(REVIEW ARTICLE)

Heat transfer improvement in latent heat thermal energy storage: A review paper

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Abstract

This paper provides a comprehensive review of the current advancements in heat transfer improvement strategies inside latent heat thermal energy storage (LHTES) systems. Enhancement of heat transmission in LHTES systems can be accomplished by modifying the geometric configuration or by enhancing the thermal conductivity. The incorporation of expanded surfaces, such as fins or heat pipes, is a commonly employed technique to enhance heat transfer in LHTES systems. Consequently, this study provides a comprehensive evaluation review of this methodology. Subsequently, an examination was conducted on approaches aimed at enhancing thermal conductivity. The thermal conductivity of the composite phase change material (CPCM) exhibits an increase as the concentration and aspect ratio of the additive is increased. Metallic foam and expanded graphite exhibit notable thermal conductivity and favorable thermo-physical characteristics, while concurrently serving as effective barriers against the leakage of PCM. Encapsulated PCM exhibits significantly improved thermal conductivity and extended lifespan as a result of the presence of a thermally conductive shell. This shell not only enhances thermal conductivity but also serves as a protective barrier, preventing direct exposure of the PCM to the surrounding environment. In this work, an examination is conducted on research that investigates the use of integrated approaches to promote heat transmission. This paper examines the existing research deficiencies in the techniques employed to promote heat transfer in LHTES systems and puts forth a set of recommendations.

Keywords: Latent heat thermal energy storage; Phase change material; Heat transfer enhancement; Thermal conductivity improvement; Nanomaterials

1. Introduction

The advantages of energy storage are economic savings and preservation of fossil fuels. In recent times, there has been a growing emphasis on energy conservation and the utilization of energy in an efficient manner [1]. The energy storage provided by these systems is crucial for meeting the energy demand [2][3]. There is an urgent need for advanced thermal energy storage systems due to the worsening energy crisis and environmental issues [4][5]. There exist multiple methodologies for energy storage, encompassing the subsequent approaches. The various types of energy storage include mechanical energy storage, electrical energy storage, chemical energy storage, electrochemical energy storage, and thermal energy storage. At present, there exist three distinct thermal energy storage technologies, namely Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermochemical Energy Storage (TCES) [6]. SHS process of sensible heat storage pertains to the retention of thermal energy by elevating the temperature of the storage without enduring any change in its physical state. The SHS has poor energy density and variable discharging temperatures. As a result, they can't compete with the efficiency of systems that use LHS or TCES [7]. The process of LHS encompasses the conversion of the storage material from one state to another, including solid-liquid, solid-solid, or liquid-gas, and vice versa.

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This transition occurs when the substance is heated to reach the temperature at which the phase change takes place. TCES is the third type of energy storage, the system employs a reversible physio-chemical process to chemically store thermal energy and subsequently retrieve energy through the provision of heat. In contrast, TCES exhibits a notable capacity for storing significant amounts of energy, although it remains at an early stage of study and development. Figure 1 shows a method of thermal energy storage [8]. Table 1 shows a comparison between types of thermal energy storage [9][10]. Latent heat materials, also known as Phase Change Materials (PCMs), possess several advantageous characteristics including high energy storage density, substantial latent heat capacity, and the capability to sustain a nearly constant temperature. Consequently, they have gained significant popularity and are extensively employed in various applications. PCMs are widely recognized as the most effective method for storing cold energy [11] or for heat recovery [12]. There are two methods utilized for cooling electrical devices: passive cooling and active cooling [13][14][15]. An exhaustive analysis of energy storage systems utilizing PCMs was conducted [16][17][18].The physical process of vapor condensation has numerous real-world applications, including thermal and nuclear power plant cooling systems, air conditioners, and other heat exchange devices. The process of condensation can be described as the transition of a substance from its gaseous phase to its liquid phase. During this transition, a substantial quantity of energy is liberated in the form of heat. PCMs refer to substances that possess the ability to store and release significant quantities of energy during state transitions. This unique property renders them suitable for a wide range of applications, including energy storage and the regulation of thermal comfort [19]. The implementation of PCMs insulation in buildings contributes to the reduction of energy consumption and subsequent emissions. This is achieved by the ability of PCMs insulation to store surplus thermal energy and subsequently release it when required [20]. The initial investigation in this field can be dated back to 1996, Rabin and Korin integrated PCMs storage units into a ground thermal energy storage system with a helical heat exchanger of substantial diameter [21]. PCMs have been utilized in various domains, including building energy preservation, solar energy harnessing, recuperation of waste heat, and other systems for storing thermal energy [22][23].

The utilization of solar sunlight as a power source for PCM devices was initiated in 1942 [24]. Solar water heating systems are one of the most common applications that can be used to save energy and can be used as an alternative to electricity and fossil fuels [25]. Solar heaters cannot be used on cloudy days and nights, however, the efficiency of solar heaters is decreased with increasing the wind speed [26], [27]. The PCMs can be used in solar heater systems to enhance efficiency. Pure PCMs encounter two primary challenges: low heat conductivity of about $0.1\ W/m.K$ and leakage, hence restricting their applicability across various industries [28]. Figure 2 displays the melting temperature and fusion heat characteristics of many types of PCMs, including organics, nitrates, and carbonates [29].
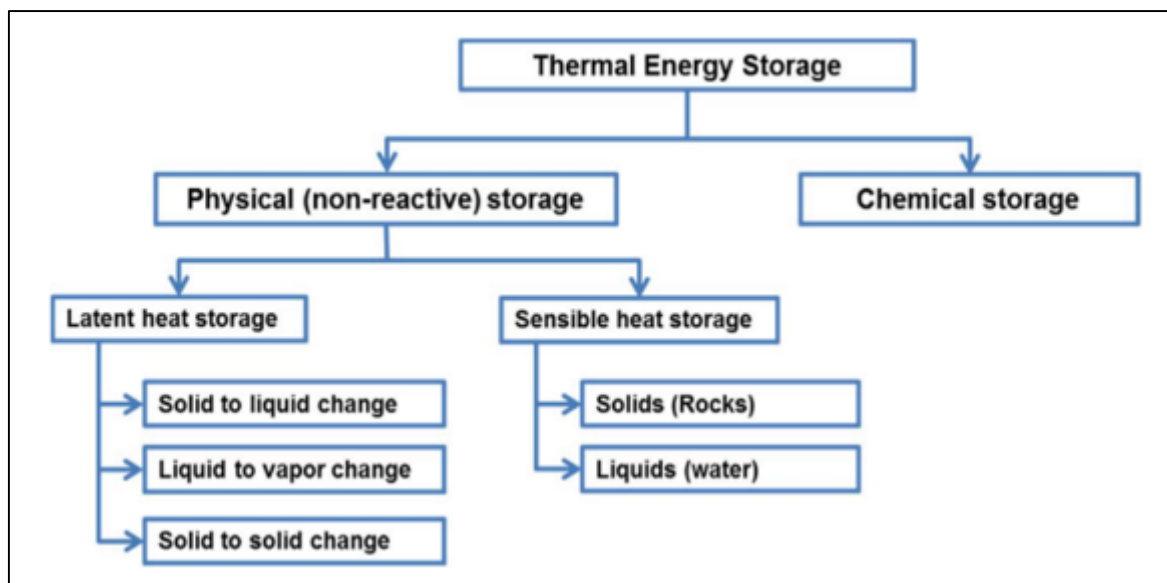

Figure 1 Thermal energy storage methods [8]

The study conducted by Rehman et al. presented a comprehensive review of the enhancement of heat transmission in PCMs by the use of porous metal foams and carbon materials [30]. In their study, Bottarelli et al conducted a numerical analysis to evaluate the thermal performance of a horizontal flat-panel ground heat exchanger. They investigated the incorporation of PCMs directly mixed with the backfill materials. The researchers concluded that the utilization of PCMs has the potential to effectively dampen the thermal wave within the ground, enhance the coefficient of performance of

the heat pump, and alleviate the depletion of stored thermal energy [31]. The paper aims to investigate the increase of heat transfer in LHTES to enhance system performance and enhance efficiency. Fin and heat pump can be used to increase the surface area causing to improve the heat transfer. However, heat transfer in LHTES can be enhanced by enhancing thermal conductivity.

Table 1 Comparison of various thermal energy storage technologies [9][10]

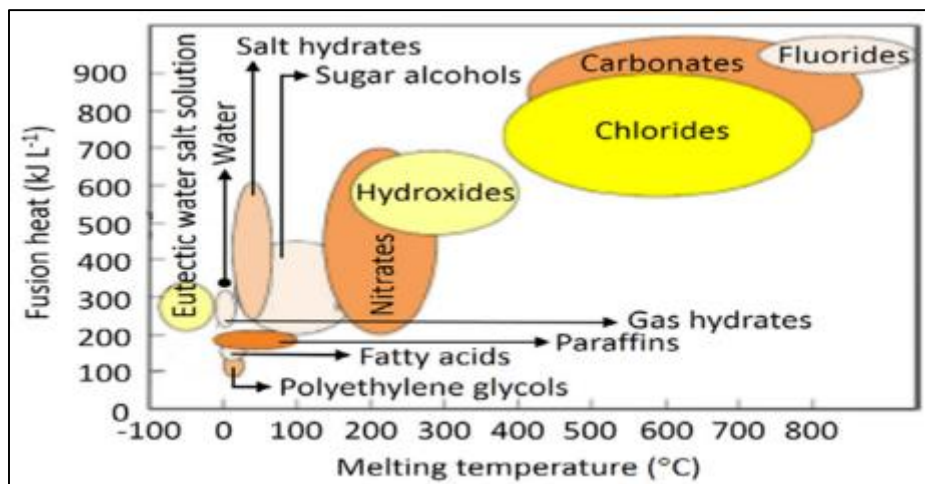| Feature	SHS	LHS	TCES
The Core Concepts	The storage of energy occurs through the process of increasing temperature. Depends on how much temperature increases	The phenomenon of energy storage that occurs during a phase shift of a material at a constant temperature. Depends on latent heat.	The energy that is stored during the reversible processes of endothermic and exothermic reactions. Depends on reaction enthalpy.
The amount of heat that can be stored	$Q = m.C_p.\Delta T$	$Q = m.L$	$Q = n.\Delta H_r$
Energy content per unit of volume	$\sim 50\ kWh/m^3$	$\sim 100\ kWh/m^3$	$\sim 500\ kWh/m^3$
Gravimetric energy density	$0.02-0.03\ kWh/kg$	$0.05-0.1\ kWh/kg$	$0.5-1\ kWh/kg$
Energy transport	Shorter distance	Shorter distance	Theoretically long distance
Storage temperature	Charging step temperature	Charging step temperature	Ambient temperature
Technology	Simple	Medium	Complex

Figure 2 Melting temperature with fusion heat of PCMs [29]

2. The investigation of heat transfer issues related to phase change materials

Phase change materials are substances that possess a significant capability for storing latent heat energy. These materials possess the ability to store and subsequently release significant quantities of thermal energy during periods of high demand. Phase transformation refers to the phenomenon wherein a substance undergoes a transition from a solid state to a liquid state, or vice versa, resulting in the absorption or release of significant amounts of energy.

Analyzing the heat transfer characteristics of PCMs poses challenges due to the shifting thermal boundaries caused by the varying heat transfer rate at the interface between the solid and liquid phases [32]. Heat transmission occurs through conduction in solid PCMs, which is described by a governing equation.

$$\dot{q} = -KA\frac{dT}{dX} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

In the given context, the symbols $\dot{q}$, k, A, dT, and dX denote the heat transfer rate, thermal conductivity, surface area, temperature difference, and thickness respectively. Heat transmission through conduction can be inferred from;

$$Q_1 = \int_{T_i}^{T_m} mC_p \, dT \quad \ldots\ldots\ldots\ldots\ldots\ (2)$$

where Q_1, m, C_p, T_m, and T_i represent the heat transfer rate, mass, specific heat, molten PCMs temperature, and initial temperatures respectively. The latent heat of fusion can be expressed as;

$$Q_2 = mf_m dh_m \quad \ldots\ldots\ldots\ldots\ (3)$$

where f_m, and dh_m represent the melted PCM fraction and enthalpy change in PCM respectively. Following PCM, it undergoes an increase in energy absorption in the form of sensible heat, which is given by;

$$Q_3 = \int_{T_m}^{T_f} mC_p \, dT \quad \ldots\ldots\ldots\ldots(4)$$

where T_f is the final temperature. The calculation of the total heat contained in PCMs can be determined using;

$$Q_{total} = \int_{T_i}^{T_m} mC_p \, dT + mf_m dh_m + \int_{T_m}^{T_f} mC_p \, dT \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

3. Heat transfer enhancement

The pure PCMs have a low thermal conductivity. As a consequence, the low thermal conductivity results in a poor heat exchange between the PCM and the heat transfer fluid, which is why there is a requirement for improvement. One of the most popular methods of augmentation is the utilization of expanded surfaces, such as fins and heat pipes, or the utilization of multiple PCMs with varying melting points.

3.1. Enhancement with fins

Adding fins to an LHTES system improves its thermal performance by increasing the area of heat transfer between the PCM and the heat transfer fluid (HTF). The thermal conductivity, density, cost, and corrosion potential of the material are the criteria that are used to pick the fin [33]. Table 2 lists common fin material qualities and pricing.

Table 2 Common fin materials' properties [33]

Properties	Copper	Aluminum	Graphite foil	Carbon steel	Stainless steel
Density (kg/m^3)	8800	2700	1000	7800	7800
Thermal conductivity ($W/m.k$)	350	200	150	30	20
Proposed expense per unit of volume ($\$/m^3$)	40,000	7000	10,000	15,000	20,000

Velraj et al. conducted a study that involved computational and experimental investigations on the augmentation of heat transfer in a thermal storage system. This system was comprised of a vertical cylindrical tube that contained a PCM and was equipped with an internal longitudinal fin arrangement. The cylindrical vertical tube is positioned within a separate container filled with water, which serves as a medium for transferring heat, as depicted in Figure 3 [34].
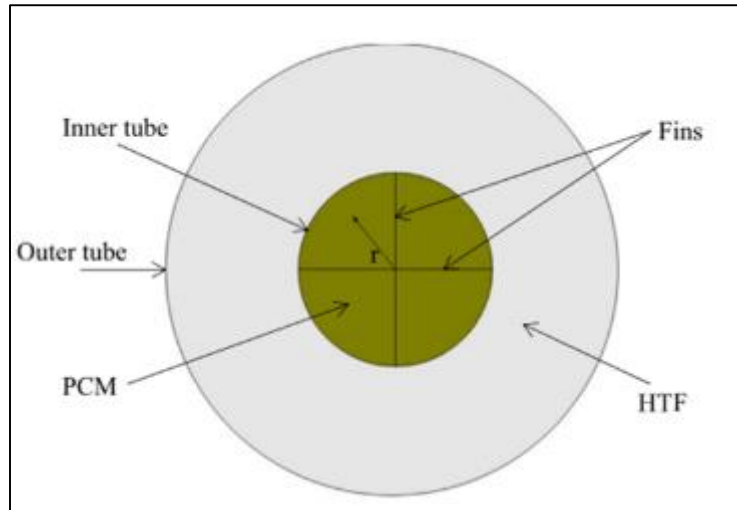
Figure 3 A typical LHTS system's tube-fin configuration [34]

In their study, Jmal and Baccar conducted an investigation on the PCM system thermal efficiency involving a heat exchanger utilizing internally and externally finned tubes as shown in Figure 4. The findings of their study demonstrated a more rapid transfer of energy from the PCM to the surrounding air, resulting in an elevation in the outlet air temperature [35].
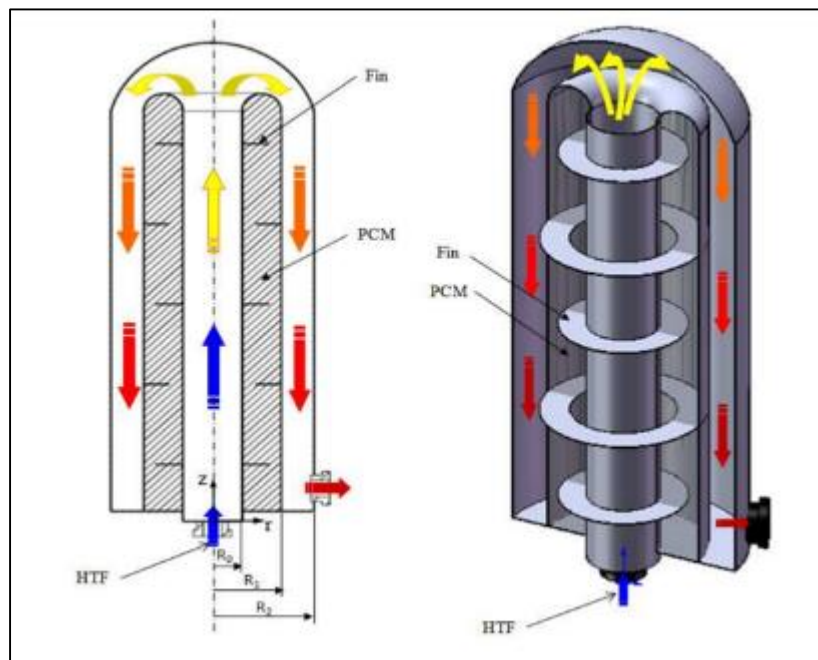

Figure 4 Configurations and computational domain [35]

In a study conducted by Sciacovelli and Verda, Y-shaped fins were utilized in a shell-and-tube latent heat thermal energy storage (LHTES) system as shown in Figure 5. This was followed by a numerical investigation employing computational fluid dynamics (CFD) techniques. The findings indicated that the unit was capable of attaining a 24% enhancement in system efficiency [36].
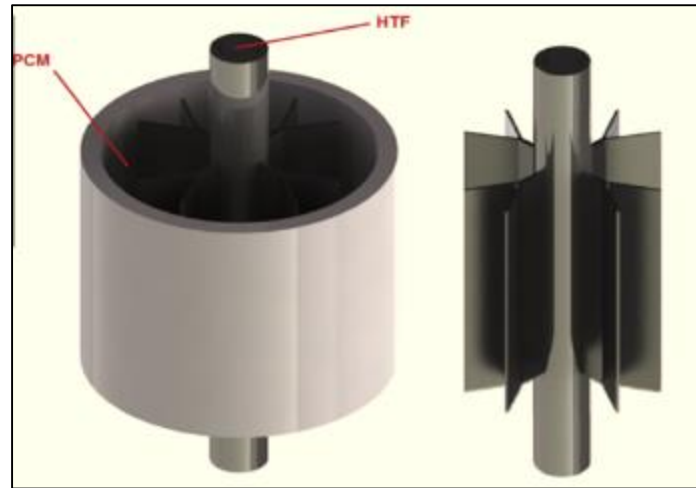
Figure 5 LHTES system [36]

3.2. Heat pipes application

The heat pipe (HP) functions as a thermal conduit, facilitating the transfer of heat between the HTF and PCM through the processes of evaporation and condensation. These processes take place in the evaporator and condenser sections of the heat pipe, respectively. The utilization of HP in LHTES systems holds significant potential as a strategy to enhance the efficiency of the charging and discharging processes of PCM. This is particularly relevant in systems that include repetitive charging and discharging cycles, such as those found in cooling and heating applications, energy recovery systems, and heat sink devices.

Bergman et al. conducted a numerical investigation on a shell-and-tube LHTES operating at high temperatures. The system was further combined with HPs to enhance its performance within a solar thermal power plant context. The simulation took into account both charging and discharging modes, and the findings demonstrated a notable enhancement in the rates of charging and discharging as a result of the inclusion of heat pipes for two distinct high-temperature fluid flow patterns [37].

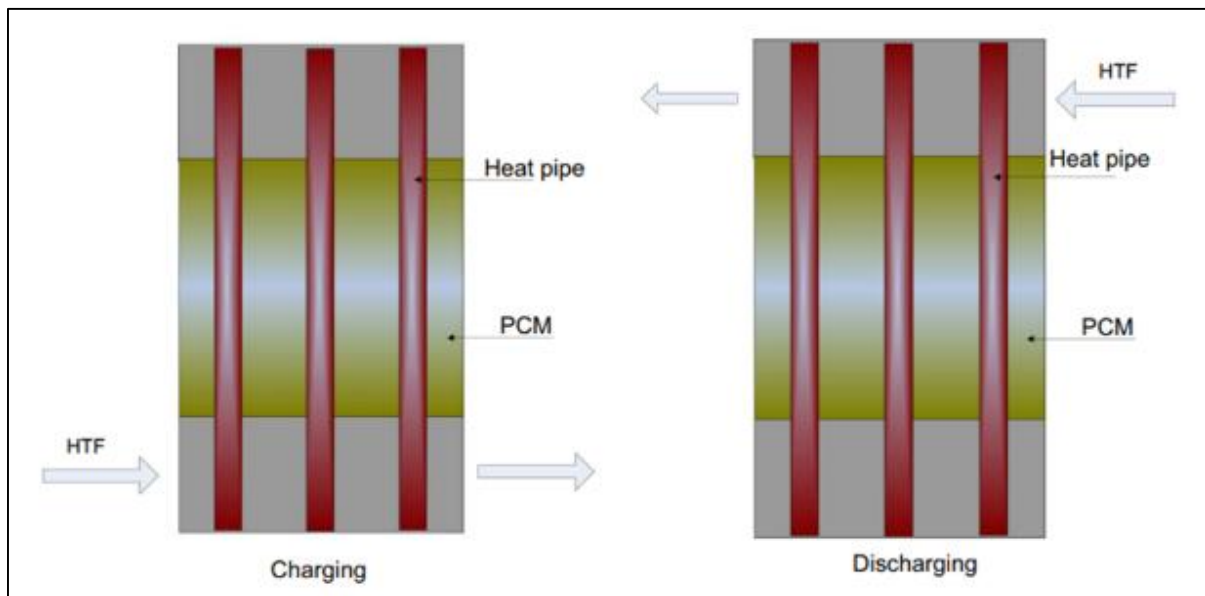**Figure 6** LHTES system charging/discharging cascade [39]

The transient response of an HP-assisted LHTES system was examined by Shabgard et al. through the utilization of a two-dimensional numerical model. The study also considered the influence of HP spacing on the system's behavior. The researchers examined three distinct activities, namely: (i) charging, (ii) charging and discharging, and (iii) discharging.

The findings indicate that the exergy efficiencies of all the units are above 97%, with the unit featuring the smallest HP spacing demonstrating the highest efficiency [38].

HPs are commonly utilized in cascaded latent heat storage systems, wherein the system's charging and discharging processes involve the incorporation of one or more channels. In this particular scenario, the HPs are positioned at a right angle to the flow direction of the HTF. They traverse through the channels and traverse the PCM, resulting in an augmentation of the heat transfer rate between the HTF and the PCM, as depicted in Figure 6.

Another notable configuration, similar to the cascaded storage system, is the PCM-heat pipe heat exchanger. In the given situation, the PCM is located at the central region of the HP, while the two HTF channels are thermally connected to the condenser and evaporator sections of the heat pipe, as seen in Figure 7. The PCM facilitates simultaneous charging and discharging processes, leading to the generation of cooling effects at the evaporator region and heating effects at the condenser region [40].
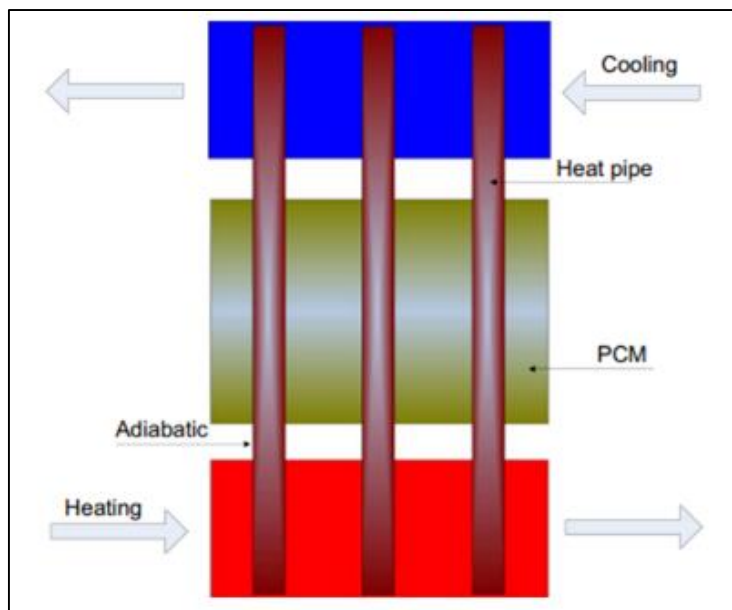

Figure 7 Two HTF flow channels in PCM-HP heat exchanger [39]

3.3. Multiple phase change materials

The utilization of various families of PCMs in LHTES is an additional method documented in scholarly literature for augmenting heat transfer. The primary objective of employing numerous PCMs is to uphold a consistent temperature differential between the HTF and the PCMs throughout the processes of charging and discharging. This approach serves to enhance the thermal efficiency of the LHTES. In a conventional shell-and-tube LHTES system, a series of PCMs with varying melting temperatures are stacked in descending order based on their respective melting points. This arrangement is observed throughout the charging process, as depicted in Figure 8.
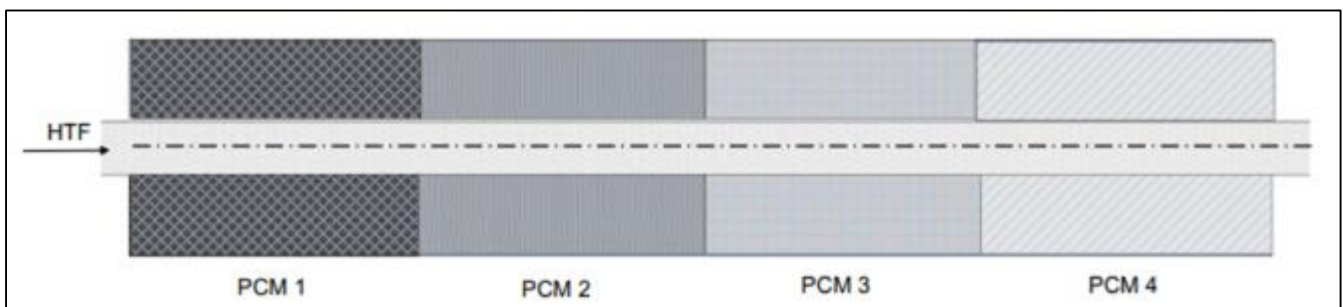

Figure 8 A schematic depicting a shell-and-tube LHTES unit with numerous PCMs [39]

In their study, Adine and El Qarnia conducted a numerical investigation of the thermal characteristics and efficiency of LHTES systems. The researchers examined the results from LHTES systems employing both a single PCM and two PCMs. The researchers investigated the impact of various operating and geometric factors, such as the input temperature and mass flow rate of the HTF, as well as the lengths of the PCM sections, on the thermal performance of the LHTES units during the charging process. The findings demonstrated that the utilization of numerous PCMs resulted in an average increase of around 57% in the rate of heat transfer [41].

4. Thermal conductivity measurements

The transient hot-wire approach is used to measure the thermal conductivity of PCM. This process is illustrated in Figure 9. In their study, Harish et al. employed a Platinum hot wire with a diameter of 76.4 mm as a heating element and resistance thermometer. This wire was subsequently electrically insulated by a Teflon coating with 33.6 mm thickness. An electric current is applied to the platinum wire while it is submerged in the fluid. The measurement of the change in resistance of a wire, when it is heated, can be conducted by utilizing a Wheatstone-bridge circuit. The determination of temperature increase is achieved through the analysis of changes in resistance [42].

The determination of thermal conductivity is based on Fourier's equation of heat transport, which is expressed using Equation (6).

$$k = \frac{Q}{4\pi L}\frac{d \ln(t)}{dT} \quad \ldots \ldots \ldots (6)$$

Here, k, L, Q, T, and t stand for the fluid's thermal conductivity, the hot wire's length, the power applied to the wire, the wire's temperature, and time respectively.

The determination of the thermal conductivity of materials can also be achieved indirectly by the measurement of their thermal diffusivity [43]. The thermal diffusivity PCM can be calculated by using the laser flash method, and thermal conductivity can be calculated by using Equation (7).

$$k = \alpha.\rho.C_p \quad \ldots \ldots \ldots \ldots \ldots (7)$$

where α, ρ, and C_p represent the thermal diffusivity, density, and specific heat respectively.
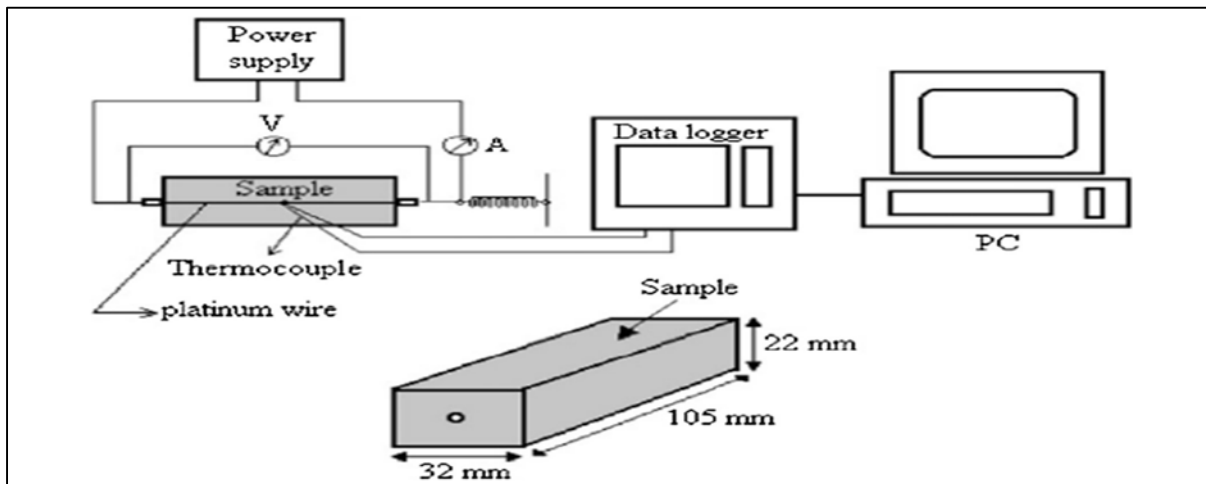
Figure 9 Thermal conductivity measurement using transient hot-wire [44]

5. Thermal conductivity enhancement

PCMs have a significantly reduced thermal conductivity, resulting in a diminished heat transfer rate. Consequently, this characteristic hampers the efficiency of heat storage and cooling systems. There exists a compelling necessity to enhance the rate of heat transmission in PCMs. Figure 10 shows different techniques of heat transfer enhancement.

5.1. Using nanoparticles

Nanoparticles, such as carbon-based and metallic nanoparticles, exhibit a notable capacity for high thermal conductivity. Carbon-based nanoparticles exhibit a lower density, enhanced stability, and improved dispersion in PCM compared to nanoparticles composed of metals.

The impact of Nano Graphite on the thermal conductivity of paraffin was examined by Min Li et al. The incorporation of nano graphite into paraffin resulted in a significant enhancement of heat conductivity in the composite PCM. The addition of 10 wt% of Nano Graphite was seen to result in a 7.41-fold increase in the thermal conductivity of paraffin [45].

In their study, Wang et al. developed a form-stable phase transition material with enhanced conductivity. This was achieved through the blending of Polyethylene glycol, silica gel, and b-aluminum nitride. The experimental findings indicated that the incorporation of b-aluminum nitride in the PCM at a concentration range of 5-30 wt% resulted in a significant enhancement of thermal conductivity, with values increasing from 0.3847 to 0.7661 W/m.K [46].
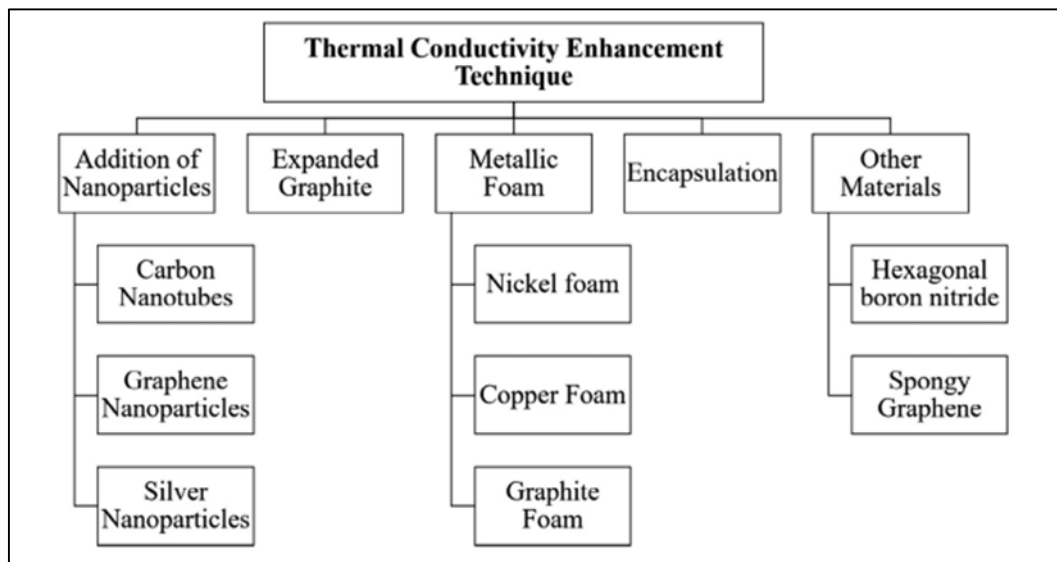

Figure 10 Thermal conductivity improvement techniques in PCMs [47]

A study conducted by Cui et al. demonstrated that PCM, namely soy wax, which has a thermal conductivity of 0.324 W/m K, was enhanced through the incorporation of carbon nanofibers and carbon nanotubes. Soy wax, with a melting temperature range of 52-54°C, was employed as PCM in this study. Additionally, carbon nanofibers with an outer diameter of 200 nm and carbon nanotubes with an average diameter of 30 nm were included in the soy wax at various mass ratios ranging from 1 to 10 wt%. According to the results of the experiments, the soy wax's thermal conductivities were increased to 0.469 and 0.403 W/m K when including 10% by weight of carbon nanofiber and carbon nanotube, respectively [48].

A study conducted by Harish et al. examined the impact of graphene Nanoplatelets (GnP) on the thermal conductivity of a CPCM of lauric acid. The experimental findings indicated that the incorporation of graphene Nano platelets at a concentration of 1% by volume in lauric acid resulted in a significant enhancement in its thermal conductivity, exhibiting a remarkable rise of 230%. The thermal properties were enhanced by the incorporation of graphene Nanoplatelets. The conductivity of lauric acid exhibits a significant degree of effectiveness while maintaining its original melting temperature and enthalpy of phase shift [49].

In their study, Xu and Li observed a significant improvement in the thermal conductivity of paraffin/diatomite composite PCM with the incorporation of multi-wall carbon nanotubes with diameters ranging from 10 to 20 nm and lengths ranging from 5 to 15 mm. The results demonstrated that the process of adding and incorporating a weight percentage of 0.26 wt% of multi-walled carbon nanotubes into paraffin results in an alteration of the thermal conductivity. The quantity of diatomite had a significant increase of 42.45%. Multi-walled carbon nanotubes have shown an augmentation in thermal conductivity [50].

5.2. Using metallic foam

The utilization of metallic foam is a prevalent practice in enhancing the thermal conductivity of PCM due to its remarkable attributes, including high thermal conductivity, consistent thermos physical properties, and substantial porosity. One of the benefits associated with the utilization of metal foam, as opposed to metallic nanoparticles, is its lower density, higher aspect ratio, and improved stability. Xiao et al. conducted a study in which they fabricated a composite material consisting of paraffin and nickel foam. Additionally, they generated paraffin/copper foam composite phase change materials using the vacuum impregnation method. Nickel and copper foams with varying pore diameters and porosities were employed in the study. The experimental findings demonstrated that the heat conductivity of paraffin/copper foam and paraffin/nickel CPCM, both possessing pores with a size of 5 PPI, exhibited enhancements of 15-fold and 3-fold, respectively, compared to pure paraffin [51]. In their study, Zhao et al. conducted an experimental investigation to examine the heat transfer rate characteristics of PCMs in the presence and absence of metal foams. The researchers discovered that heat transfer was increased by a factor of 3-10, with the extent of enhancement dependent on the density of pores [52].

5.3. Using expanded graphite

The utilization of expanded graphite is widespread in enhancing the thermal conductivity of PCM due to its remarkable thermo-physical properties. Expanded graphite exhibits notable characteristics such as elevated thermal conductivity, a substantial aspect ratio, exceptional chemical stability, and a very low density.

In their study, Sari et al. introduced a methodology aimed at improving the thermal conductivity of Paraffin, namely n-docosane with a thermal conductivity value of k = 0.22 W/m K. The researchers created a form-stable composite phase change material (CPCM) by introducing paraffin n-docosane into the mixture. The extended graphite has a surface area of 46 m^2/g and a bulk density of 300 kg/m3. The findings revealed that the thermal conductivity of the CPCM exhibited variations at concentrations of 2%, 4%, 7%, and 10% of ethylene glycol EG. The values of thermal conductivity were seen to exhibit a rise, reaching magnitudes of 0.40, 0.52, 0.68, and 0.82 W/m.K, respectively. The thermal conductivity of the composite phase change material (CPCM) exhibited a notable increase of 3.73% upon the incorporation of 10 wt% of ethylene glycol [44].

Ahmet conducted the preparation of a composite material consisting of paraffin and high-density polyethylene. The researcher employed two distinct paraffin variants characterized by melting temperatures ranging from 42 to 44 ℃ Celsius for Sample 1, and 56 to 58 ℃ Celsius for Sample 2. A thermal conductivity enhancer was incorporated into the system, consisting of expanded and exfoliated Graphite at a concentration of 3 wt%. Sample 1 and sample 2 exhibited enhancements of 14% and 24% respectively [53]. In their study, Wu et al. employed a combination of paraffin, which possesses a thermal conductivity (k) value of 0.268 W/m.K, and expanded graphite to fabricate a PCM known as CPCM. The incorporation of 20% EG resulted in a notable enhancement in the thermal conductivity of the composite, which reached a value of 7.654 W/m.K [54].

5.4. Encapsulating PCM

PCMs exhibit limitations in terms of low heat conductivity and leakage during the solid-to-liquid phase transition, hence imposing restrictions on their potential applications. The preceding issues can be addressed by encapsulating PCM within a shell composed of an organic material that exhibits good thermal conductivity and stability. Encapsulated PCMs exhibit considerable potential as viable options for heat storage and cooling systems in various indoor and outdoor settings due to their exceptional thermal conductivity, mechanical robustness, and thermal stability. In their study, Zhang et al. employed silica (SiO2) as an additive to enhance the thermal conductivity of a PCM mostly composed of n-octadecane. A total of five samples of microencapsulated phase change material were synthesized, each containing varying concentrations of SiO2. The addition of 47.8 wt% of SiO2 resulted in an increase in the thermal conductivity of n-octadecane from 0.1505 W/m K to 0.6213 W/m K [55].

In their study, Li et al. incorporated spongy graphene with a density of 3 mg/cm^3 into a PCM composed of docosane. This resulted in the formation of a composite PCM consisting of docosane and graphene. The experimental findings indicated that the thermal conductivity of docosane exhibited an increase from 0.26 **W/m.K** to 0.59 **W/m.K** [56].

Chai et al conducted a study in which they synthesized microencapsulated phase change material. This was achieved by encapsulating n-eicosane as the core material within a titanium dioxide shell, which was derived from tetra butyl titanite TBT. The experimental findings indicated that the microencapsulated mixture of n-eicosane and TBT, with a weight ratio of 40/60, exhibited a thermal conductivity of 0.865 W/m.K. This value was seen to be 18.6% more than the thermal conductivity of pure n-eicosane [57].

6. Results and Discussion

The heat transfer and thermal conductivity approaches discussed in this paper are successful in improving heat transfer in PCMs. Fins, heat pipes, and multiple PCMs are all focused on augmenting heat transmission by expanding the surface area available for heat exchange.

The review indicates a notable disparity in the publication of studies about the utilization of fins in comparison to those focusing on heat pipes and multiple PCMs. One potential factor contributing to this phenomenon may be the relative ease of designing fins on storage systems, which consequently leads to a greater prevalence of experimental investigations. A variety of materials have found widespread application in improving thermal conductivity, including nanoparticles, metallic foams, expanded graphite, and encapsulating PCM.

Table 3 shows the comparison between the thermal conductivity improvement techniques in PCMs. The thermal conductivity increase of PCMs is significantly influenced by the form, size, and aspect ratio of particles. Metal-based additives have superior thermal conductivity compared to carbon-based additives.

Metallic foams exhibit favorable stability, low density, and a significant aspect ratio, hence surpassing nanoparticles in their ability to boost thermal conductivity. CPCM thermal conductivity containing expanded graphite is influenced by various factors, including packing density, surface area, and thickness.

Table 3 Thermal conductivity improvement techniques in PCMs

Type of PCM	k_{PCM} (W/m·K)	Type of additive	Concentration	k_{CPCM} (W/m·K)	Increase (%)	Ref.
Palmitic acid matrix	0.22	Multi-walled carbon nanotube	1 wt%	0.33	150%	[58]
Sodium acetate trihydrate	0.777	Copper nanoparticles	0.5 wt%	0.936	120%	[59]
Polyethylene glycol	0.29	Carbon nanotubes	3 wt%	0.463	160%	[60]
Myristyl Alcohol	0.1701	Copper foam	40 PPI	1.45	852%	[61]
Paraffin	0.2	Nickel foam	20 PPI	1.16	580%	[62]
Sodium acetate trihydrate	0.59	Copper foam	15 PPI	6.8	1153%	[63]
Palmitic & Capric acid	0.119	Expanded Graphite	5 wt%	0.149	125%	[64]
Paraffin	0.369	Expanded graphite	20 wt%	8.86	2401%	[65]
Polyethylene glycol	0.07	Expanded graphite	10 wt%	0.67	957%	[66]
Polyethylene glycol	0.06	Silver nanowires	19.3 wt%	0.68	1133%	[67]
Palmitic-Lauric Acid	0.24	Carbonized abandoned rice	21.8 wt%	0.44	183%	[68]
Polyethylene glycol	0.263	Expanded Perlite with carbon layer	33.62 wt%	0.479	182%	[69]
Paraffin	0.3	Shell (SiO_2 + GO)	Spherical 20 μm	1.162	387%	[70]
n-eicosane	0.161	Shell (TiO_2)	Spherical 1.5–2 μm	0.865	537%	[57]
n-octadecane	0.15	Shell ($CaCO_3$)	Spherical 5 mm	1.674	1116%	[71]

Nomenclature			
m	Mass (kg)	T_i	Initial temperatures (°C)
T	Temperature (°C)	T_f	Final temperatures (°C)
n	Moles number	f_m	Melted PCM fraction
L	Length (m)	dh_m	Enthalpy change in PCM (kJ/kg)
k	Thermal conductivity (W/m. K)	T_m	Molten PCMs Temperature (°C)
Q	Quantity of heat stored (W)	α	Thermal diffusivity (m^2/s)
C_p	Specific heat ($J/kg. K$)	ρ	Density (kg/m^3)
ΔH_r	Reaction of enthalpy (kJ/mol)	LHTES	Latent heat thermal energy storage
$\dot{q}$	Heat transfer rate	SHS	Sensible Heat Storage
dT	Temperature difference	LHS	Latent Heat Storage
k_{PCM}	Thermal conductivity of PCM (W/m. K)	TCES	Thermochemical Energy Storage
k_{CPCM}	The thermal conductivity of composite PCM (W/m. K)	PCMs	Phase Change Materials
PPI	Parts Per Inches	HTF	Heat Transfer Fluid
dx	Thickness	HP	Heat Pipe
HBN	Hexagonal Boron Nitride		

7. Conclusions

This paper provided a comprehensive overview of recent advancements in several methodologies aimed at enhancing heat transfer in LHTES systems. The study showcased that enhancements in heat transfer can be attained through two basic approaches: increasing the surface area of the heat transfer system or improving the thermal conductivity of the storage material, particularly the PCM. Extended surfaces, such as fins and heat pipes, are frequently employed to augment the heat transmission area. Likewise, the thermal conductivity of the PCM can be enhanced through the incorporation of materials or particles with high conductivity. An essential aspect of the augmentation of heat transfer in LHTES is the approach of combined heat transfer enhancement.

The technique focuses on concurrently expanding the surface area for heat transfer and improving the thermal conductivity of PCM. The utilization of expanded surfaces, such as fins and heat pipes with the incorporation of high-conductivity materials can be used to promote heat transmission in LHTES systems in future research.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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