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Review Article

Review on latent thermal energy storage using phase change material

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ABSTRACT

One of the appealing technologies that contributes to raising the energy storage density is latent heat thermal energy storage. The heat of fusion is isothermally stored at a temperature representing the temperature at which a phase-change material transitions between phases. The current research provides a review of how phase transition materials are used in melting and solidification. Generally, the range of working temperature extends from -20 °C to 200 °C for solidification and melting applications. The first range (-20 to 5 °C) is employed for commercial and domestic refrigeration. The second range (5 to 40 °C) is utilized to lower the energy requirements for air-conditioning applications. The applications includes in third range (40 to 82 °C) are solar collector and heating of water. Applications of absorption cooling, waste electricity generations, and heat recovery are operated at high temperature range (82 to180 °C). There are various types of PCMs for all the above temperature ranges. The present review paper will discuss the application fi eld, Geometry, PCM type, heat transfer augmentation technique and their effects on the performance. The conclusions are mentioned to give more insight about the PCM behavior in various applications.

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INTRODUCTION

Any thermal system's thermal performance can be increased by using thermal energy storage. Because they have a large capacity to charge and discharge at a fixed temperature, high-efficiency materials are utilized to store the energy. Phase Change Materials, denoted by PCM [1], are materials that may change their physical state during the phase change process in a constrained temperature range. Different physical, chemical, and thermal characteristics apply to these materials. The density, thermal conductivity, and viscosity are less significant features but still need to be taken into account [2]. The latent heat of fusion and the temperature of phase shift are also among the most crucial ones. Phase transition materials come in a variety of forms, some of which are naturally occurring and others which are created. Though typically they can be divided into three groups as organic (O), inorganic (IO), and eutectic (E) materials for the solid to liquid phase transformation. Figure 1 provides a more detailed classification of these materials

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as a discussed in [3]. Phase change materials applications includes: casting, melting, freezing, cryosurgery ablation, and soldering. Conduction heat transfer throughout phase change process is described by a moving interface which separates the two phases. These problems are considered as "moving boundary problems". They vary with time during interface movement. The motion of interface with its location are changing with time. So, it should be regarded as an essential part of the general solution. Changing the material properties leads to transform the phase from state to another. Moreover, temperature gradient is discontinuous at the interface. Result in, temperature function for each phase must be assigned. Additionally, changing the density leads to increasing the motion of the liquid phase. a convective term should be included in the heat equation of the liquid phase if the influence of motion is effective. However, this effect in most problems can be neglected [4]. Applications, physical characteristics, and techniques used to improve TES performance were all briefly examined in the literature. The best performance comes from selecting PCMs with the right qualities for a certain application.

The experimental and numerical literatures are reviewed in this work, and combined experimental and theoretical investigations that utilized PCM materials in different cases especially in the field of mechanical engineering.

The literatures are divided into three parts: experimental; theoretical; combined experimental -theoretical parts including the geometry type of PCM, type of heat transfer fluid. The primary goal of this investigation is to cover uncommitted studies in this field with the headlines of researches during last years.

EXPERIMENTAL INVESTIGATIONS

In a vertical tube concentric annular energy storage unit, stearic acid solidification processes were examined by Zhongliang Liu et al. [5]. A copper fin was attached to the hot rod to increase the stearic acid's thermal conductivity by 250%. The PCM's two mechanisms of heat transport are 250% better with this improvement. For the purposes of melting and solidifying paraffin as PCM, Mithat et al. [6] devised and built a thermal storage vertical unit (shell and tube heat exchanger system SATHES). Water worked as the fluid media (HTF) flowing inside the inner tube while the paraffin was maintained in the gap. It has been shown that tilting the outer shell surface at an angle of 5o improves the heat transfer process. Additionally, when the inlet temperature and mass flow rate increased, the total melting time decreased by 30%.

Mete and Yusuf [7], focused on the physics of thermal variations concerned with charging and discharging of Paraffin as a PCM in (ESS) of the horizontal shell-and-tube heat exchanger. The distilled water was used as the HTF flowing in the inner tube. The findings demonstrate that changing the HTF inlet temperature either increased or decreased the rate of melting or solidification inside the PCM. Rathod and Banerjee [8], used shell and tube heat exchanger as ESS with paraffin wax as PCM, for both processes. It has been noted that the total melting time of the PCM decreases with increase in the inlet temperature and mass flow rate of HTF. Jesumathy et al. [9], investigated the PCM processes of paraffin wax in horizontal double pipe HSU. They studied different parameters as a temperature distribution along the axial direction of PCM, heat transfer coefficient, and flow rate. It was noticed that, during melting process the heat flow rate increased by 25% with increase or decrease in the inlet HTF temperature by 2 °C. While, the increasing of heat transfer during solidification process was 11%. Moreover, the melting time decreased about 31% with increase inlet fluid temperature from 70 °C to 74 °C, Mustafa Yusuf et al. [10], studied the eccentricity effect of a horizontal tube on solidification of a PCM in shell storage unit. Results show that the total solidification time increases as the position of the HTF tube deviates from the center of annulus towards the top or bottom of the outer shell.

Yifei Wang et al. [11], presented the thermal action of PCM process of erythritol and air as (HTF) on a vertical shell and tube latent heat thermal storage unit (LHTSU). It was obvious that increase inlet fluid temperature during melting obviously leads to increase in the heat transfer enhancement and decrease in the charging time. While, there was a slight effect for increasing the pressure of the HTF at the same mass flow rate on the thermal behavior of the PCM. Ashish and Sarviya [12], studied the effectiveness by latent heat storage (LHS) for drying of food product. The shell and tube type of (LHS) was used for solar dryer with paraffin wax as a PCM. It was noticed that the LHS is convenient for equipping the heated air to dry the food product during low intensity of solar energy (no sunshine hours). During discharging of LHS, the temperature of air increases in the range of 17 °C to 5 °C for nearly 10 hours duration.

PCM

Solid / Gas	Liquid / Gas	Solid / Solid	Solid / Liquid
Materials	**Organic**		**Inorganic** ⇩
• Organic- Organic • Inorganic- Inorganic	• Metallics • Salt-hydrate		• Paraffin • Non paraffin

Figure 1. Phase Chang Materials (PCM) categories.

Ramalinga and Marimuthu [13], studied the charging and discharging of paraffin wax in a double tube PCM storage in solar collector. The fusion occurred radially towards tube wall. It was observed that melting of wax was ineffective in bottom region of tube because of temperature gradients. Gang Shen et al. [14], utilized RT60 as a PCM in a vertical multi-tube thermal ESS as application of household thermal energy storage. Five HTF tubes were selected to modify the heat transfer phenomena in the system. It was shown that arranging the HTF tubes had a significant influence on the thermal characteristics during melting and solidification processes. Additionally, natural convection was dominated during the melting process, During the early stages of discharge, PCM solidification was quicker in the lower liquid PCM space; however, after that, conduction took over as the primary mechanism of heat transmission.

Digant et al. [15], studied the influences of orientation (0°, 45°, 90°) on thermal behavior of stearic acid PCM (melting point 55.7 to 56.6 °C) in a shell and tube type (LHSU). Where water used as a fluid media. It is shown that the lowest melting time occurs at angle 45°. Kousha et al. [16], used different arrangements of inner tubes in a multitube heat exchanger for different fluid temperatures. The shell was filled with (RT35) while the tube carrying water as (HTF). It is observed that a shorter time of the phenomena was obtained as the number of inner tubes increased. Result in decreasing the surface-averaged Nusselt number was obtained. Table 1. shows a summary of above literatures.

In a solar absorption refrigeration system, PCM was applied. In a high temperature range, it both stores and releases thermal energy. An absorption chiller can be operated for a long time using this energy as a continual source of intake heat. Consequently, the efficiency will be enhanced. In order to enhance the thermal performance of a thermal storage system, Francis et al. [17] employed a concentric annulus filled with erythritol (melting point equal 117.7 °C) as a PCM and provided it with longitudinal fins on the shell side. The amount of store energy during solidification was 70.9% of the maximum energy charged and it used to run an absorption cooling system. Gil et al. [18] designed and built pilot thermal energy storage with an operating temperature extended from 150 to 200 °C. Hydroquinone (melting temperature=166 °C and 173 °C) was applied as a PCM and utilized on refrigeration systems by solar cooling. It was discovered that the hydroquinone

Table 1. Summary of experimental investigations

Researcher	PCM Type	Geometry	HTF	Remarks
Zhongliang Liu [5]	Stearic acid	Vertical annulus	Water	The electrical heating rod was fitted with a new copper fin.
Mithat et al. [6]	Paraffin wax melting point (58-60) °C	Vertical SATHES	Water	Outer surface of the container was tilting to heat transfer Enhancement
Mete and Yusuf [7]	Paraffin wax of P56-58	Horizontal SATHES	Distilled water	Using several flow rates and inlet temperatures
Rathod and Banerjee [8]	Paraffin wax	SATHES	Water	Using different mass flow rates
Jesumathy et al. [9]	Paraffin wax	Double-pipe horizontal latent heat storage unit	Water	Using several flow rates and inlet temperatures
Mustafa Yusuf et al. [10]	Paraffin of P 56-E 58	Horizontal SATHES		Eccentricity effect of inner tube was studied.
Yifei Wang et al. [11]	Erythritol	Vertical Shell-Tube LHTSU	Air	There was a slight effect for increasing the pressure of the fluid on the thermal performance of the PCM.
Ashish and Sarviya [12]	Paraffin wax	Shell-Tube LHS for solar dryer	Air	During times of darkness or when solar energy is of very low intensity, hot air is used to dry food products.
Ramalinga and Marimuthu [13]	Paraffin wax	Concentric annulus	Water	Melting of wax was ineffective in bottom region of tube
Gang Shen et al. [14]	Paraffin wax RT60	Vertical multi-tube	Water	Heat transmission is performed using five HTF tubes.
Digant et al. [15]	Stearic acid (Melting point=56 °C)	Shell-and-tube (LHSU)	Water	The influence of annulus orientation (0°, 45°, 90°) on thermal behavior of PCM
Kousha et al. [16]	paraffin (RT35	Multitube HE	Water	In a multitube heat exchanger, various inner tube configurations were used.

could operate a pilot installation for combined influence absorption.

THEORETICAL INVESTIGATION

Wei-Wei Wang et al. [19], analyzed the influences of the flow rate at the inlet on thermal efficiency of melting and solidification processes. It was shown that these processes had three levels for changing the temperature in PCM processing time. Seddegh et al. [20], studied the thermal efficiency of a vertical shell-tube latent heat (ESS). The findings revealed that the conduction heat flow was more importance in the solidification cases. Additionally, the dominating mode of thermal process in the PCM in the melting cases was natural convection, while conduction was the dominating thermal mode in the solidification cases. Esapour et al. [21], examined the influencing factor of inner tubes numbers filled with water inside a multi tube in the heat exchanger (MTHX) as a geometrical parameter during charging process of RT35 as PCM as shown in Figure 2. It is noted that increasing inner tubes numbers from one to four in the MTHX leads to increase the rate of melting and decrease time period by 29%.

Saeid Seddegh et al. [22], analysed the position effect of shell and tube ESS using PCMs process. It is noticed that, the horizontal position has an excellent thermal performance during part load energy charging because of strong convective heat transfer in the upper part of the solid PCM. However, convection heat transfer in the vertical position has the same intensity in the charging time. In the opposite process, there is no difference between positions. The thermo-convective features between a water (HTF) and paraffin wax (PCM) result in conduction and forced convection in ESS was studied by Abderrahmane et al. [23]. Enthalpy evaluation was employed to investigate the thermal characteristics during phase change processes. It was shown that, the tube and shell dimensions had more impact on the time of storage system. Additionally, compared to the first unit that included paraffin wax only, the thermal storage unit comprising RT60 and paraffin wax produced a greater rate and required less time for storage. Seyed Soheil et al. [24], examined the impact of channel geometries like a circular, elliptical, rectangular, square, and diamond as on melting process in a cylindrica storage. The charching time was found to be 75% of PCM is nearly to same as for all geometries. Then, the main differences occur depending on the PCM geometry and the buoyant force intensity.

Latifa Begum et al. [25], modeled numerically the (SLE) in the heat exchanger with horizontal double pipe and arbitrary-shaped cross section area. It is observed that the temperature change of the fluid is more distinguish on the (SLE) discussed to changing of the flow rate. Moreover, the oblate geometry of inner tube produced higher storage energy than the other geometries. Esapour et al. [26], discussed melting and solidification phenomena of RT-35 PCM mixed with porous foam from metallic in a multitube heat exchanger. PCM was used in middle shell, while water (HTF) flowed across tubes diameters. It was shown that the increase of internal tubes numbers with adding of metallic foam increased significantly charge and discharge rates. when metallic foam exist with porosities equal 0.7 to 0.9 led to decreasing the melting time to 55% and 14%, respectively. Mustafa et al. [27], compared between the RT-50 PCM distributed in the annular space of horizontal double pipe configuration of latent heat thermal energy storage device (case A) and the inner tube (case B) to determine each case gives the best thermal performance. The findings indicate that case B had a 50% faster melting time than case A. Additionally, case A solidification time is 43.4% faster than case B. Hadi et al. [28], the influence of melting, solidification, configurations of multi-layers of RT-65 PCMs. It was obvious that the inner cylinder is more oversensitive than the outer cylinder to the change fluid temperature. Moreover, the inlet saving energy was 23.28% of inlet energy in the case of one-layer of RT-65. While, this percentage increased to 41.67% in the case of three-layers of PCM.

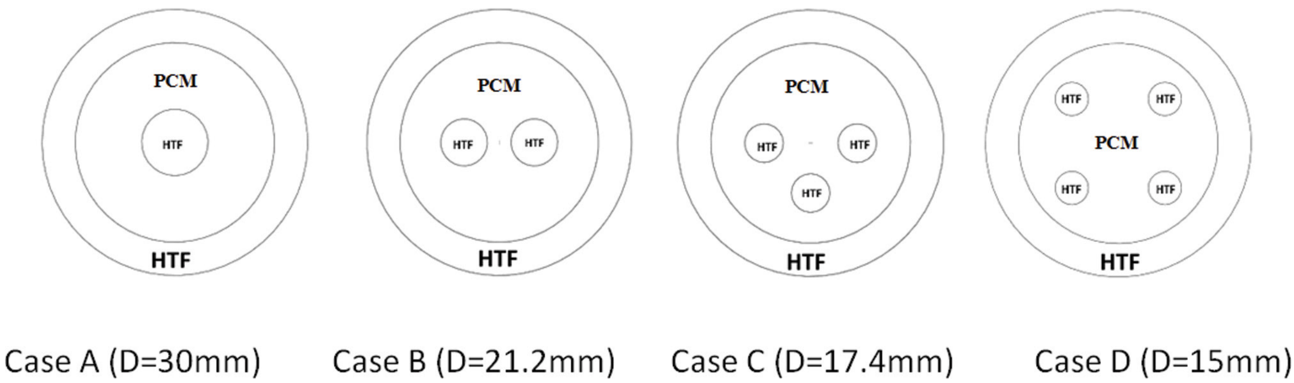

Figure 2. Geometrical configurations for four cases of inner tubes.

Mohammad and Jun [29], investigated the conjugate heat transfer of (PCMs) metal foam bounded between double annuli. A pulse heat power used at the inner annulus wall, while the external wall was cooled by cold fluid. It was concluded that the heat sink packed with metal foam caused heat transfer rate increasing along the hot wall, particularly at Biot number is less than 0.2 (low cooling power). Mahmoud et al. [30], studied ice melting containing Cu nanoparticle with metallic porous matrix in inclined elliptical annulus. Results show that there is no effect of inclination of the elliptical annulus on the liquid fraction. Furthermore, For rest and inclined configurations, the porous matrix was suggested.

Ahmed [31], investigated the ability of PCM as a thermal performance of refrigerator by photovoltaic. Enthalpy method used to model the numerical solution, the study parameters were the PCM thickness and atmospheric temperature. The results show that, can be used PCM in the solar system instead of electric batteries high efficiency and low cost. Christiano et al. [32], investigated the melting of ice inside a cavity using numerical code. The goals of this study were to verify the effect of the heating during melting case and the sub-cooling effect. This issue was solved using the enthalpy-porosity approach, where the convective effects have an action on the melting profiles, performance and melting rates. Table 2 shows a summary of above literatures.

Ben Zohra [33] improved the hot fluid production generated by solar heater used in the thermal storage system (TSS). It was concluded that, inclination angle had an important impact on the on the phase change system

Table 2. Summary of theoretical investigations

Researcher	PCM Type	Geometry	HTF	Remarks
Wei-Wei Wang et al. [17]	n-octadecane	SATHES	Water	There are three levels in the PCM operations where the temperature changes over time.
Seddegh et al. [18]	Paraffin wax	Vertical SATHES	Water	Conduction heat transfer has a larger role in the discharging process.
Esapour et al. [19]	RT35	Multi-tube heat exchanger	Water	Using multi-tube heat exchanger
Saeid Seddegh et al. [20]	Paraffin wax	SATHES	Water	Using two positions, vertical and horizontal
Abderrahmane et al. [21]	Paraffin wax	Thermal energy storage (TES) unit	Water	Using combined Paraffin wax and RT60 to decrease the time of storage.
Seyed Soheil et al. [22]	N-eisocane	Cylindrical storage	Constant wall temperature 56 ºC	Several cross-section channels as a circular, rectangular, elliptical, square, and diamond-like.
Latifa Begum et al. [23]	Gallium	Heat exchanger with arbitrary-shaped cross-section	Air	Using outer hexagonal shell.
Mehdi Esapour et al. [24]	RT-35 embedded in metallic porous foam	Three dimensional multitube heat exchanger	Water	1. Multi-tube H. E. 2. Non-equilibrium thermal boundary conditions
Mustafa et al. [25]	Paraffin type RT-50	Double pipe solar thermal power systems	Water	Two cases were considered: 1. PCM Inside inner tube 2. PCM outside inner tube
Hadi et al. [26]	RT65	Coaxial cylinders	Constant wall temperature	Each section's number of layers and thickness were examined.
Mohammad and Jun [27]	Metal foam	Annulus	The inner cylinder received a pulse heat load.	Conjugate flow and heat transfer were considered.
Mahmoud et al. [28]	Ice as PCM + Cu + metallic porous matrix	Inclined elliptical annulus	Water	Nanoparticles were inserting in the oblate annulus to enhance the liquid fraction.
Ahmed [29]	Photovoltaic panels	Solar system + PCM storage Technique	Air	PCM bater than electric batteries in solar system according to efficiency and cost.
Christiano et al. [30]	Ice melting	rectangular cavity	Water	The convective effects have an effect on the melting profiles, thermal efficiency.

because of more accelerating of the melting and increasing the melting rate. Sevilla and Radulovic [34] tested numerically four different fluid encapsulated materials placed in four design types to state their effectiveness as a small scale, low temperature thermal energy storage (TES). The fluid media was water and PCMs were water, glycerol, MDM and MD3M. It was concluded that the PCM with the highest relevant properties could not charge the tank the fastest. Aditionally, the system heating dynamics was affected greatly by the design of the inlet.

Korty [35] analyzed the heat storage filled with PCMs to conserve available heat and improve its utilization. Water was used as fluid media through the inner tube. The findings indicate that, acceleration in a melting process was caused by an increase in the number of pass, mass quantity of PCM, and flow rate of fluid.

For higher temperature, Fan et al. [36] presented the combined influence of solar absorption system and a latent storage system. Hydroquinone was applied as a phase change media. Two models of these two systems were coupled with each other. The outcomes indicate that, cooling workload of 100 kW able to fulfilled with a hydroquinone volume of 12.5 m^3 without any additional supplied external energy. Three wayes for electricity generation from low temperature heat recovery were predicated by Johansson and Soderstrom [37]. These technologies included thermoelectric generator, organic Rankine cycle, and PCM engine. The findings demonstrate that the PCM system can function effectively for all temperature values taken into account, and that its size may be appropriately controlled to benefit heat recovery sources below 55°C.

Nomura et al [38] studied the lost heat recovery for the latent heat transportation system (LHTS) by NaOH (PCM) at high temperatures grater than 300 °C in steel works. The recovery heat was supplied to a distillation tower of Benzene, Toluene, and Xylene (BTX). According to the findings, the greatest amount of heat that could be stored in a (LHTS) was 2.75 times greater than the amount of heat that could be kept in a sensible HTS..

COMBINED EXPERIMENTAL AND THEORETICAL INVESTIGATIONS

Jian-you [39], used three concentric cylinders (ESU). The middle cylinder contained PCM. The outer cylinder contained the flowing hot fluid for melting process. While, the inner cylinder contains the flowing cold fluid for solidification process. On the thermal energy storage, the effects of inlet temperature and heat rate were investigated. Hosseini et al. [40], studied the action of increasing inlet flow temperature during the charging process of PCM in a shell and tube HE. The experimental study presented the melting happened at various times near to the flow in the tube and getting outwards towards the shell. While, the numerical results presented that the average time period was decreased to 37% as the inlet temperature increases to 80 °C. Martin et al. [41], selected shell and tubes HE as a latent thermal storage unit (LTESU) filled by paraffin RT35 using in Concentrated Solar Power systems. It was concluded that, an upper injection for charging process and a lower one for discharging process were advised. Hosseini et al. [42], presented the thermal case of RT-50 during PCM processes in a shell and tube HE. It was shown that, increasing inlet fluid temperature by 5 °C and 10 °C led to increasing the efficiency in melting process from 81.10% to 88.40% and solidification process from 79.70% to 81.40%.

Kibria et al. [43], investigated the PCM processes dominated by heat conduction in a shell and tube storage unit (TSU) by a paraffin wax filling the shell and water used inside the tube. Results indicate that, heat rate and melting and solidification times are significantly influenced by inlet temperature. Moreover, tube diameter has a more impact than tube thickness for enhancing the thermal features between the fluid and PCM. Agus et al. [44], used three models of (TESU): nozzle, tube, and inner cylinder located concentrically inside shell to study the charging process and find temperature profile, mean surface Nusselt number, and liquid solid interface. The objective of this investigation was finding the melting temperature distribution. The results show that the first model (nozzle-shell) produced best charging process.

Kousha et al. [45], investigated thermal performance of an inclined shell and tube HE with Paraffin RT35 filling the shell as (PCM). It was noticed that the inclination angle didn't influence the heat rate and the temperature variation in discharging case at which the conduction was the dominating mode in this process. Additionally, the heat transfer rate at horizontal position during charging, was more than that at vertical position, and vice versa for the solidification process. Saeid Seddegh et al. [46], studied the development of the solid/liquid interface of a PCM in vertical cylindrical LHTES. It was observed that, during the liquid melting process moved towards top region of the system and the melting front moved towards bottom region. While, in the solidification process, the solidification front moves longitudinally and radially. Idris et al. [47], used three inclination positions of a PCM cylindrical thermal storage system to study the discharge characteristics performance of Paraffin wax. It was noticed that, the PCM cylindrical thermal storage orientation angle had an importance effect on the PCM period time and temperature distribution. Moreover, the inclination angle near to 45° will produce shortest melting time compared with 0° and 90° positions. Yue et al. [48], developed a PCM solar air HE built-in ventilated window to enlarge stored/released latent heat to preheat the ventilated air. It was shown that, the maximum PCM plate depth was 90mm and maximum air space thickness was 6mm for a solar charging period of 6-hours. Wanchun et al. [49], improved the overall thermal study of ventilation system integrated with the inorganic PCM panels by modifying air

Table 3. Summary of combined experimental and theoretical investigations

Researcher	PCM Type	Geometry	HTF	Remarks
Long Jian [31]	n-Hexacosane	Three concentric cylinders.	Water	1. The middle cylinder contains PCM. 2. The outer cylinder contains the flowing hot fluid for melting process. 3. The inner cylinder contains the flowing cold fluid for solidification process.
Hosseini et al. [40]	commercial paraffin RT50 (Rubitherm GmbH)	Horizontal SATHES	Water	the melting happened at different times at positions near to the HTF tube (melting only)
Martin et al. [41]	A paraffin RT35 with a melting temperature of 35 °C	Vertical SATHES	Water	Studied the impact of HTF injection side on the system.
Hosseini et al. [42]	Paraffin RT50	Horizontal SATHES melting and solidification	Water	Using of single and two PCMs system in melting process
Kibria et al. [43]	Paraffin wax	Horizontal SATHES	Water	Tube radius has a greater effect than thickness for enhancing the heat transfer rate between fluid and PCM
Agus et al. [44]	Paraffin wax Melting process	Three models were used: (Nozzle, tube, reducer) and Shell H. E. Models (vertical position)	Water	The first model (nozzle-shell) produced best charging process.
Kousha et al. [45]	A paraffin RT35	Inclined shell and tube HE 0°, 30°, 60°, 90°	Water	No effect for inclination angles on solidification process and the horizontal position gives better results for charging process
Saeid et al. [46]	RT-60 paraffin wax	Vertical cylindrical shell and tube systems	Water	Experimental Visualization Numerical study for melting and solidification process.
Idris et al. [47]	A paraffin wax RT35	A single copper tube is encased in an acrylic shell to display the PCM melting profile.	Water	45° gives faster melting of PCM than 0° & 90°
Yue et al. [48]	50% paraffin wax impregnated fiberboard.	Solar air heat exchanger	Air	Using different PCM plate depth and air space thickness to prove the thermal performance.
Wanchun Sun et al. [49]	Inorganic PCM panels	Plexiglass used to process the shell and channels of the rectangular ventilation system.	Air	Using panels to modify the overall performance in ventilation system

inlet temperature and PCM thermal properties. The results show that, the outlet temperature fluctuation decreases with decrease inlet flow rate or increase panels thickness.

CONCLUSIONS

Latent thermal energy storage (TES) units (or systems) are used widely in concentrated solar power systems. Moreover, the enhanced storage density allows for designing more effective heat exchanger. The most favorable technology used here is the shell and tube HE due to its availability and price. However, PCM process carrying out in solidification and melting cases need to be carefully understand. To comprehend heat transfer better, the present paper reviews the experimental and theoretical studies concerned this phenomenon for different types and geometries of latent energy storage systems (LESS) and PCM. The most important conclusions educed from these studies can be written as follows:

1. The charging and discharging operations are unaffected by an increase in volume flow rate.
2. Arrangement of inner tubes of multitube heat exchanger has no influence on melting time, mixed metal foam rate, and PCM.

3. The melting process quickens and the time needed to complete melting decreases as the inlet temperature increase.
4. The inclination angle of PCM cylindrical thermal storage has a high impact on the PCM melting time and temperature distribution
5. Conduction and convection modes are occurring during PCMs process. However, enhancement techniques of heat transfer cause increasing the heat conduction and vanished of heat convection. Also, investigations of heat conduction and convection by PCMs are required for the optimization methods and techniques.
6. heat transfer enhancement used with PCM due to low thermal conductivity.
7. There is no effect for changing the channel geometry on the discharge time.
8. The annulus eccentricity, radius ratio, angle of inclination of shell-tube heat exchanger has significant effects on charging and discharging process.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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