.1007/s002310100268.

Sharifi N., Bergman T. L., and Faghri A. (2011). "Enhancement of PCM melting in enclosures with horizontally-finned internal surfaces,"

Int. J. Heat Mass Transf., vol. 54, no. 19–20, p. 4182, https://www.sciencedirect.com/science/article/abs/pii/S0017931011003176.

Sharma A., Tyagi V. V., Chen C. R., and Buddhi D. (2009). "Review on thermal energy storage with phase change materials and applications," *Renew. Sustain. Energy Rev.*, vol. 13, no. 2, pp. 318–345, https://www.sciencedirect.com/science/article/abs/pii/S1364032107001402.

Shatikian V., Ziskind G., and Letan R. (2005). "Numerical investigation of a PCM-based heat sink with internal fins," Int. J. *Heat* Mass Transf., vol. 48, pp. 3689–3706, https://cris.bgu.ac.il/en/publications/numerical-investigation-of-a-pcm-based-heat-sink-with-internal-fi-6.

Shatikian V., Ziskind G., and Letan R. (2008). "Numerical investigation of a PCM-based heat sink with internal fins: constant heat flux," *Int. J. Heat Mass Transf.*, vol. 51, no. 5, pp. 1488–1493, https://cris.bgu.ac.il/en/publications/numerical-investigation-of-a-pcm-based-heat-sink-with-internal-fi-6.

Singh D., Dadhich J., Bhadoriya Y., and Taneja S. (2023). "A review on the prospects of various gaseous fuel as an automotive fuel and for reducing environmental pollution," *Evergr. J.*, vol. 10, no. 4, pp. 2661–2674, doi: 10.5109/7160925.

Solomon G. R. and Velraj R. (2013). "Analysis of the heat transfer mechanisms during energy storage in a Phase Change Material filled vertical finned cylindrical unit for free cooling application," *Energy Convers. Manag.*, vol. 75, pp. 466–473, https://www.sciencedirect.com/science/article/abs/pii/S0196890413003567.

Son Y. S. and Shin J. Y. (2001). "Performance of a shell-and-tube heat exchanger with spiral baffle plates," *KSME Int. J.*, vol. 15, no. 11, pp. 1555–1562, https://link.springer.com/article/10.1007/BF03185746.

Srikanth R. and Balaji C. (2017). "Experimental investigation on the heat transfer performance of a PCM based pin fin heat sink with discrete heating," *Int. J. Therm. Sci.*, vol. 111, pp. 188–203, https://www.sciencedirect.com/science/article/abs/pii/S1290072916300539.

Srivatsa P. V., Baby R., and Balaji C. (2014). "Numerical investigation of PCM based heat sinks with embedded metal foam/crossed plate fins," *Numer. Heat Transf., Part. A: Appl.*, vol. 66, no. 10, pp. 1131–1153, https://www.tandfonline.com/doi/abs/10.1080/10407782.2014.894371.

Stritih U. (2004). "An experimental study of enhanced heat transfer in rectangular PCM thermal storage," *Int. J. Heat Mass Transf.*, vol. 47, no. 12, pp. 2841–2847, https://www.sciencedirect.com/science/article/abs/pii/S0017931004000365.

Sun J. Q., Zhang R. Y., Liu Z. P., and Lu G. (2007). "Thermal reliability test of Al-34%Mg-6%Zn alloy as latent heat storage material and corrosion of metal with respect to thermal cycling," *Energy Convers. Manag.*, vol. 48, no. 2, pp. 619–624, doi: 10.1016/j.enconman.2006.05.017.

Talukdar S., Afroz H. M. M., Aziz A., and Hossain M. (2019). "Heat transfer enhancement of charging and discharging of phase change materials and size optimization of a latent thermal energy storage system for the solar cold storage application," *J. Energy Storage*, vol. 24, no. 2, pp. 100797–100799, https://www.sciencedirect.com/science/article/abs/pii/S2352152X18308144.

Tan F. L., Hosseinizadeh S. F., Khodadadi J. M., and Fan L. (2009). "Experimental and computational study of constrained melting of phase change materials (PCM) inside a spherical capsule," *Int. J. Heat Mass Transf.*, vol. 52, no. 15, pp. 3464–3472, https://www.sciencedirect.com/science/article/abs/pii/S0017931009001896.

Taneja S., Jain A., and Bhadoriya Y. (2013). "Green hydrogen as a clean energy resource and its applications as an engine fuel," *MDPI Eng. Proceedia*, vol. 59, p. 159, doi: 10.3390/engproc2023059159.

Taneja S., Singh P., and Singh G. (2018). "Comparative analysis of the Performance and Emission Characteristics of ethanol-butanol-gasoline blends," *IOP Conference Series: Material Science and Enineering*, vol. 310, p. 012136, doi: 10.1088/1757-899X/310/1/012136.

Taneja S., Singh P., Sharma A., and Singh G. (2021). "Use of alcohols and biofuels as automotive engine fuel," *Energy Systems and Nanotechnology*, vol. 1, Singapore, Springer, pp. 161–183, https://link.springer.com/chapter/10.1007/978-981-16-1256-5_10. Accessed July 15, 2023.

Tay N. H. S., Bruno F., and Belusko M. (2013). "Comparison of pinned and finned tubes in a phase change thermal energy storage system using CFD," *Appl. Energy*, vol. 104, pp. 79–86, https://www.sciencedirect.com/science/article/abs/pii/S0306261912007593.

Tian Y. and Zhao C. Y. (2011). "A numerical investigation of heat transfer in phase change materials (PCMs) embedded in porous metals," *Energy*, vol. 36, no. 9, pp. 5539–5546, https://www.sciencedirect.com/science/article/abs/pii/S0360544211004671.

Tian Y. and Zhao C. Y. (2013). "A review of solar collectors and thermal energy storage in solar thermal applications," *Appl. Energy*, vol. 104, pp. 538–553, https://doi.org/10.1016/j.apenergy.2012.11.051.

Tiari S., Qiu S., and Mahdavi M. (2015). "Numerical study of finned heat pipe – assisted thermal energy storage system with high temperature phase change material," *Energy Convers. Manag.*, vol. 89, pp. 833–842, https://www.sciencedirect.com/science/article/abs/pii/S019689041400942X.

Trelles J. P. and Dufly J. J. (2003). "Numerical simulation of porous latent heat thermal energy storage for thermoelectric cooling," *Appl. Therm. Energy*, vol. 23, no. 13, pp. 1647–1664, https://www.sciencedirect.com/science/article/abs/pii/S135943110300108X.

Trp A. (2005). "An experimental and numerical investigation of heat transfer during technical grade paraffin melting and solidification in a shell-and-tube latent thermal energy storage unit," *Sol. Energy*, vol. 79, no. 6, pp. 648–660, https://www.sciencedirect.com/science/article/abs/pii/S0038092X05001337.

UmaMaheswari C. and Reddy M. (2004). "Thermal analysis of thermal energy storage systemwith phase change material," *Int. J. Eng. Res. Appl.*, vol. 3, no. 4, pp. 617–622.

Velraj R., Seeniraj R., Hafner B., Faber C., and Schwarzer K. (1997). "Experimental analysis and numerical modelling of inward solidification on a finned vertical tube for a latent heat storage system unit," *Sol. Energy*, vol. 60, no. 5, pp. 281–290, https://www.sciencedirect.com/science/article/abs/pii/S0038092X96001673.

Venkata-chalapathy S., Kumaresan G., and Suresh S. (2015). "Performance analysis of cylindrical heat pipe using nanofluids – An experimental study," *Int. J. Multiph. Flow.*, vol. 72, pp. 188–197, https://www.sciencedirect.com/science/article/abs/pii/S0301932215000270.

Wang W., Yang X., Ding J., and Yan J. (2009a). "Preparation and thermal properties of polyethylene glycol/expanded graphite blends for energy storage," *Appl. Energy*, vol. 86, no. 9, pp. 1479–1483, https://www.sciencedirect.com/science/article/abs/pii/S0306261908003206.

Wang W., Yang X., Fang Y., Ding J., and Yan J. (2009b). "Enhanced thermal conductivity and thermal performance of form-stable composite phase change materials by using β-Aluminum nitride," *Appl. Energy*, vol. 86, no. 7–8, pp. 1196–1200, https://www.sciencedirect.com/science/article/abs/pii/S0306261908002626.

Wang Z. and Li Y. (2016). "Layer pattern thermal design & optimization for multistream plate-fin heat exchangers- A review," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 500–514, https://www.sciencedirect.com/science/article/abs/pii/S1364032115009727.

Xia L., Zhang P., and Wang R. Z. (2010). "Numerical heat transfer analysis of the packed bed latent heat storage system based on an effective packed bed model," *Energy*, vol. 35, no. 5, pp. 2022–2032, doi: 10.1016/j.energy.2010.01.018.

Ye W., Zhu D., and Wang N. (2011). "Numerical simulation on phase-change thermal storage/release in a plate-fin unit," *Appl. Therm. Eng.*, vol. 31, pp. 3871–3884, https://www.sciencedirect.com/science/article/abs/pii/S1359431111003942.

Yuan Y., Cao X., Xiang B., and Du Y. (2016). "Effect of installation angle of fins on melting characteristics of annular unit for latent heat thermal energy storage," *Sol. Energy*, vol. 136, p. 365, https://www.sciencedirect.com/science/article/abs/pii/S0038092X16302729.

Zayed M. E., Zhao J., Li W., Elsheikh A. H., Elbanna A. M., Jing L., et al. (2020). "Recent progress in phase change materials storage containers: Geometries, design considerations and heat transfer improvement methods," *J. Energy Storage*, vol. 30, p. 101341, doi: 10.1016/j.est.2020.101341, https://www.sciencedirect.com/science/article/abs/pii/S2352152X20300098.

Zhang H., Baeyens J., Cáceres G., Degrève J., and Lv Y. (2016). "Thermal energy storage: Recent developments and practical aspects," *Prog. Energy Combust. Sci.*, vol. 53, pp. 1–40, https://doi.org/10.1016/j.pecs.2015.10.003.

Zhang Y. and Faghri A. (1996). "Heat transfer enhancement in latent heat thermal energy storage system by using the internally finned tube," *Int. J. Heat Mass Transf.*, vol. 39, no. 15, p. 3165, https://www.sciencedirect.com/science/article/abs/pii/0017931095004025.